PDEC TOWER COOLING ENERGY PERFORMANCE ASSESSMENT USING SPECIFIC ENTHALPY CALCULATION METHODOLOGY

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ABSTRACT

Passive downdraught evaporative cooling (PDEC) is a method of passively cooling an internal space using water micronisation i.e. introducing moisture into ventilation supply air streams. To date, PDEC design tools are very limited and varying relative humidity limits are not fully considered. This paper presents a design methodology using specific enthalpy calculations. A theoretical commercial building case study is developed (base case) using dynamic thermal simulation (DTS). Climate locations are hot climates (Lisbon, Portugal and Nairobi, Kenya) to compare differences in cooling potentials. Calculated values show that humidity levels at 50% have a greater rate of cooling capacity compared with lower RH values. Calculated annual mechanical cooling energy reductions while incorporating PDEC Tower are:

- 12% (30% RH), 14% (40%RH) and 16% (50% RH) for Portugal.
- 7% (30% RH), 8% (40% RH) and 9% (50% RH) for Kenya.

This methodology is effective for calculating minimum PDEC cooling available in these climates. This method can be used for RIBA stage 2 analyses (concept design) and enable assessment PDEC system payback.

INTRODUCTION

For internal space cooling, normal practices adopt mechanical air conditioning/comfort cooling systems to maintain indoor thermal comfort, in particular hot climates. These mechanical cooling systems are utilised in continuous operation during working hours for commercial buildings. The use of passive systems such as passive down draught evaporative cooling (PDEC) enables reduction of mechanical ventilation/cooling systems energy. The main aim of sustainable design is to maintain internal thermal comfort temperatures and humidity while minimising usage of mechanical cooling. The application of PDEC into a building is a complex process and requires a great deal of expertise, skill and computational assessment (e.g. CFD). Common arrangements can comprise of either high level microniser system (high level atrium) or PDEC tower treating hot supply air as part of a natural ventilation and cooling strategies within mixed mode (hybrid) type. Figure 1 below indicates how water vaporisation reduces upper level inlet air temperatures and creates negative buoyancy within the tower stack, the reverse of the natural ventilation process.

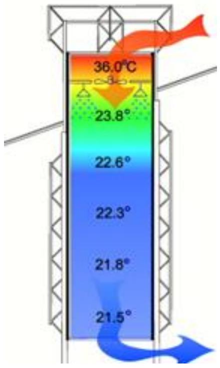

Figure 1- PDEC Airflow and Temperature Process (Ben-Gurion University of Negev, 2016)

When incorporating PDEC within natural ventilation strategies, a higher temperature band can be tolerated (De Dear & Brager, 1998) as humans are more accepting to higher internal temperatures when natural ventilation is available i.e. openable windows. The higher the air temperature limit i.e. natural ventilation can operate <28ºC as opposed to <26ºC, greater cooling energy saving (kWh/Annum) can be realised as detailed in British Standards (1991) and Ford (2002). In order to design PDEC system effectively, main limitations/recommendations are identified by Phillip (2011), detailed below:

- Winds and sand storms: ventilation louvre outlet baffling can be implemented to prevent air back flow caused by high external air pressure.
- Water sourcing (misting towers): water sourcing and harvesting is energy intensive, in countries such as Riyadh; and can be addressed by using alternative tower types/systems (e.g. cool towers)
- Maintenance: Prevention of legionella bacteria.

Furthermore, Phillip, 2011 also identifies that improved residential cooling using PDEC shows a significant difference between ventilation systems i.e. natural ventilation only and final case of using a PDEC system. These results indicate a peak temperature reduction between June and July of approximately 15ºC; where peak temperatures are

46ºC for natural ventilation and 31ºC for PDEC (approximate). Furthermore, research completed for Torrent Research Centre in Ahmedabad, India (Patel et al, 1998), a laboratory building spread over 14,000m^2, was completed to understand how PDEC cooling could reduce annual mechanical cooling energy consumption. PDEC was utilised to serve a number of laboratories and offices via a central open concourse over three levels. Measured results from summer period indicated that internal temperatures are 10-15ºC below peak external air temperatures.
To demonstrate how effective PDEC systems, in terms of annual energy consumption, a study completed by Bowman et al (1998) for commercial offices located in Seville, Spain and Catania, Italy, showed the following predicted energy savings (Table 1):

Table 1
Predicted Annual Cooling Energy Demand Using PDEC System.

