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AN ASSESSMENT OF SINGLE-SIDED NATURAL VENTILATION POTENTIAL OF FORT BEAUFORT, SOUTH AFRICA

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ABSTRACT
Natural Ventilation Potential (NVP) is the possibility to ensure acceptable indoor air quality and thermal comfort through natural ventilation only. Natural ventilation is possible if the building envelope is strategically oriented in such a way that the occupied zone can harvest relevant quantities of wind and solar commensurate with seasonal needs. Strategic orientation of the building envelope is a requirement that calls for a site specific natural ventilation potential assessment prior to construction. However, site specific natural ventilation assessment may increase construction costs and even delay the construction exercise. Knowledge of the Natural Ventilation Potential of the host region is therefore fundamental as it gives an overview of how the ventilation system will perform under different weather conditions. The paper presents an assessment of the natural ventilation potential of Fort Beaufort and identifies ideal geometrical orientation of buildings for optimum use of wind and solar energy for natural ventilation. The Pressure Difference Pascal Hours concept was used to quantify natural ventilation potential of Fort Beaufort. It was observed that inlet openings should be concentrated on the South while outlets should be on the North for optimum wind induced natural ventilation. Also, the inlet openings should be avoided in the range 230º-260º so as to protect occupants from cold winter winds but concentrated within 160º-185º so that occupants can enjoy the cooling summer winds. Average seasonal NVP values are all positive therefore, meteorological conditions for Fort Beaufort are suitable for natural ventilation.

Keywords: Natural ventilation potential, Pressure Difference Pascal hours, urbanisation, natural ventilation

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INTRODUCTION
South Africa has a high urbanisation rate, standing at 62% as of 2011, with prospects to continue increasing at a rapid rate (Property24, 2016). Urbanisation comes with narrow streets flanked by buildings. Air circulation in such built-up areas is often characterised by recirculation vortexes where contaminants face difficulties in escaping resulting in serious indoor air pollution problems (Bu et al, 2009). It is therefore good engineering practice to envision natural ventilation characteristics of the candidate site prior to construction. Natural ventilation refers to the spontaneous replacement of air in any space with solar and wind being the parent sources of energy responsible for the airflow. Thus, Natural Ventilation Potential (NVP) is the possibility, or probability, to ensure acceptable indoor air quality (IAQ) and thermal comfort through natural ventilation only (Germano & Roulet, 2005). NVP is used as a referral tool for predicting the performance and lifespan of a ventilation system with respect to climatic conditions of the candidate site. Knowledge of the NVP prior to construction therefore allows a building envelope(s) to be strategically oriented so that the enclosure can proportionately harvest relevant quantities of wind and solar energy commensurate with seasonal ventilative cooling/heating needs (Axley & Emmerich, 2002).
To date, researchers are more inclined towards assessing wind and solar resources potential for generating electricity. Thus, no conclusive literature is available on the NVP of Fort Beaufort. Unfortunately, wind and solar patterns vary with geographical location hence NVP is not uniform. Carrying out site specific NVP assessment would be most ideal but this may increase construction costs and even delay the construction exercise. Therefore, prior knowledge of Natural Ventilation Potential of the prospective host region for the proposed construction work is imperative for climate sensitive design.

Exceedance probability analysis is the most common method used by researchers in quantifying NVP. Exceedance probability refers to the frequency at which a random process exceeds some critical value. Bu et al (2009) introduced exceedance probability analysis as a criteria for assessing local wind environment at pedestrian level. Bu & Kato (2011) extended the use of exceedance probability analysis into wind-driven natural ventilation potential analysis in areaway-attached basements. In both publications, exceedance probability was found to be a useful tool for assessing wind driven ventilation potential. Though useful, exceedance probability is less flexible for use in multivariate stochastic meteorological phenomena. Yang et al (2005) therefore introduced the concept of Pressure Difference Pascal Hours (PDPH). The PDPH concept is an equivalent of Heating Degree Days used in calculating heating/cooling loads of a building (Ghiaus & Allard, 2002). PDPH is a measure of how much (in Pascals) and how long (in hours) the ventilation rate was above a certain critical level commensurate with seasonal needs. The PDPH concept was therefore used in this study with the aim of statistically assessing single-sided natural ventilation potential of Fort Beaufort.

