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ORIGINAL ARTICLE

Optimising ventilation to control odour in the ventilated improved pit latrine

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Abstract

The rate of ventilation through the vent pipe of a ventilated improved pit latrine is the main technical factor that determines its efficiency in odour control aside the maintenance and cleaning practices of the users. Even though the factors affecting the ventilation rate have been well researched, they have not been previously related in a mathematical model to quantify the relative effect of the various factors on the ventilation rate. The objective of this paper is to develop such a model that could be used to optimise and predict the ventilation rate as a function of relevant design criteria and weather conditions. The ventilation rates produced by various design modifications in an experimental ventilated improved pit latrine were measured under monitored weather conditions. A linear regression model was used to assess the relative effect of the various design modifications and the elements of weather on the ventilation rate. It was found that the diameter of the vent pipe is the most important factor which accounts for 53% of variations in the ventilation rate, followed by the external wind speed, which accounts for 25% of changes in ventilation. The provision of windows in other sides of the superstructure other than the windward side leads to a reduction of 32% in the ventilation rate and accounts for 9% of the variations in the ventilation rate. A regression model developed in this study could be used to optimise and predict the ventilation rate based on a set of design criteria and meteorological data.

Keywords VIP latrine · Ventilated improved pit · Ventilation rate · Dry sanitation technology · Modelling

Introduction

Dry on-site sanitation technologies are the most widely used among households in low-income communities (Obeng et al. 2015). With proper design and construction, they qualify as improved sanitation technologies (Karnib 2014). They are especially popular in communities where the use of septic tanks with water closet and other water-dependent systems is technically unfeasible due to inadequate water supply, lack of motorable access roads to empty tanks or some other site constraints (Brikké and Bredero 2003; Paterson et al. 2007). In such situations, even households that could afford the more convenient and 'prestigious' water closet system are compelled to rely on dry sanitation technologies. For instance, Obeng et al. (2015) reported that some households in a Southern Ghana community had abandoned their septic-tank-with-water-closet systems and resorted to ventilated improved pit (VIP) latrines due to irregular water supply to the community. Consequently, the study reported that 70% of the residents depended on dry sanitation systems.

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In spite of their usefulness in resource-constrained communities, dry sanitation technologies are often associated with intense odour. Odour nuisance discourages some potential users from adopting these technologies in their homes or avoiding existing ones (Appiah and Oduro-Kwarteng 2011; Keraita et al. 2013). Consequently, some persons who have access to some types of dry sanitation facilities sometimes resort to open defecation (Obeng et al. 2015). This has made odour control a key focus in the quest for innovations in dry sanitation technologies. An example of major breakthroughs include the use of a water seal, i.e. a layer of water in a bent pipe section, to prevent odorous gases from escaping from excreta retention systems as applied in the pour-flush toilet (Franceys et al. 1992; Harvey et al. 2002). Perhaps, the earliest and simplest innovation to control odour in the traditional simple pit latrine is the removal of the odorous gases through a vent pipe which directs the gases from the pit into the atmosphere. This led to the development of the VIP latrine (Mara 1984; Ryan and Mara 1983a), which has emerged as a compromise choice for households that are constrained by environmental factors from adopting technologies that are at higher levels on the sanitation ladder (Lenton and Wright 2005; Kvarnstrom et al. 2011).

It has been reported that a properly constructed and maintained VIP latrine can afford the users most of the health benefits and conveniences of conventional sewerage at a relatively lower cost (Kalbermatten et al. 1980; Ryan and Mara 1983a). In terms of odour generation, the technology has been found to perform much better than the traditional pit latrine. For instance, using the concentrations of hydrogen sulphide in latrine cubicles as a surrogate for the level of odour, Obeng et al. (2016) found that the levels of the gas measured in VIP latrines in Ghana was significantly lower (mean 0.03 ppm; SD 0.06 ppm) than those measured in the traditional pit latrine (mean 0.13 ppm; SD 0.22 ppm). The study established a correlation between the concentrations of the gas and the latrine users' perception of the level of odour in the cubicles.