Parameter	**Office Location: Catania, Italy**	**Office Location: Seville, Spain**
Air Conditioning Annual Energy Cooling Load (kWh/M^2)	28.5	23.8
Air Conditioning Annual Energy Cooling Load with PDEC Support (kWh/M^2)	20.9	8
Percentage Saving for Each Location (%)	26	66

The aim of this work is to develop a simplified design approach to PDEC system performance assessment enabling building services engineers (CIBSE/ASHRAE) to apply PDEC tower strategies and calculate minimum cooling capacities based upon external air conditions. Currently, existing research is limited to analysing air flow behavior and temperature stratification. This provides scope to adapt these findings and create basic assessment design method for annual mechanical cooling energy reduction. The aim is realised by the following three objectives:

1. Develop new calculation methodology for assessing PDEC cooling potentials.
2. Detail approximate analytical performance for a hot climate to determine maximum available cooling potential (kW_c) at a stated temperature and relative humidity
3. Comparing PDEC energy reduction against a dynamic thermal simulation base case building model (kWh/Annum).

As this system is high pressure water based, particular attention is made to humidity and its associated boundaries. Ideal relative humidity of incoming supply air should be limited i.e. <50% RH. A major part of this research is to determine the ability to calculate PDEC cooling output in order to reduce mechanical cooling load (kWc) and energy consumption (kWhc/m^2). The main variables for this study are external air temperatures (ºC), air moisture analysis using CIBSE psychrometrics, mass flow rate of water from PDEC system (kg/s) and mass flow rate of air (kg/s). Moisture content will be fixed according to acquired weather data within Dynamic Thermal Simulation (DTS) Software.

METHODOLOGY

A new methodology has been created to provide a simplified approach to PDEC design where engineers/designers can incorporate this system within building thermal model calculations as an extension to Dynamic Thermal Simulation process. This incorporates a multitude of different methods such as air psychrometrics, DTS, analytical assessment and validation.

The methodology is summerised in Figure 2 flow diagram below:

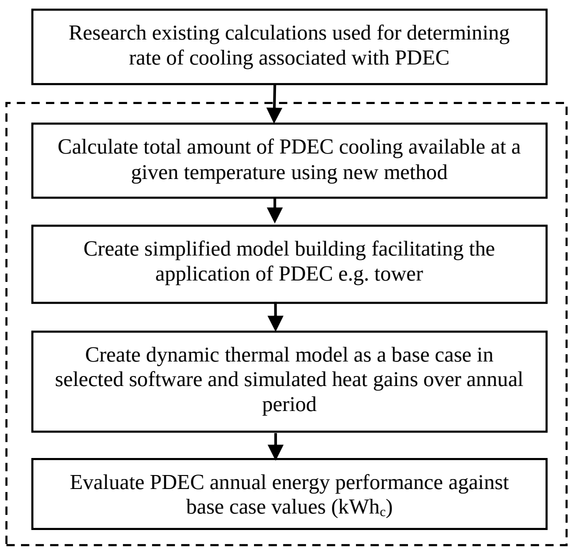

Figure 2 PDEC Design Flow Diagram

A base case (DTS) is created using Designbuilder software, based upon pre-determined assessment tool parameters. Following review for capabilities of various dynamic thermal simulation software, it was decided that this software had an easier user interface and specific cooling outputs were suited to this type of analysis when compared to IES VE & EDSL TAS. Using Design builder software version 3.0.0.105 incorporating DB Sim v1.0.2.1, dynamic thermal building simulations for mechanical cooling loads and input energy are required for the cooling system operation were completed over monthly and annual period (365 days). A solution algorithm of finite differencing and adaptive convection algorithms are used for interior convection including McAdams algorithm used for exterior convection. Within the building simulation calculation, internal air velocities for comfort are 0.1370 m/s (0.4495ft/s). Climate data is design summer year (DSY) in the building simulations for Lisbon, Portugal and Nairobi, Kenya.