Theory on Natural Ventilation Potential Quantification

Natural ventilation depends on pressure difference generated by thermal buoyancy (ΔP_{ther}), wind incidence (ΔP_{wind}) as well as pressure due to fluctuations of air movement through the orifice (ΔP_{fluct}) (Larsen & Heiselberg, 2008). Therefore, the ventilation rate (Q) through a single opening can be determined using the orifice equation;

$$Q = \pm C_d \frac{1}{2} A \sqrt{\frac{2\left|\Delta P_{wind} + \Delta P_{ther} + \Delta P_{fluct}\right|}{\rho}} \quad (1)$$

C_d is the discharge coefficient, A is the area of the orifice and ρ is air density. Equation (1) can be rewritten in terms of meteorological parameters as;

$$Q = A\sqrt{c_1\left|C_p\right|v^2 + c_2\Delta T\Delta h + c_3\frac{\delta C_p \Delta T}{v_r^2}} \quad (2)$$

c_1, c_2 and c_3 are constant weighting factors that cater for position of the ventilation opening relative to wind direction (Larsen, 2006). δC_p is the largest deviation between wind pressure drop coefficient (C_p) values that were calculated using the relationship;

$$C_p = ln\left[1.248 - 0.703sin\frac{\theta}{2} - 1.175sin^2\theta + 0.131sin^3\left(2\theta\frac{L_1}{L_2}\right) + 0.769cos\frac{\theta}{2} + 0.07\left(\frac{L_1}{L_2}\right)^2 sin^2\frac{\theta}{2} + 0.717cos^2\frac{\theta}{2}\right] \quad (3)$$

Angle θ is the angle of wind incidence on the orifice of height Δh. L_1/L_2 is a ratio of lengths of adjacent sides of the building. θ is very useful when choosing positions for ventilation openings so as to facilitate for adequate ventilation depending on summer and winter seasonal needs. In general, pleasant winds associated with summer should be enjoyed and protection is needed from harsh winds while enjoying the sun's warmth in winter (Abed, 2012; Falakian & Falakian, 2013). Thus, majority inlet openings should be perpendicular to summer winds for optimum ventilative cooling (Piquer, 2003). On the other hand, fenestration should be optimised on the side facing the low winter solar path so that ventilative heating is optimised during winter as this complements buoyancy driven natural ventilation (Killough, 2015).

Assuming that indoor temperature (T_{in}) is well mixed and applying energy balance concepts, ΔT can be obtained by subtracting outdoor temperature (T_{out}) from its corresponding indoor temperature. Wind speed measurements at the weather station (v_r) are usually taken at a height of $10m$, therefore normalisation should be done to cater for building height differences and terrain conditions using the formula;

$$v = kv_o H^a \quad (4)$$

H is the building height and k,a are constants for terrain conditions. The ventilation rate calculated using equation (2) may not necessarily meet comfort standards for which the required ventilation rate (Q_r) is given by;

$$Q_r = 0.0075N_p + 0.0001A_f \quad (5)$$

A_f is the floor area and N_p is the number of occupants. Again using the orifice equation, pressure difference (ΔP) between the values calculated using equations (2) and (5) can be determined;

$$\Delta P = \frac{\rho_o(Q^2 - Q_r^2)}{2C_d^2 A^2} \quad (6)$$

Three possible scenarios exist as;

$\Delta P > 0$ then natural forces have the potential to drive ventilation, (7)

$\Delta P = 0$ natural forces alone are not sufficient to meet ventilation needs otherwise (8)

$\Delta P < 0$ showing that natural forces cannot support ventilation. (9)

Thus, pressure difference (ΔP) determines whether ventilation can depend entirely on natural forces or not with the condition represented in (8) being the most favourable. Due to the chaotic nature of the atmosphere, ΔP is bound to change within short intervals therefore an hourly average value of ΔP can be used to summarise ventilation activities within the respective hour. Therefore, Yang et al, (2005) extended the concept of Heating Degree Days used in calculating heating/cooling loads of a building to quantify the Natural Ventilation Potential (NVP) of an area using Pressure Difference Pascal Hours (PDPH) as;