Nevertheless, the odour control function of the VIP latrine still needs some improvement. Even though the average levels of hydrogen sulphide measured by Obeng et al. (2016) in the VIP latrines is lower than the threshold of 0.05 ppm recommended by the World Health Organisation (WHO) for the avoidance of "substantial complaints about odour annoyance" (WHO 2000), it was still three times the average levels found in water closet toilets (mean 0.01 ppm; SD 0.02 ppm). Besides, the wide variation in the levels of the gas measured in the VIP latrines (SD 0.06) suggests that some of the VIP latrines could have levels that are significantly higher than the WHO's recommended threshold and could, therefore, elicit "substantial complaints about odour annoyance" from the users and lead to open defecation. With odour levels in VIP latrines found to vary inversely with the rate of ventilation in the vent pipe (Obeng 2016), it is imperative to ascertain the factors that affect the ventilation rate and how to optimise them to minimise odour.

The technical design and odour control mechanism of the VIP latrine are discussed in pioneering works such as Kalbermatten et al. (1980), Ryan and Mara (1983a, b) and Mara (1984) and illustrated in Fig. 1. Air entering the superstructure through an opening provided in the windward side is pushed down the pit through the squat hole where it displaces warm, odorous air through the vent pipe into the atmosphere. This mechanism is controlled by similar scientific principles as those which govern airflow through chimneys.

The major factor that determines the rate of ventilation or airflow in a vent pipe is the difference in pressure between the ends of the pipe (ASW 2011), i.e. the difference between the pressure of air in the pit of the latrine and the external air at the top of the pipe. This pressure difference has been attributed to two main phenomena, namely: the stack effect and Bernoulli's principle (Awbi 1994). The stack effect, which is also referred to as natural draft, is the phenomenon in which a mass of hot air rises or is displaced by a colder air mass due to the relatively lower density of the hot air (Wong and Heryanto 2004). This phenomenon occurs in the VIP latrine as cold external air enters the pit through the superstructure and displaces hot air in the pit through the vent pipe. This effect is enhanced by the heating effect of the sun on the vent pipe which increases the temperature of the column of air in the pipe (Ryan and Mara 1983a). Enhancement of stack ventilation is the reason why it is sometimes recommended that vent pipes should be painted black in order to absorb and retain the sun's heat energy (Mara 1984).

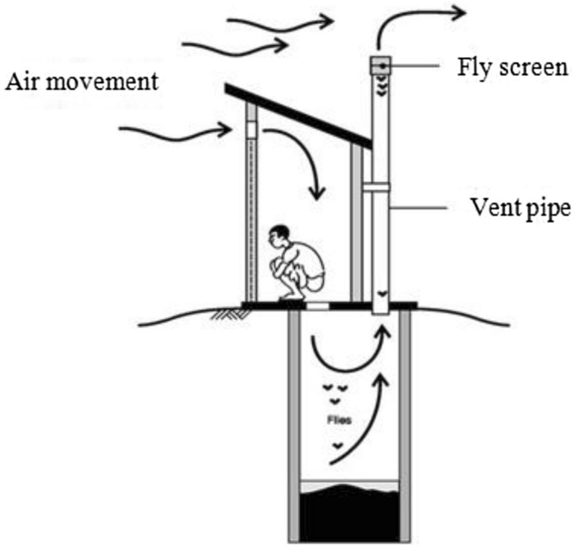

Fig. 1 The chimney effect in a VIP latrine. Source: Harvey et al. (2002)

On the other hand, the pressure gradient between the ends of the vent pipe is established by the faster movement of air across the top of the vent pipe which reduces the pressure at the top of the pipe in accordance with Bernoulli's principle (ASW 2011). According to Bernoulli's principle, in the absence of energy (head) losses, the sum of the pressure energy, kinetic energy and potential energy possessed by a fluid remains constant (Darby 2001). Thus, with potential energy remaining constant at a constant height, increase in kinetic energy or wind speed leads to a drop in air pressure at the top of the vent pipe. Since external air farther from the ground is less obstructed and moves faster, the reduction in pressure is enhanced if the height of the vent pipe is increased. The suction effect of wind is also enhanced by installing a pipe of a bigger diameter which provides a relatively larger cross-sectional area over which the action of wind takes place (Ryan and Mara 1983a).