PDEC ANALYTICAL PERFORMANCE ANALYSIS

The following equations identified as the method of calculating total cooling capacity of a PDEC system (Q_{PDEC}).

$$Q_{PDEC} = \dot{m}_a\,(\omega_2 - \omega_1)\,hg \qquad (1)$$

Where: $\dot{m}_a$ is the mass flow rate of air; hg is the enthalpy of water at the stated temperature; ω_1 is the moisture content of air at the inlet; and ω_2 is the moisture content of air at the outlet.To calculate building cooling energy reductions when taking into account available PDEC cooling capacities:

$$Qr = Qsim - (Q_{PDEC}\,t) \qquad (2)$$

Where: Qr is revised building cooling energy consumption (kWh/Annum); Q_{SIM} is simulated building base case model for annual cooling (kWh/Annum) and t is estimated time of operation for PDEC system (hours).

EXTERNAL AIR FLOW/MOISTURE CONTENTS

In order to determine cooling potentials of micronised vapour, analysis was completed to calculate optimum micronised water to air absorption based on external air temperature. Table 2 below shows the amount of water that can be absorbed into dry air for each temperature as detailed on CIBSE psychrometric chart (CIBSE, 2012), hence providing base data for performance analysis. Taking into account a 0.001kg/s deduction to allow for water absorption from PDEC system in order to a set limit of how much moisture can be introduced without exceeding 50% relative humidity.

Table 2

Maximum Rate of Moisture Absorption

Ability of Moisture Absorption at Temperature (°C)	Maximum Water Absorption Rate (kg/s) (50%RH)	Assumed External Air Moisture Content to Enable PDEC System Operation (0.001kg/s)
24	0.0094	0.0084
25	0.0104	0.0094
26	0.0107	0.0097
27	0.0114	0.0104
28	0.0121	0.0111
29	0.0128	0.0118
30	0.0138	0.0128

Analysis detailed in Figure 3 below shows total amount of water vapour that can be introduced (kg/hr) at variable flow rates (0.5, 1, 1.5 & 2kg/s) at a stated temperature without exceeding 50% relative humidity. Increasing the air flow rate enables more moisture to be absorbed per kilogram per second.

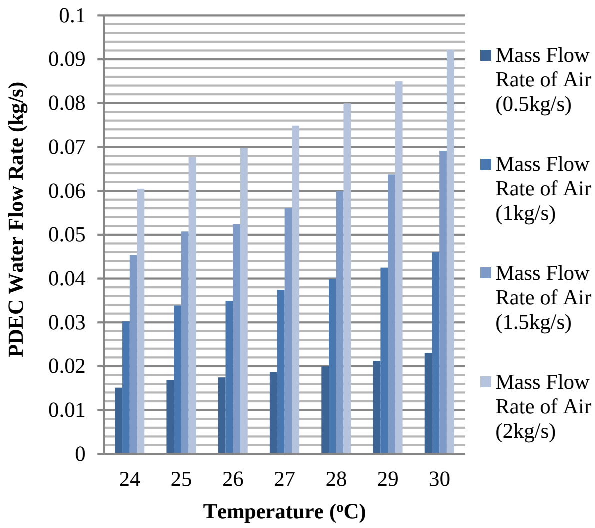

Figure 3 Maximum External Air Moisture Content of Air at Differing Air Flow Rates

Maximum water flow rates are depended on external relative humidity where lower external air moisture contents limit ability to absorb moisture (latent heat of vapourisation). Total change in enthalpy and moisture content can be determined from CIBSE psychrometric chart (CIBSE, 2012). Values for specific enthalpy (dry air) and moisture content for relative humidity's 30%, 40% and 50% are taken from CIBSE psychrometric chart. Interpolation of these values leave an approximate error of +/-5%. The differing values of specific enthalpy and moisture content are shown below in Figure 4 and 5.