$$PDPH = NVP = 1hour \times \sum \Delta P \quad (10)$$

They used the PDPH concept to assess the NVP of selected Chinese cities using meteorological data of the respective cities. Their model was however limited as it fixed temperature to $22°C$, an assumption too ideal since indoor temperature can vary in response to the chaotic atmosphere. Luo et al (2007) therefore improved the model by incorporating thermal comfort and IAQ issues. Nonetheless, the two models fell short of catering for solution multiplicity, window opening percentage, air velocity and humidity as was revised by Yin et al (2010). The researchers were also silent on single-sided ventilation yet it is very common in residential buildings (Jin, Yang, & Du, 2016). Single-sided natural ventilation is a condition where ventilation is facilitated by openings on only one side of an enclosure Mohamed et al (2011). In a separate study, Yin, et al. (2010) therefore developed a model for single-sided natural ventilation potential motivated by studies done by Larsen & Heiselberg (2008) on single-sided ventilation. Yin, et al. (2010) further noted that single-sided ventilation has lesser PDPH compared to two-sided ventilation. Therefore, single-sided natural ventilation was adopted for this study as it gives the baseline NVP that can be improved by using the double-sided natural ventilation strategy.

METHOD

The basic assumption for the study was that indoor air temperature was uniformly distributed within the occupied space for the North facing energy efficient house. Ten year average meteorological data (temperature, wind velocity and humidity) for Fort Beaufort obtained from the South African Weather Services was used to determine ventilation rate using equation (2). Wind speed was first normalised using equation (4). Terrain conditions for Fort Beaufort's peripheral zone, which can be classified as sub-urban, were assumed to be constant for the whole study area. Thus, terrain constants for wind speed normalisation used were $k = 0.35$ and $a = 0.25$.

After normalising wind speed, indoor air temperature values were estimated using a model developed by (Makaka, 2015);

$$T_{in} = 0.8182T_{out} + 0.013562\varphi - 0.12907v + 0.00038I + 8.18 \quad (11)$$

φ is the outdoor relative humidity and v is the normalised wind speed. ΔT was then obtained by subtracting outdoor temperature from its corresponding indoor value. Values of ΔT were then substituted into equation (2) whence the corresponding ventilation rate was calculated. The opening was assumed to be on the windward side hence $c_1 = 0.0012$, $c_2 = 0.0006$ and $c_3 = -0.0006$ (Larsen, 2006). Values of C_p were approximated by substituting values of θ into equation (3) where $L_1 = L_2$. The required ventilation rate for a five member family, assumed to be occupying a $9.5m^2$ room with a ventilation opening of dimensions: $0.75m \times 1.35m$, was then calculated using (5). Equation (10) was then used to evaluate NVP using values of ΔP calculated using equation (6). Dear and Brager's thermal comfort model (Brager & de Dear, 2001) was used to filter for NVP values corresponding to temperatures that meet adaptive thermal comfort standards whose neutral temperature (T_{com}) is given by;

$$T_{com} = 19.7 + 0.30T_o - 4(\varphi - 70\%) + \frac{11}{3}v \quad (12)$$

φ is the humidity, v is the air velocity corresponding with the required ventilation rate and T_o is the monthly outdoor average temperature. Results from calculations carried out are presented in the section below.

RESULTS AND DISCUSSION

NVP values for the ten-year period from 2006 to 2016 were averaged. Table 1 shows seasonal average values of NVP, wind characteristics, temperature, relative humidity and the corresponding coefficients of variation.

Table 1: Values of average seasonal NVP values and corresponding temperature, humidity, wind characteristics and coefficient of variation for Fort Beaufort.

Season	Wind velocity		T_{out}(°C)	T_{in}(°C)	φ	Average
	v	θ			(%)	$NVP\ (Pahr)$
Summer	1.3	164.2	27.2	23.0	68.6	14.2
Autumn	1.1	203.3	23.4	22.1	65.9	11.3
Winter	1.3	238.0	14.1	21.0	57.0	15.5
Spring	1.4	170.2	19.7	22.6	66.7	16.9
Coefficient of variation (%)	9.3	16.1	19.3	14.9	7.8	30.0

It can be observed from Table 1 that seasonal average NVP values are all positive. This shows that climatic conditions for Fort Beaufort are favourable for natural ventilation. Spring has the highest seasonal average NVP value of $16.9Pahr$ while autumn is the lowest NVP with $11.3Pahr$. Summer and winter NVP values are close to the yearly average of 14.4Pahr at a deviation of -0.2Pahr and 1.1Pahr respectively. Figure 1 is a graphical representation of the seasonal average NVP values.