Based on these theoretical considerations, a set of design codes and guidelines have been recommended to guide the design of the VIP latrine including the following (Franceys et al. 1992; Mara 1984):

- Windows or openings should be provided only in the windward side of the superstructure to prevent a significant decrease in air pressure needed to push air through the squat hole.
- Insect screens should not be installed in windows or openings to avoid head losses across the screen.
- For vent pipes made of PVC, which is the most common, a minimum diameter of 150 mm should be used in single pit latrines but 100 mm may be used where the local wind speeds exceed 3 m/s.
- Vent pipes should be installed to a minimum height of 500 mm above the roof.

Observations made in the use of the VIP latrine in Ghana reveal that some households ignore some of these guidelines and introduce innovations and preferences ostensibly to address their own perceived challenges with the use of the conventional design. For instance, some latrines were seen with windows provided in other sides of the superstructure, a measure the owners explained to have adopted to minimise heat in the cubicle. Others had insect screens installed in the windows and openings to prevent entry of insects, rodents and reptiles (Obeng et al. 2015). Such modifications point to a need to assess the relative effect of 'violations' of guidelines on the ventilation rate in the vent pipe. Further, they suggest a need to assess the extent to which advantage could be taken of favourable environmental factors such as high wind speeds or some other design criteria to compensate for or accommodate any purposeful modification in the superstructure and optimise the ventilation rate.

The above-mentioned calls for a mathematical model for quantifying the relative effect of the various design criteria and environmental factors on the ventilation rate. Even though existing VIP design guidelines are based on verified scientific principles, as discussed above, the magnitudes of the relative effects of various design parameters and elements of weather, which are needed to optimise the ventilation rate, are currently not established. The objective of this paper is to develop such a model that could be used to optimise and predict the ventilation rate as a function of relevant design criteria under varying weather conditions.

Methods

Study location

The study was conducted in Prampram, the administrative capital of the Ningo-Prampram District in the Greater Accra Region of Ghana. It is situated between latitudes 5°45′N and 6°05′N and longitudes 0°05′W and 0°20′W along the coast of the Gulf of Guinea. It has a population of 7800 and an estimated 1635 households. The major occupations of the residents are fishing, farming and trading (Ningo Prampram District Assembly 2012).

Description of model variables

Based on the theoretical considerations discussed in the previous section, the design parameters and environmental factors presented in Table 1 were selected. Variations of these parameters were monitored simultaneously with the ventilation rate in the vent pipe of an experimental VIP latrine.

Experimental setup combinations

An experimental VIP latrine which had internal cubicle dimensions of 1.2 m × 1.5 m was built on a pit of internal dimensions 1.2 × 2.5 × 3.0 m as shown in Fig. 2. A window of dimensions 0.2 × 0.7 m was provided in each side of the latrine in a wooden frame that allowed the installation of an insect screen of apertures 1.2 mm × 1.2 mm as and when it was required in the experimental setup. The dimension of the window was chosen so that the area of the opening was at least three times the cross-sectional area of the biggest vent pipe (200 mm diameter) used in the setup modifications (Ryan and Mara 1983a). The wooden frame also allowed closure of any window at any time by covering with a piece of plywood nailed into the frame.

For the purpose of installing vent pipes of variable diameters (100 mm, 150 mm and 200 mm), three starter pipes for these pipe diameters were cast into the concrete slab behind the latrine. However, only one vent pipe was installed at

Table 1 Variable definition

Variable	Type	Variable definition (unit)
Q[a]	Continuous	Ventilation rate in vent pipe measured centrally at the mid-point of the vent pipe (m^3/h)
D	Continuous	Diameter of vent pipe (mm)
H	Continuous	Height of vent pipe above highest point of roof (mm)
SPT	Categorical	Type of superstructure: 0 if standard (i.e. window provided only in windward direction); 1 if window provided in other directions; 0 was the reference category
SCR	Categorical	Provision of insect screen in windows: 0 if no screens are provided in windows; 1 if screens are provided; 0 was the reference category
Tpipe	Continuous	Temperature of air in vent pipe measured at same point as Q (°C)
Vwind	Continuous	Wind speed measured at the top of the vent pipe (m/s)
Temp	Continuous	External or ambient air temperature (°C)
Hum	Continuous	Relative humidity (%)
Patm	Continuous	Atmospheric pressure (kPa)

