Original Research Article

Wind speed thresholds for adjusting conventional design criteria for the ventilated improved pit latrine without compromising odour control

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ABSTRACT

Aims: Wind speed plays an important role in the mechanism by which the ventilated improved pit (VIP) latrine controls odour. Higher wind speeds can be leveraged upon to adjust conventional design criteria to minimise cost or accommodate some user preferences that are otherwise discouraged. However, existing technical guidelines pay little attention to opportunities for innovation and cost saving in locations with high wind speeds. In particular, while existing guidelines allow the use of 100 mm PVC vent pipes instead of the default 150 mm in areas with wind speeds exceeding 3 m/s, there is a growing concern that the significant saving in cost could be enjoyed even at a lower wind speed threshold. The objective of this paper is to re-evaluate the wind speed threshold at which the 100 mm pipe may be used without compromising the ventilation rate (20 m^3/h) required for effective odour control. The paper also sought to investigate the chances of leveraging upon high wind speeds to grant user preferences for multiple windows and installation of insect screens, which are conventionally forbidden.

Methodology: The above design parameters were studied in an experimental VIP latrine with simultaneous monitoring of external wind speed and the ventilation rate in the vent pipe.

Results: The results of the study indicate that the 100 mm vent pipe could attain the recommended ventilation rate at an average wind speed as slow as 1.5 m/s. Also, at this wind speed threshold, either the multiple-window design or insect screen used in combination with the 100 mm vent pipe could attain the recommended ventilation rate and should not be outrightly forbidden.

Conclusion: However, for users who desire to adopt the multi-window design with insect screens and still save cost with the 100 mm vent pipe, a wind speed threshold of 2.5 m/s is required.

Keywords: VIP latrine, ventilated improved pit, vent pipe, wind speed, odour control, on-site sanitation

1. INTRODUCTION

The use of safely managed sanitation facilities is one of two indicators for assessing progress towards the sanitation target (Target 6.2) of the Sustainable Development Goal (SDG) 6 [1]. This underscores its importance as an index of human development. Basically, there are three technical options for pursuing safely managed sanitation services. These are the use of facilities that are connected to or involve: (i) centralised wastewater collection and off-site treatment; (ii) excreta emptying from non-sewered systems for off-site treatment; and (iii) excreta treatment and disposal in-situ in non-sewered systems [2]. Resource-constrained regions of the world such as Sub-Saharan Africa face significant challenges in pursuing the sanitation SDG through options (i) and (ii). This is due to the high capital and operational costs of centralised wastewater treatment facilities. The above challenge, among other socio-economic and developmental constraints, restricts many households in low-income communities in Sub-Saharan Africa and parts of Central and Southern Asia to option (iii). Particularly, many low-income households tend to depend on dry on-site sanitation facilities due to their low cost, no requirement of water for flushing and simplicity of operation [3, 4].

Among dry sanitation technologies, the ventilated improved pit (VIP) latrine has gained popularity due to its technical capability to deal with the problems of odour and fly nuisance that are commonly associated with the simple pit latrine [5]. For instance, it is estimated that more than 90% of the population of Lesotho depend on VIP latrines [6]. When properly designed and constructed, users of the VIP latrine can derive most of the health benefits of water-borne sanitation from it at a far cheaper capital and operation cost. It is a favourable alternative to the septic tank and water closet technology for households that are either constrained by unreliable water supply, absence of cesspit emptying services or lack of motorable roads for access to households by cesspit emptying trucks.

The most important external or environmental factor which influences the odour control function of the VIP latrine is the external wind speed. As shown in Fig. 1, odorous air in the latrine pit is 'forced' out through the vent pipe instead of returning into the privy room through the squat hole to generate bad odour.