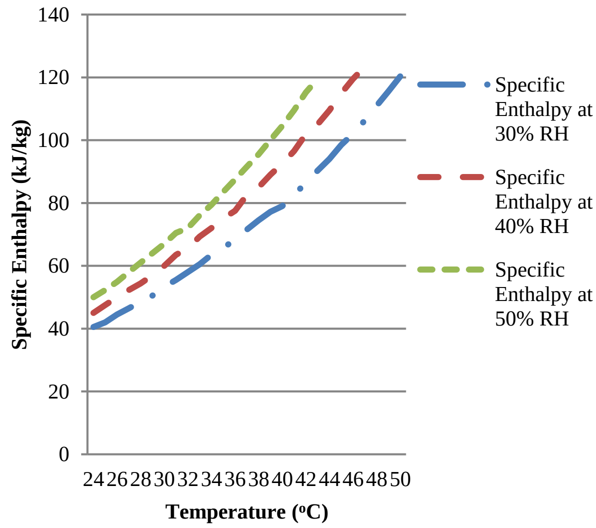

Figure 4 Specific Enthalpy at Varying Humidity's

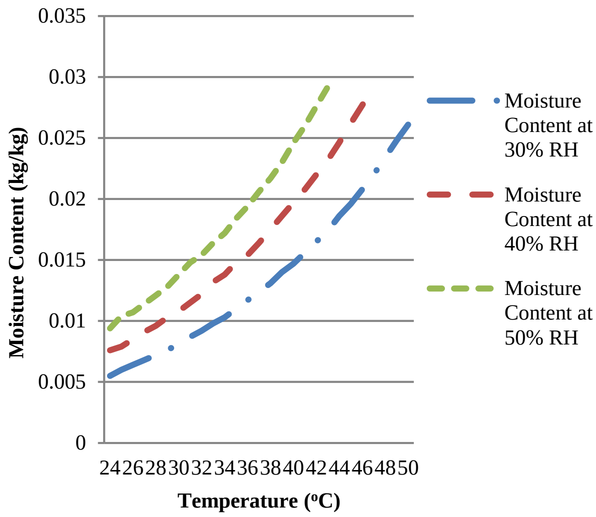

Figure 5 Moisture Content at Varying Humidity's

PDEC POTENTIAL COOLING

In order to calculate PDEC cooling potential, the following process applies:

- Determine PDEC system parameters (analytical).
- Use values obtained for specific enthalpy and moisture contents based on external temperature at varying relative humidity's (30%, 40% & 50%).
- Calculate PDEC cooling potential using equation 1.
- Calculate mechanical energy reductions using equation 2.

PDEC cooling capacity can be calculated using a combination CIBSE psychrometric charts (CIBSE, 2012) and equations (1 and 2) to determine cooling potential for each temperature and external air humidity enabling cooling load to be deducted from simulated base case (Q_{Sim}). Typical parameters for PDEC system operation are detailed in Table 3 below.

Table 3
Typical PDEC System Parameters.

External Temperature (°C) Range	Air Velocity (m/s)	Microniser Flow Rate (kg/s) Range	Relative Humidity (%) Range	Internal Heat Gains (kW) Range
26-45	0.5-1	0.001-0.01	30-40	1-20

It is important to ensure thermal comfort parameters within target comfort zones are achieved as defined by research completed on bioclimatic charts (Lomas et al, 2004). Total cooling load associated with a PDEC system is a function of external air temperature, air mass flow rate and rate of water micronisation (Q_{PDEC}) using specific enthalpy. PDEC cooling potential is determined for temperatures between 24°C to 50°C and micronised water flow rates of 0.0092kg/s. Calculating cooling load potential (Q_{PDEC}) at different relative humidity's (30%, 40% and 50%) is detailed below in Figure 6.