[a] Dependent variable; all others were independent variables

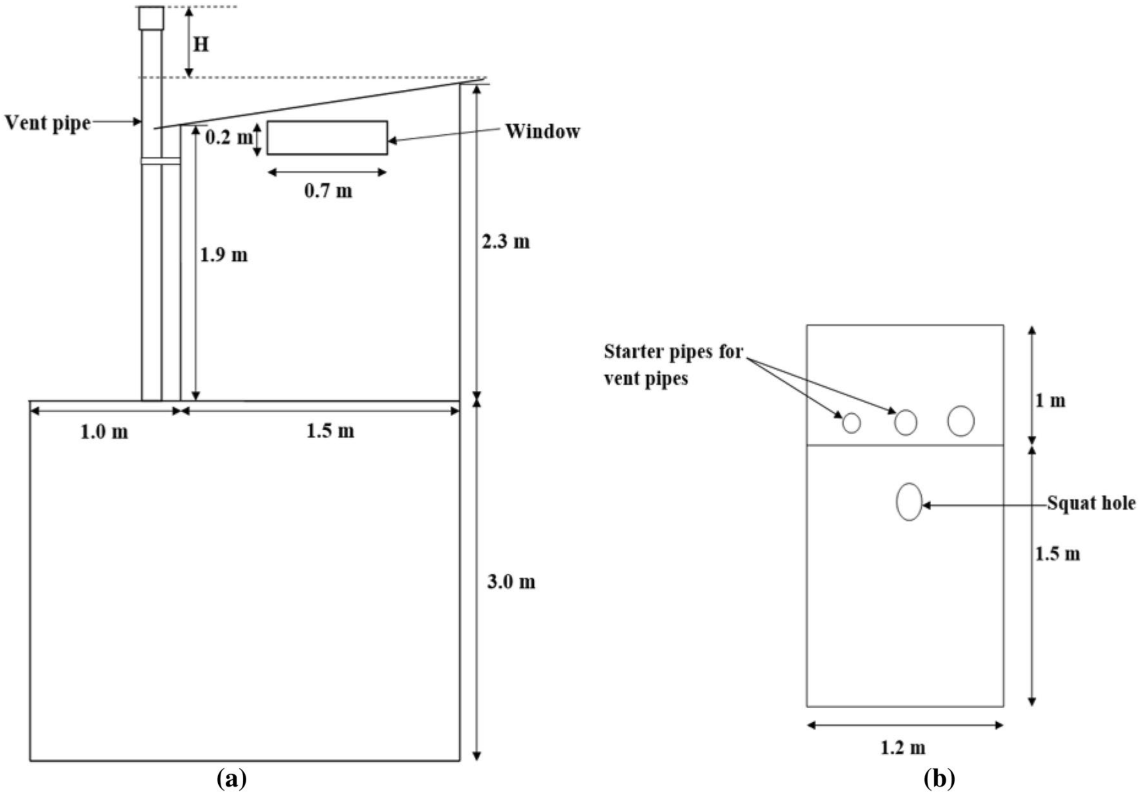

Fig. 2 Plan and side elevation of experimental VIP latrine

a time while the other two starter pipes were capped. The latrine was constructed close to the compound of a basic school where it was used by an average of 20 school children daily during the monitoring period.

The experimental latrine was set up to test the effect of only one design modification at a time under prevailing weather conditions. Three pipe diameters of 100 mm, 150 mm and 200 mm were tested at the recommended minimum height of 500 mm. Each diameter was repeated for heights (H) of 250 mm, 750 mm and 1000 mm. For each pipe diameter and height, the latrine was set up with only one window opened in the windward direction as in a standard or conventional VIP design. Then, for the same diameter and height, all four windows were opened. These setups were then repeated with an insect screen of aperture 1.2 mm × 1.2 mm installed in the window(s).