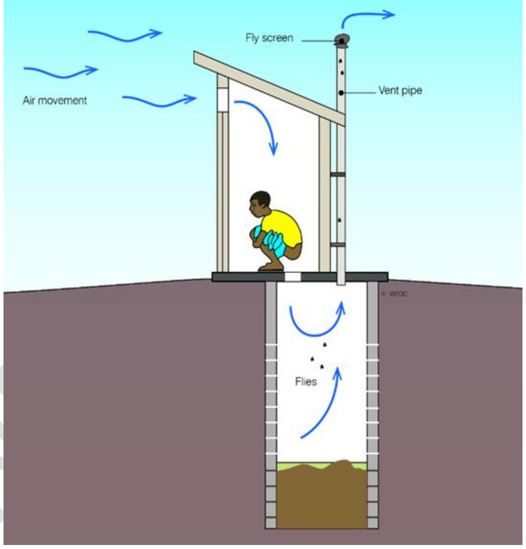

Fig. 1. Action of wind in VIP latrines (Source: Reed [5])

This occurs as a result of pressure difference between the ends of the vent pipe. Pressure difference along the pipe arises from two phenomena involving the action of wind [7, 8]. First, cold air entering the pit through the superstructure displaces warm air due to the higher density of the cold air. This is variously referred to as the stack or chimney effect or buoyancy-driven ventilation [8, 9]. Secondly, pressure difference across the vent pipe is generated by the action of fast-moving air at the top of the vent pipe which creates a negative pressure or suction effect in accordance with Bernoulli's principle [10, 8]. By this action, the vent pipe serves as a syphon by which external air sucks out the air in the latrine pit. Thus, the two phenomena caused by the action of wind work hand-in-hand to replace hot, malodorous air in the pit with cold, fresh air drawn through the superstructure.

Obviously, the higher the wind speed, the greater the effects of the two phenomena and, hence, the greater the rate of ventilation through the vent pipe. Achieving higher ventilation rates through the vent pipe is a keenly desirable outcome of the design of the VIP latrine since it determines its odour control efficiency. It has been established that a minimum ventilation rate of 10 m^3/h is required to maintain odourless conditions in the privy room but to allow for adequate factor of safety, 20 m^3/h is recommended [11]. This implies that, if this level of ventilation is achieved and the latrine is hygienically maintained, there would not be bad odour in the privy room. In other words, if the recommended ventilation rate is achieved, any incidence of bad odour in the latrine cubicle would not be as a result of poor structural design but rather from poor maintenance and management practices. Such poor maintenance and management practices may include the fouling of the squat hole with faeces and urine, storage of used anal cleansing material in the cubicle instead of dropping them into the pit or the depth of the sludge in the pit being too high.

To enhance the chances of maintaining the recommended ventilation rate and, hence, prevent the development of odour in the latrine, initial field investigations on the design of the latrine led to the development of a number of technical guidelines to guide the design of the superstructure and other structural elements. These guidelines mostly seek to derive maximum benefit from the action of wind to control odour generation in the latrine. Detailed discussions of the relevant VIP design guidelines are available in classical publications such as Kalbermatten et al. [12], Ryan and Mara [13, 14] and Mara [11]. Among the design guidelines are those summarized in Box 1.

Keeping to some of the design guidelines in the field have encountered some challenges or conflicts with the interests of some prospective users. For instance, in Ghana, nearly all VIP latrines are routinely fitted with 100 mm PVC vent pipes without any recourse to the prevailing wind speed [15]. This is apparently due to the high cost of the 150 mm PVC pipe. In their study, Obeng et al found that the cost of the 150 mm pipe was 300% that of an equivalent length of the 100 mm pipe and that the difference in price was 540% the daily minimum wage at the time of their study. While existing guidelines provide a caveat for leveraging on high wind speed to avoid this high cost, the question that some practitioners have asked is whether such cost saving can only be considered when the average wind speed is as high as 3 m/s or the 100 mm pipe could achieve adequate ventilation at a lower wind speed?

Box 1. Key VIP latrine design guidelines

1. For vent pipes made of polyvinyl chloride (PVC) material, a minimum diameter of 150 mm should be used to provide an adequate area over which the action of wind takes place. However, the diameter may be reduced to 100 mm in locations where the wind speed exceeds 3 m/s.
2. A window or other openings should be provided in only the windward side of the superstructure. This is to ensure that air entering the cubicle is forced to enter the pit rather than escaping through windows or openings in other sides of the superstructure.
3. An insect screen should not be placed in the window to avoid loss of air pressure across the screen. This is to ensure maximum pressure in the cubicle to push the air down the pit.