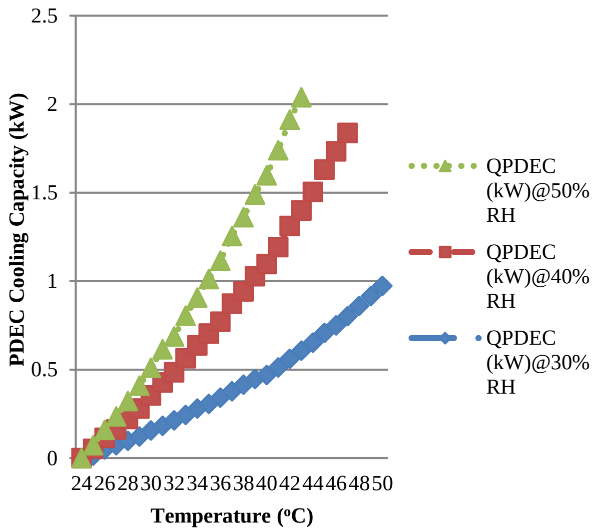

Figure 6 PDEC Cooling Capacities

Increasing PDEC water flow rates can improve the rate of cooling capacity available as shown in Table 4 below at a limiting humidity of 50%RH.

Table 4
Cooling Capacities at Varying PDEC Water flow rates

Minimum External Air Temperature (°C)	Total Amount of Moisture Absorption At Temperature (kg/s)	% Increase in Cooling Capacity
26	0.0095	3.15
27	0.0105	12.38
28	0.0115	16.36
29	0.0122	24.59
30	0.0132	30.30

The limiting factor identified is additional cooling capacity's can only be achieved at given external air temperature i.e. higher PDEC water flow rates at lower temperatures will increase relative humidity beyond 50%. Using cooling capacities shown in Figure 6, diurnal analysis of temperature reduction for varying relative humidity (hourly) is shown below in Figure 7 where the mass flow rate of air is 0.5kg/s. The greater temperature reductions are observed at 14:30. For maximum daily temperature reductions using PDEC system, calculated values show maximum temperature differences of 1.24°C (30% RH), 1.46°C (40% RH) and 1.67°C (50% RH). Figure 7 below temperature differences between each relative humidity.

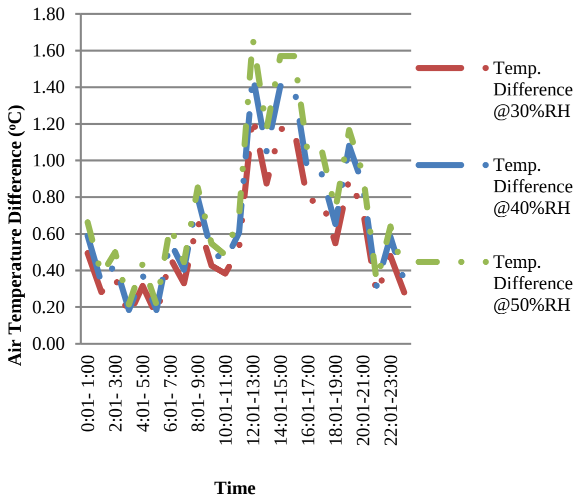

Figure 7 Diurnal Temperature Reduction Comparison

BASE CASE OFFICE BUILDING

A theoretical commercial building model was created for different combinations of passive ventilation and cooling strategies. The building locations selected are Portugal & Kenya. 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 8 below which shows the South facade view.

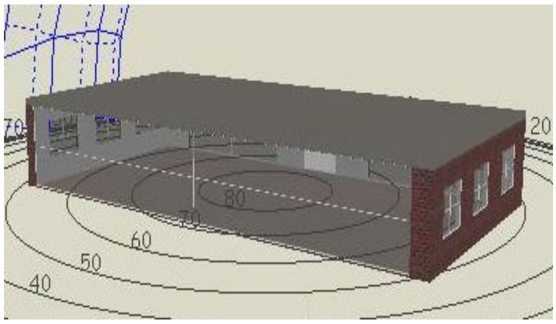

Figure 8 South View of Office Building (Graphic)

Table 5 above shows maximum temperature, minimum temperatures and height above sea level (World Meteorological Organisation, 2016a & 2016b). Climate data used is design summer year (DSY) in the building simulations (DTS). For building parameters and construction materials refer to Table 6 below.