Table 2 summarises how the various design modifications were combined in 16 setups involving the 100 mm diameter vent pipe.

For the three different vent pipe diameters, a total of 48 different setups were studied. Each setup was monitored for a day from 5 am to 5 pm. The ventilation rate and air temperature in the vent pipe were measured at hourly intervals as well as the external weather conditions comprising the wind speed, temperature, humidity and absolute pressure.

Field measurements

Ventilation rates and air temperature in vent pipes were measured with the aid of a hot wire anemometer, Airflow Model TA430, manufactured by TSI Incorporated of the US, following procedures described in the device's Operation and Service Manual. The probe of the anemometer was horizontally inserted into a hole drilled in the vent pipe at half-way along the pipe length (Ryan and Mara 1983b) and taped to avoid any escape of air. For each experimental setup, data was logged at a minute interval for ten continuous minutes. This was repeated at hourly intervals over the period of monitoring (5 am–5 pm).

Elements of weather comprising external wind speed, temperature, humidity and atmospheric pressure were measured with the aid of the PCE-FWS 20 Weather Station manufactured by PCE Instruments UK. The device was mounted "at a point near as possible to, and at the same height as, the top of the vent pipe" (Ryan and Mara 1983b, p. 6). The device was programmed to log data at 5-min intervals, which was its minimum data logging interval.

Table 2 Setup combinations for 100 mm diameter vent pipe

Setup	Diameter (mm)	Height (mm)	Window type	Net installed
1	100	250	Standard	No
2	100	250	Multiple	No
3	100	250	Standard	Yes
4	100	250	Multiple	Yes
5	100	500	Standard	No
6	100	500	Multiple	No
7	100	500	Standard	Yes
8	100	500	Multiple	Yes
9	100	750	Standard	No
10	100	750	Multiple	No
11	100	750	Standard	Yes
12	100	750	Multiple	Yes
13	100	1000	Standard	No
14	100	1000	Multiple	No
15	100	1000	Standard	Yes
16	100	1000	Multiple	Yes

Data analysis

Out of a total of 624 observations generated from 48 setup combinations, 96 observations, comprising two randomly selected from each setup, were reserved for model validation and were not included in the model data. After removing observations with missing data and outliers, a total of 478 observations were used for developing the model using the Minitab statistical software.

Multiple linear regression analysis was used to identify which design criteria and elements of weather were most influential on the ventilation rate and to predict the ventilation rate that may be achieved by various combinations of design criteria and weather elements. The multiple linear regression model and the fitted model were specified as shown in Eqs. (1) and (2) respectively (Simon 2003):

$$\mathrm{Yi} = \beta_0 + \beta_1(\mathrm{x1})_i + \beta_2(\mathrm{x2})_i + \beta_3(\mathrm{x3})_i + \cdots + \beta_K(\mathrm{xK})_i + \varepsilon_i \tag{1}$$

$$\hat{\mathrm{Y}} = \mathrm{b}_0 + \mathrm{b}_1(\mathrm{x1}) + \mathrm{b}_2(\mathrm{x2}) + \mathrm{b}_3(\mathrm{x3}) + \cdots + \mathrm{b}_K(\mathrm{xK}) \tag{2}$$

where Y is a linear function of predictors x1, x2, x3… xK and some statistical noise or error term, ε, β_0 is the intercept, β_j is the coefficient of the variable xj, b_j in Eq. (2) is an estimate of the corresponding β_j in Eq. (1).

The dependent variable, Q, was transformed by taking natural logs prior to analysis to minimise skewness and linearize its relationship with the independent variables. Thus, from the variable definition in Table 1, the model for the ventilation rate in the vent pipe was initially specified as:

$$\begin{aligned} lnQ = {} & b_0 + b_1D + b_2Vwind + b_3SPT + b_4Hum \\ & + b_5SCR + b_6Temp + b_2H \end{aligned} \tag{3}$$

The multiple linear regression model was constructed by forward selection, with variables allowed to enter the model at a t-test probability level, α, of 0.25.