(Kalbermatten et al. [12]; Ryan and Mara [12, 13]; Mara [11])

Furthermore, compliance to the requirement to allow a window in only the windward direction and avoidance of insect screens have also seen resistance from some prospective users of the latrine. Obeng et al. [15] found that over 30% of latrines they surveyed had windows or other openings in more than one side of the superstructure and as high as 86% had insect screens fixed in the windows. The authors related these observations to the pursuit of some user comforts and aspiration. Provision of windows in multiple sides of the superstructure was linked to minimising heat in the latrine while installation of insect screens was linked to prevention of entry of reptiles and rodents into the latrine cubicle. The presence of reptiles and rodents in the cubicle scares away some users, especially children, and encourage open defecation. Even though these design choices have been proven to compromise the ventilation rate as compared to the standard design based on conventional guidelines [16], could they be indulged by those users who have the benefit of high wind speeds? In other words, at what wind speed thresholds do their effects become critical or insignificant? At present, no such investigations have been seen in scientific literature. It would be helpful to determine the wind speed thresholds at which these design modifications may be adopted to satisfy the convenience and aspirations of latrine users in order to encourage latrine adoption and regular usage.

This paper hypothesizes that, it is possible to attain the recommended ventilation rate with the 100 mm PVC vent pipe and save some cost at a lower wind speed threshold than 3 m/s. Secondly, some users' preference for multiple windows and installation of insect screens in windows may be satisfied at some wind speed threshold without necessarily failing to achieve the recommended ventilation rate. Hence, the objective of this paper is to re-evaluate the wind speed threshold at which the 100 mm PVC vent pipe may be used to save cost and also to establish the thresholds at which user preferences for multiple windows and installation of insect screens may be satisfied without compromising the odour control function of the latrine.

2. MATERIAL AND METHODS

2.1 Description of Experimental Setups

The study was designed to investigate whether the use of the 100 mm diameter PVC vent pipe in a single-cubicle VIP latrine could attain the recommended ventilation rate of 20 m^3/h at a wind speed threshold lower than the 3.0 m/s previously suggested by Ryan and Mara [13, 14] and Mara [11]. In addition, some modifications of the standard VIP design, which are known to compromise the ventilation rate, were also studied to determine whether they may be adopted at some wind speed without compromising the recommended ventilation rate when they are fitted with the 100 mm PVC vent pipe. Hence the experimental setups comprised the following four designs of the VIP latrine fitted with a 100 mm diameter PVC vent pipe:

i. Single-window design with no insect screen in the window (SWUNS): a standard design based on conventional technical guidelines which require that a window is provided in only one (the windward) side of the superstructure and not fitted with an insect screen.
ii. Single-window design with an insect screen in the window (SWSCR): based on a modification of the standard design in which an insect screen is fitted in the window.
iii. Multi-window design with no insect screen in the windows (MWUNS): based on a modification of the standard design in which windows or other openings are provided in more than one side of the superstructure and not fitted with insect screens.
iv. Multi-window design with insect screens in the windows (MWSCR): based on a modification of the standard design with windows fitted with insect screens provided in more than one side of the superstructure.

The base superstructure had a cubicle with internal dimensions 1.2 m x 1.5 m constructed over a pit of internal dimensions 1.2 m x 2.5 m x 3.0 m deep. Windows were provided in the four sides of the superstructure with dimensions (0.2 m x 0.7 m) arbitrarily chosen to allow an effective area which exceeds three times the cross-sectional area of the vent pipe [13]. Pieces of plywood were used to seal off any of the windows as required by the intended design modification to be investigated at any stage of the study. The insect screen used in the study had apertures 1.2 mm x 1.2 mm. The experimental setup was located on the compound of a public basic school in Prampram, a peri-urban coastal community in Southern Ghana, which is located between latitudes 5°45’ – 6°05’N and longitudes 0°05’ – 0°20’W.

2.2 Measurement of wind speed and ventilation rate

The external wind speed was monitored with the PCE-FWS 20 Weather Station. Data was logged at five-minute interval, which was the device’s minimum logging interval. Concurrently, TSI Incorporated’s Airflow Model TA430 was used to monitor the ventilation rate through the vent pipe with data logging at a minute interval. The weather station and hot wire anemometer were mounted as recommended by Mara 1983b. Each setup was monitored for twelve hours a day (5 am to 5 pm) for three days.