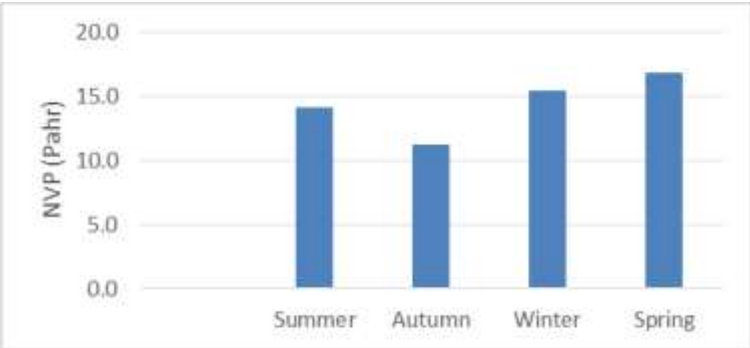

Figure 1: Average seasonal NVP values for Fort Beaufort

With reference to Figure 1, it can be observed that the distribution of NVP is not even. This confirms the fact that NVP has the highest coefficient of variation at 30.0% as shown on Table 1. The comparatively large coefficients of variation for NVP can be explained in terms of temperature difference and wind action (speed and direction). The coefficient of variation for humidity is the lowest at 7.8% hence its contribution to variations in NVP is minimal.

Considering equations (2) and (6), it can be observed that ΔP is a function of temperature (indoor and outdoor), wind (speed and direction) and humidity. Therefore, changes in NVP are explained in terms of variations of these variables. Wind speed influences the speed at which indoor air flows which in turn is determines the occupants' natural evaporative cooling rate facilitated by perspiration (Lim et al, 2012). Humidity in turn is associated with indoor air humidity that influences the evaporative cooling potential of the body.

With reference to the effects of ΔT on NVP variation, the coefficient of variation of indoor temperature is 10.1% against 18.6% for outdoor temperature. Indoor temperature is bound to exhibit minimal variation for the energy efficient house as per assumption made. Hence outdoor temperature is more liable to influence variations in ΔT for NVP calculations. Considering the coefficient of variation for outdoor temperature that is higher than that for wind characteristics, then outdoor temperature is more likely to influence changes in

NVP. This shows that buoyancy contributes more to the variations in NVP compared to wind. Therefore, NVP for Fort Beaufort can be improved by increasing solar gain characteristics of the house and minimising convective cooling during the cold season(s). Thus, maximising fenestration on the northern side of the house will increase insolation during winter. At the same time, minimising ventilation openings in the range of 178 ^{o} -247 ^{o} can minimise convective cooling of indoor air during autumn when temperatures gradually fall to the characteristically low temperatures of winter.

As for wind action, average seasonal wind speed is uniform at 1.3 ms^{-1} except for autumn when it falls by 8% to 1.1 ms^{-1}. This shows that the influence of wind speed on NVP is almost uniform for all seasons for the north facing house hence variations in NVP cannot necessarily be attributed to it. Angle of wind incidence, on the other hand, plays a more crucial role in NVP variation with a 16.1% coefficient of variation. This agrees with the fact that orientation of the building envelope with respect to wind incidence is crucial for optimising natural ventilation. As for wind incidence, wind direction is in the range of 163^{o}-247^{o}. Summer winds range from 163^{o} to 166^{o} while winter winds are in the range of 225^{o}-247^{o}. As temperatures begin to fall in autumn, wind incidence falls within the range of 178 ^{o} -228 ^{o}. As for spring, when temperatures begin to rise, wind incidence ranges from 170 ^{o} -193 ^{o}. This shows that inlet ventilation openings should be concentrated within 163^{o} to 166^{o} for harvesting cooling summer winds while the range 225^{o}-247^{o} should be avoided as this might expose occupants to the harsh winter winds.

CONCLUSION

Based on the reported analysis, meteorological conditions for Fort Beaufort are suitable for single-sided natural ventilation since NVP is favourable for all seasons. Cognisant of wind direction, inlet openings should be concentrated on the South within the range of 160^{o}-170^{o} for the occupied space can benefit from the cooling summer winds. Since wind direction fall within the range of 160^{o}-270^{o}, the southern side experiences an under pressure hence outlet openings should be concentrated on the North that in turn would experience a negative pressure. Also, to protect occupants from harsh winter winds, inlet openings should be avoided within the range of 230^{o}-260^{o} since the unpleasant winds are from this direction range. Future studies should be carried out to explain the uneven distribution of seasonal natural ventilation potential with particular emphasis on relative contribution of each driving force. Such information is vital as it can assist contractors with detailed information on position and sizing of fenestration and ventilation openings. The studies should incorporate terrestrial and house density as these greatly affect air flow and heating characteristics of the house.

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