Model diagnosis

This multiple linear regression model was diagnosed to assess its suitability to describe the relationship between the dependent and independent variables. To diagnose a multiple linear regression model, the following assumptions on which the model is based are usually verified (Nau 2014; Simon 2003):

1. The relationship between the dependent and independent variables is linear.

2. Consecutive errors in time series are statistically independent.
3. There exists a constant variance or homoscedasticity among the errors.
4. The errors are normally distributed
5. A high degree of multicollinearity does not exist among the independent variables

However, the independence of consecutive errors was not verified since the data was not time sequenced.

Linearity of the relationship between dependent and independent variables

If the relationship between the dependent and independent variables is linear, the points of the scatter plot of the errors (residuals) are symmetrically distributed around the horizontal axis (Nau 2014). Figure 3 shows the plot of residuals versus fitted values as being fairly symmetrical about the horizontal axis.

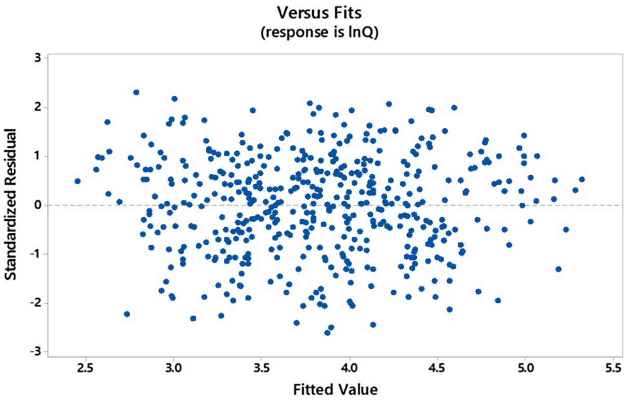

Fig. 3 A plot of residuals versus fitted values

Homoscedasticity of errors

From the plot of residuals versus fitted values shown in Fig. 3, the errors do not get larger in one direction by any significant amount, and this is a proof of homoscedasticity (Nau 2014).

Normality of the distribution of errors

Figure 4 shows the normal probability plot of the standardised residuals.

If the errors are normally distributed, a normal probability plot of the residuals shows the points being close to the diagonal reference line as seen in Fig. 4. Statistically, the Anderson–Darling test of normality confirms that the distribution of the standardised residuals is significantly normal (AD = 1.063; p-value = 0.009).

Check for multicollinearity

As a rule of thumb, multicollinearity is ignored when no individual independent variable has a variance inflation factor (VIF) of 10 or higher (Simon 2005). However, some analyst treat VIFs of 5–10 as high collinearity (Minitab 2015). Table 3 shows the Pearson correlation coefficients among the variables and the variance inflation factors for the independent variables when regressed on the dependent variable. It is