2.3 Data analysis

For each design type, primary data of interest were the external wind speed (logged at five-minute intervals) and five corresponding airflow rates in the vent pipe (logged at a minute interval). The average airflow rate for each five-minute interval was calculated and matched with the corresponding wind speed. The data were sorted using the wind speed as the sorting variable. The data were classified into five categories based on average wind speed thresholds. Category one consisted of data points for which the wind speeds, taken from the lowest over a range whose average yielded a threshold of 1.0 m/s or the closest approximate figure. Similarly, category two consisted of data with speeds from the lowest over a range with an average of 1.5 m/s. Categories three, four and five consisted of data with average wind speed thresholds of 2.0 m/s, 2.5 m/s and 3.0 m/s respectively as shown in Table 1. The range and intervals of the wind speed thresholds were arbitrarily selected to investigate whether the 100 mm vent pipe could attain the recommended ventilation rate at a lower wind speed threshold than the 3.0 m/s previously suggested by Ryan and Mara [13, 14].

Outlier data points were removed and the cleaned data checked for normality of the distribution. Due to observation of non-normality in the distribution of the ventilation rates, non-parametric statistical methods were used in the subsequent data analysis. Consequently, for each design type, the medians of the ventilation rates are reported alongside the interquartile ranges, means and standard deviations. The Kruskal-Wallis test (H) was used to compare the ventilation rates attained within the various wind speed categories for each design type. Where a significant difference was observed among the groups, post analyses using the Dunn's test were performed to establish the pairs of categories whose ventilation rates differed significantly. The data analyses were done using a combination of the Microsoft Excel and SPSS software.

3. RESULTS AND DISCUSSION

3.1 Overview of prevailing wind speeds

It is emphasised that the external wind speed that generated the draught in the vent pipe was not a controlled variable in this study. For each experimental setup or VIP design modification, the prevailing wind speeds during the monitoring of that setup that yielded the average thresholds of 1.0 m/s, 1.5 m/s, 2.0 m/s, 2.5 m/s and 3.0 m/s have been summarised in Table 1. The overall average wind speed was 2.1 m/s.

Table 1. Prevailing wind speeds for various experimental setups

Experimental setup (or VIP design) type	Prevailing wind speeds (m/s)			
	Average (threshold)	SD	Minimum	Maximum
SWUNS	1.0	0.25	0.69	1.36
	1.5	0.36	0.69	2.06
	2.0	0.76	0.69	3.73
	2.5	1.05	1.36	5.53
	3.0	0.97	1.80	5.53
SWSCR	1.0	0.20	0.69	1.26
	1.5	0.41	0.69	2.03
	2.0	0.73	0.69	3.30
	2.5	0.80	1.36	4.54
	3.0	0.58	2.03	4.54
MWUNS	1.0	0.15	0.80	1.23
	1.5	0.41	0.80	2.17
	2.0	0.70	0.80	3.39
	2.5	0.79	1.36	4.63
	3.0	0.63	2.36	4.63
MWSCR	1.0	0.19	0.56	1.23
	1.5	0.60	0.56	2.93
	2.0	0.91	1.13	4.06
	2.5	0.89	1.46	4.06
	3.0	0.76	1.93	4.06

The lowest wind speed threshold that has been reported to have some technical significance is 0.5 m/s. Below this level, the contribution of thermally-induced ventilation is considered to be significant. Therefore, in areas where the mean wind speed is below 0.5 m/s, it is generally recommended to enhance the magnitude of this component of ventilation by painting the vent pipe black to increase absorption of solar radiation [11]. With a minimum of 0.56 m/s recorded in this study, the wind speeds at the study site do not fall below this critically low level.

3.2 Comparison of ventilation rates in different VIP designs

Table 2 presents the ventilation rates in the four VIP designs for all wind speeds. It can be seen from the results of the Kruskal Wallis test that there are significant differences among the ventilation rates in the four designs (p=0.000). Post hoc pairwise comparisons of the different design types using Dunn's test indicated that the there is a significant difference between each pair except SWUNS and SWSCR. For detailed explanation of the factors responsible for variations in ventilation rates among the four types of designs, the reader is directed to Obeng et al. [15, 16].