Table 5
Climate Data for Hot Countries

Location	**Height Above Sea Level(m)**	**Max.Tem (ºC)/(ºF)**	**Min. Temp. (ºC) /(ºF)**
Lisbon, Portugal	95	27.9/82.22	8.2/46.76
Nairobi, Kenya	1,676.40	25.6/78.08	11/51.8

Table 6
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 Supply Air condition 12ºC Supply Air Humidity Ratio (g/g)- 0.08 Vents for Natural Ventilation- Large Grille (Dark Slates)- 0.5 Co-efficient of Discharge
Indoor Environmental Conditions (Summer Time Cooling)	Nominal Cooling-24ºC Cooling Set Back- 26ºC
Internal heat gains are based on occupancy and lighting heat gains only	Lighting – 12W/m^2 Occupancy Density- 10m^2/Person Activity- Light Office Work/Standing/Walking Computers 25W/m^2 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

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). 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. Building design criterion is taken from United Kingdom Building Regulations (HM Government, 2010a & HM Government, 2010b), British Standards (1991) 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 completion of dynamic thermal simulation for the base case building, various mechanical ventilation and cooling systems were modelled to determine ideal system. These were Split Cooling and Separate Extract Ventilation; Variable Air Volume (VAV) and Heat Recovery including Outside Air Reset; VAV with Outside Air Reset CAV. The first system identified had most energy efficient performance. The other systems operated within 1% energy operation hence system variation was minimal.

ENERGY PERFORMANCE ANALYSIS

PDEC energy reductions are calculated based on the premise that maximum external air temperature for passive cooling will occur for no more than 60 hours per month assuming that occupants work Monday to Friday. In order to calculate the reductions, for each months peak temperature, a PDEC cooling load is calculated using Equation 1 and deducted from the base case value using Equation 2. To calculate energy savings, the PDEC cooling load is multiplied by 60 hours and then deducted from the energy performance base case model. Qsim (base case) shows the mechanical cooling energy required to maintain thermal comfort for a yearly period. The results are shown in graph plots, Figures 9 and 10, which detail monthly performance when comparing PDEC cooling energy reductions against the base case full mechanical operation model at each relative humidity (30%, 40% and 50%).

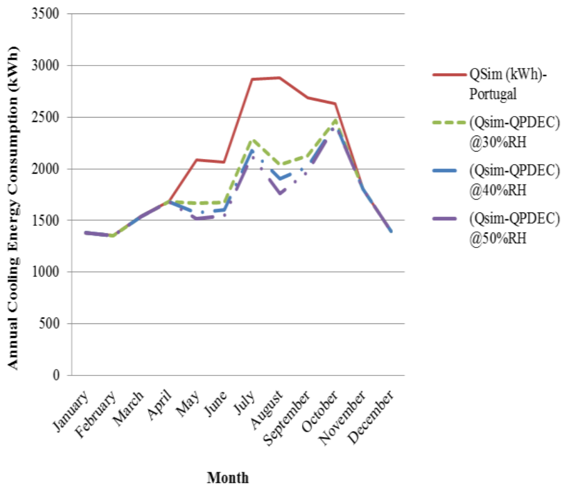

Figure 9 Annual Energy Consumption Analysis Using PDEC in Portugal

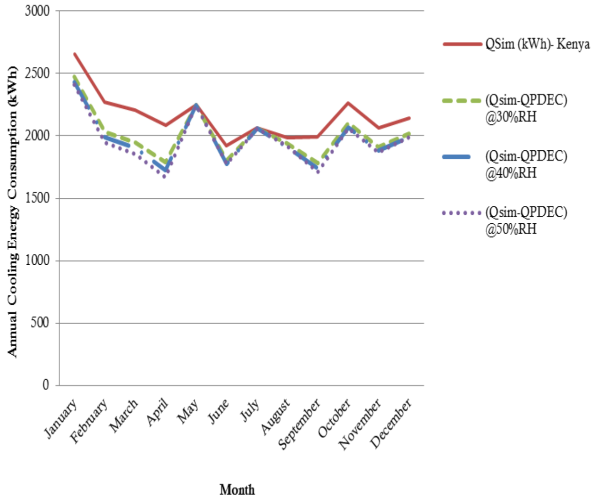

Figure 10 Annual Energy Consumption Analysis Using PDEC in Kenya

In both Figures (9 and 10), the cooling energy reduction at 50% humidity provides the greatest mechanical cooling reduction. For annual energy reduction, Table 7 below shows PDEC potential energy savings at varying humidity levels.