Table 2. Comparison of ventilation rates in different VIP designs for all wind speeds

Experimental setup (or VIP design) type	Ventilation rates (m^3/h)			Kruskal Wallis test (H)	p-value
	Median	Interquartile range	Mean rank		
SWUNS	32.65	20.49	370.47	77.653	0.000
SWSCR	33.91	22.96	364.19		
MWUNS	24.59	8.49	281.37		
MWSCR	19.50	9.61	201.14		

As mentioned earlier, the multi-window design is known to reduce the ventilation rate through the vent pipe because it allows air entering the latrine cubicle to escape through the extra window(s) instead of being forced through the squat hole [11]. This explains the lower rates of ventilation in the multi-window designs (MWUNS and MWSCR) as compared to their corresponding single window designs (SWUNS and SWSCR). On the other hand, the provision of an insect screen reduces the air pressure in the latrine cubicle due to head losses that occur as the air moves across the screen. The results of the post hoc pairwise comparisons indicated that this effect is only significant when the multi-window design is adopted.

Due to the preference of some VIP latrine owners for these design modifications for various reasons as earlier explained, this study sought to gain a deeper understanding by investigating how their adoption influence the average wind speed threshold at which the 100 mm vent pipe may attain the recommended ventilation rate. This was done by doing the comparisons at different wind speed thresholds rather than the general comparisons that have been done in previous studies. Fig. 2 shows how the ventilation rates in the four VIP designs compare to one another at different wind speed thresholds.

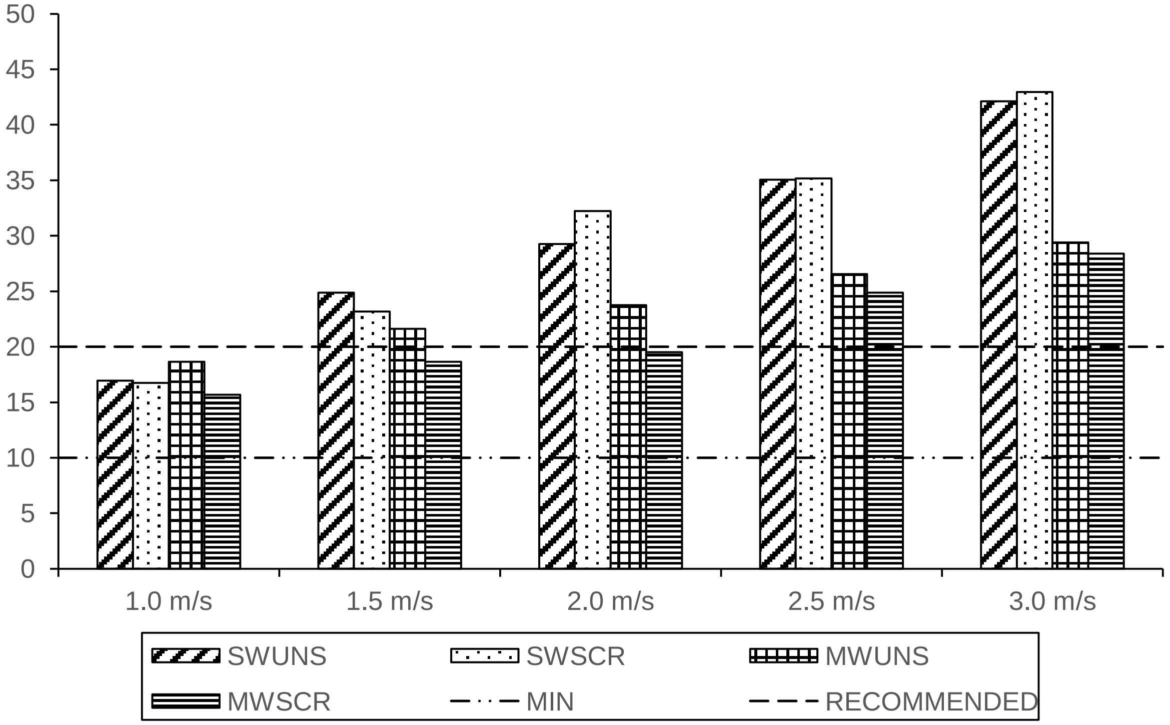

Fig. 2. Ventilation rates (m^3/h) in a 100 mm PVC vent pipe fitted to different designs of VIP latrines at varying wind speed thresholds

The comparisons done in this study for various wind speed thresholds suggest that the effect of the multi-window design on the ventilation rate is minimal at lower wind speeds – and may even be beneficial at much lower wind speeds – but increases directly proportionally with wind speed. For instance, a comparison of the median ventilation rates reported in Table 3 for the different designs reveals that the ratio of the ventilation rate in the single window without insect screen (SWUNS) to that of the multi-window without insect screen (MWUNS) increases with increasing wind speed. At a wind speed threshold of 1.0, the ventilation rate in the SWUNS fell short of that in the MWUNS by 9.10%. However, at wind speed thresholds 1.5, 2.0, 2.5 and 3.0 m/s, the ventilation rate in the SWUNS is higher by 15.03%, 23.21%, 31.93% and 43.67% respectively. This may be due to the fact that, at higher wind speeds, more air escapes through the extra windows much more quickly before the air is afforded the opportunity to enter the pit through the squat hole. On the other hand, at very low wind speeds, having additional windows may rather facilitate entry of more air into the cubicle. A comparison of the ventilation rates in the four design types at the lowest wind speed threshold of 1.0 m/s that was studied using the Kruskal Wallis test showed no significant difference among them (H=1.443, p=0.695). Nevertheless, this observation needs to be further studied and analysed with additional data from locations were the wind speeds fall below 0.5 m/s. At each of the higher wind speed thresholds (1.5 – 3.0 m/s) the differences among the design types were found to be highly significant (p<0.005).

3.3 Variation of ventilation rate with wind speed thresholds

Results in Table 3 show that the ventilation in each of the design types increases significantly among the five wind speed thresholds (p=000). Higher wind speeds facilitate both the chimney effect and Bernoulli's principle (suction effect of wind) [7, 8] and, therefore, lead to higher ventilation rates.

TABLE 3. Ventilation rates in different VIP designs at varying wind speed thresholds

VIP design type	Wind speed threshold	Ventilation rates (m^3/h)				Kruskal-Wallis (H)	P-value
		Mean	SD	Median	Interquartile range		
SWUNS	1.0	16.13	7.32	16.96	9.04	47.821	0.000
	1.5	24.73	9.39	24.87	12.72		
	2.0	30.94	14.25	29.25	18.79		
	2.5	38.04	18.34	35.04	18.79		
	3.0	44.85	18.54	42.11	26.42		
SWSCR	1.0	17.33	3.60	16.74	5.83	28.719	0.000
	1.5	24.61	8.87	23.17	16.96		
	2.0	30.64	12.41	32.22	21.72		
	2.5	35.61	13.04	35.18	18.02		
	3.0	41.27	12.37	42.96	13.78		
MWUNS	1.0	17.56	2.48	18.65	4.24	37.601	0.000
	1.5	22.10	4.86	21.62	8.97		
	2.0	24.44	5.50	23.74	8.05		
	2.5	27.04	5.19	26.56	7.63		
	3.0	28.76	5.29	29.39	7.63		
MWSCR	1.0	15.59	2.35	15.68	2.19	37.106	0.000
	1.5	19.09	4.74	18.65	5.37		
	2.0	22.07	6.19	19.50	9.33		
	2.5	25.26	5.86	24.87	11.59		
	3.0	27.86	5.78	28.40	7.98		

However, post hoc analysis using the Dunn's test revealed that, in all the VIP design types, there is no significant effect between any successive wind speed thresholds. Thus, the ventilation rates in any of the design types are not significantly different between, for example, wind speeds 1.0 m/s and 1.5 m/s or 2.5 m/s and 3.0 m/s. This implies that wind speed changes up to 0.5 m/s produce no significant difference in ventilation. On the other hand, wind speed differences of 1 m/s or above led to significant differences in ventilation rates in nearly all possible pairs of comparisons with the exception of two pairs of comparisons. These are the single window with screen design (SWSCR) in which wind speeds thresholds 1.0 m/s and 2.0 m/s produced no significant difference in ventilation rate and the multi-window with screen (MWSCR) at wind speeds 2.0 m/s and 3.0 m/s. These two exceptions may have arisen due to unusual changes in wind direction during the monitoring of those experimental setups. Generally, it has been previously reported that a unit (1 m/s) change in wind speed leads to 28.7% change in the ventilation rate if all other factors are held constant [17].