Table 7- Annual Mechanical Cooling Energy Reduction Using PDEC

Month	**% Annual Cooling Energy Reduction (Air 30% RH)**	**Annual Cooling Energy Reduction (Air 40% RH)**	**Annual Cooling Energy Reduction (Air 50% RH)**
Lisbon, Portugal	12.11	14.40	15.96
Nairobi, Kenya	6.87	8.37	9.23

The maximum value of reduction is 15.96% for Portugal and 9.23% for Kenya. This is due to the fact that Portugal has higher peak temperatures where greater PDEC cooling capacities can be realised i.e. the higher the temperature the greater the rate of micronised water vapour absorption.

VALIDATION

This approach analyses minimum potential PDEC cooling capacities that can be available at varying humidity's at a minimum air flow rate. As highlighted by existing research, greater cooling capacities can be achieved at higher relative humidity due to higher specific enthalpy's and greater air flow rates. This study shows a maximum cooling energy reduction 15.96% (Portugal) and 9.23% (Kenya). Existing research completed by Bowman et al., (1998) shows a total annual cooling energy reduction of 26% using multiple towers to spaces, hence increasing air flow into a space means greater cooling capacities are available from the PDEC system. Time of operation is also an important factor as estimated energy reduction values can be greater than 60 hours per month for PDEC system operation.
Furthermore, while attempting to validate, publish research identified in Table 1 (Bowman et al.,1998) shows greater cooling potentials, hence there is a difference between these values and this research. The reasons for these differences are as follows:

- Mass flow rate of water in this study is limited to total amount of latent heat of vapourisation at a given temperature hence limits are placed on relative humidity's.
- This study is limited to 0.5kg/s air flow rates to understand minimum amount of energy savings available.
- Humidity ranges are limited to <50% RH to ensure moisture content does not have greater impact of office space and provide a boundary condition which is useful for building services engineers to apply.

CONCLUSION

This work has been completed to create a design methodology for approximating PDEC system cooling capacity and prove viable application of calculation method. This method can enable a practicing building services engineer to complete a simple assessment to identify if PDEC is suitable for a new construction project. This also included analysis of PDEC system performance to form key outcomes, as detailed below:

- Using specific enthalpy calculations, PDEC cooling energy reductions can be determine based on minimum design requirements (M_a and M_w).
- Minimum annual cooling energy reduction of 6.87% (Kenya) can be achieved.
- It is understood that greater cooling capacities can be achieved greater than 50% RH.
- Optimisation of PDEC water flow rates is particularly important to maintain desired specific relative humidity range (future works).

This methodology is effective for calculating approximate PDEC cooling in hot climates. Ideally this can be used for RIBA stage 2 analyses (concept design) and enable PDEC system payback to be calculated.

FUTURE WORKS

To maximise the potential of this work, the following options are available:

- Develop simple calculation tool to enable fast energy performance assessment by practicing building services engineers.
- Further development of this method is to integrate into Dynamic Thermal Simulation (DTS) software, as an additional application.
- Identify how this system would affect environmental assessments i.e. BREEAM/LEED in terms of credits.
- Using calculated energy reductions, assess impacts of building regulation/code compliance.

ACRONYMS

ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BREEAM	Building Research Establishment Environmental Assessment Method
CIBSE	Chartered Institution of Building Services Engineers
DTS	Dynamic Thermal Simulation
LEED	Leadership in Energy and Environmental Design
PDEC	Passive Downdraught Evaporative Cooling

NOMENCLATURE

Q_{Sim}	Simulated Cooling Load (kWc)
Q_{PDEC}	Calculated PDEC Cooling Potential
Q_r	Revised building cooling energy consumption (kWh/Annum)
t	Time (hours)
kW_c	Kilowatt of cooling
kWh_c	Kilo Watt hours of cooling energy
ω	Air moisture content (g/g)
h_g	Specific enthalpy of air (kJ/kg)
M_a	Mass flow rate of air (kg/s)

M_w Mass flow rate of Water (kg/s)

C_{pa} Specific heat capacity of air (kJ/kg)

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