3.4 Wind speed thresholds for attaining the recommended ventilation rate

Fig. 2 shows how the ventilation rates in the four VIP design types at the various wind speed thresholds compare to the minimum and recommended ventilation rates for avoidance of odour nuisance. The least ventilation rate (15.68 m^3/h) was recorded in the multi-window with screen design (MWSCR) at a wind speed threshold of 1.0 m/s. Thus, in the most compromised superstructure design, the 100 mm vent pipe could attain the minimum ventilation rate of 10 m3/h with over 50% factor of safety. Nevertheless, none of the design types was able to attain the recommended ventilation rate of 20 m3/h at that wind speed threshold. This implies that those who make use of the 100 mm vent pipe in built-up communities where the average wind speed does not exceed 1.0 m/s are not guaranteed adequate factor of safety against the development of structurally-induced odour nuisance in their latrine cubicles.

On the other hand, all the four design types exceeded the recommended ventilation rate at a wind speed of 2.5 m/s. This implies that, at that wind speed threshold, any odour nuisance in the latrine cubicle would be arising from poor maintenance and management practices rather than the design of the latrine. Between the 1.0 m/s and 2.5 m/s thresholds, only the multi-window with screen (MWSCR) failed to attain the recommended ventilation rate. Thus, if the superstructure is designed following conventional guidelines, a wind speed threshold of 1.5 m/s is all that is needed to use the 100 mm vent pipe as opposed to the excess of 3.0 m/s that was initially recommended. At 1.5 m/s, the standard design (SWUNS) attained a median ventilation rate of 24.61 m^3/h. Hence, this study suggests that, for standard latrines constructed under professional technical supervision in areas with average wind speeds exceeding 1.5 m/s, with or without insect screens in the windows, it is safe to use the 100 mm vent pipe to save some cost as commonly seen in Ghana. On the other hand, for prospective users in such locations who seek to install insect screens to secure the latrine from entry of rodents and reptiles, the 100 mm vent pipe can still be used if the multi-window design is avoided. However, for users who insist on a multi-window design with insect screens, the only guarantee to attaining adequate ventilation rate to avoid structurally-induced odour nuisance is a wind speed threshold of 2.5 m/s or the use of the 150 mm vent pipe. Increasing the vent pipe from 100 mm to 150 mm has been previously reported to increase the ventilation rate by 58% [17].

4. CONCLUSION

From the results of the study, it can be concluded that, even though the use of the multi-window design reduces the ventilation rate in the VIP latrine, the magnitude of the effect is actually minimal at lower wind speeds and increases proportionally with the wind speed. Also, the well-known influence of wind speed on the ventilation rate is insignificant at wind speed variations not exceeding 0.5 m/s when the 100 mm vent pipe is used. Contrary to previous suggestions that the 100 mm vent pipe can only be used in the standard superstructure design in locations where the wind speed exceeds 3 m/s, this study suggests that this size of vent pipe can attain the recommended ventilation rate in places with average wind speeds as slow as 1.5 m/s. Furthermore, at this wind speed threshold (1.5 m/s), either the multiple-window design or insect screen used in combination with the 100 mm vent pipe could attain the recommended ventilation rate for effective odour control. However, in the extreme case where a prospective owner desires to adopt the multi-window design with insect screens and still save cost with the 100 mm vent pipe, the ventilation rate required for effective odour control can only be guaranteed at a wind speed threshold of 2.5 m/s. On the basis of these findings, VIP latrine users who only wish to use insect screens to prevent entry of rodents and reptiles into their latrines in areas with wind speeds exceeding 1.5 m/s but below 2.5 m/s are advised to avoid the multi-window design if they wish to avoid the extra cost of the 150 mm vent pipe. Further research is recommended to better understand the relative performances of the modified design options at critically low wind speeds (<0.5 m/s).

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