Fig. 4 Normal probability plot of standardised residuals

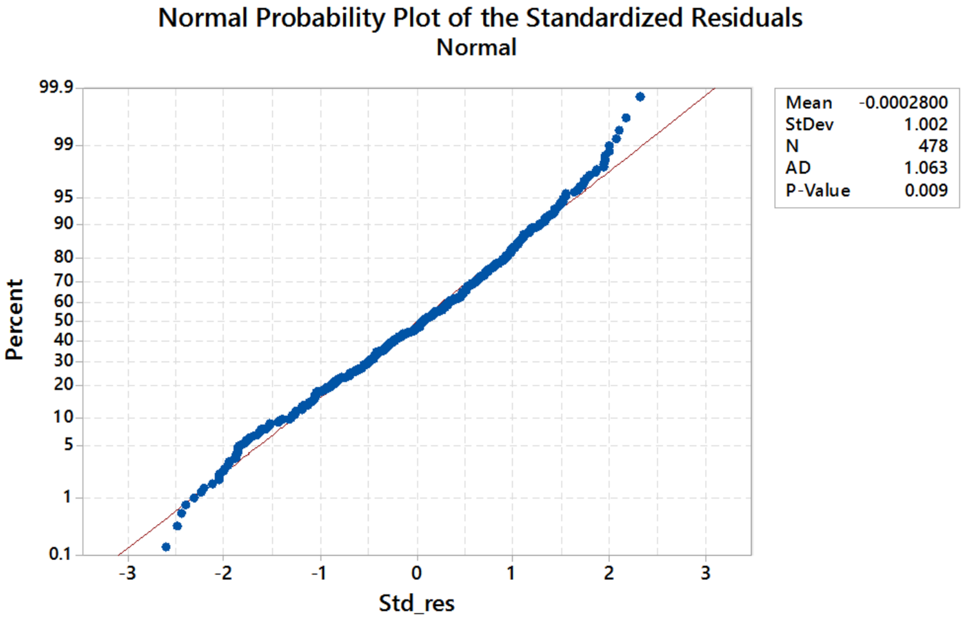

Table 3 Correlation matrix of variables. Source: Own field data

Variables	Pearson correlation (p-value)									VIF^b
	LnQ^a	D	H	SPT	SCR	Tpipe	Vwind	Temp	Hum	
D	0.72 (0.000)									1.23
H	0.24 (0.000)	0.10 (0.026)								1.86
SPT	−0.31 (0.000)	−0.04 (0.382)	−0.01 (0.857)							1.04
SCR	−0.02 (0.637)	0.01 (0.037)	0.08 (0.072)	0.01 (0.821)						1.05
Tpipe	0.00 (0.954)	−0.163 (0.000)	0.20 (0.000)	0.08 (0.095)	0.02 (0.716)					9.45
Vwind	0.43 (0.000)	−0.1 (0.036)	0.02 (0.751)	−0.14 (0.002)	−0.11 (0.016)	0.21 (0.000)				1.22
Temp	0.08 (0.075)	−0.04 (0.352)	0.20 (0.000)	0.07 (0.119)	0.05 (0.330)	0.90 (0.000)	0.26 (0.000)			8.89
Hum	0.16 (0.000)	0.01 (0.848)	0.46 (0.000)	−0.05 (0.275)	0.02 (0.666)	−0.32 (0.000)	−0.16 (0.001)	−0.47 (0.000)		3.24
Patm	−0.26 (0.000)	−0.01 (0.847)	−0.35 (0.000)	0.01 (0.841)	0.06 (0.196)	−0.61 (0.000)	−0.23 (0.000)	−0.44 (0.000)	−0.26 (000)	2.89

NB: [a]dependent variable, [b]VIF = variance inflation factor

Table 4 Ventilation rate in a VIP latrine vent pipe related to selected design criteria and elements of weather. Source: Own field data

Predictors	Unstandardized coefficients			Change in R_j^2 (%)	VIF
	b	Std. error	p-value		
Constant	0.226	0.112	0.045*	–	–
D	0.0116	0.0002	0.000**	52.68	1.02
Vwind	0.287	0.009	0.000**	25.19	1.13
SPT	−0.323	0.017	0.000**	6.84	1.04
Hum	0.0101	0.0005	0.000**	6.53	1.29
SCR	−0.068	0.017	0.000**	0.30	1.03
Temp	0.028	0.003	0.000**	0.03	1.37

Model summary: F-value = 850.45; p = 0.000
Adjusted $R^2 = 91.44$
Predicted $R^2 = 91.28$

NB: *significant at 5% level; **significant at 1% level

seen from Table 3 that variables Tpipe (temperature of air in the vent pipe) and Temp (external/ambient air temperature) had VIFs close to 10. A potentially high collinearity associated with these variables was avoided by adopting the forward selection option of multiple linear regression, which automatically eliminates variables that are either highly correlated with other variables or do not make a significant contribution to the inferential or predictive power of the model (Minitab 2015; Simon 2005).

Based on the model selection criteria described above, the height of vent pipe above the latrine roof (*H*), temperature of air inside the vent pipe (*Tpipe*) and atmospheric pressure (*Pabs*) were excluded from the model by the statistical software. This implies that these variables do not significantly contribute to the explanation of changes in the ventilation rate or are highly correlated with some other variables that better explain changes in the ventilation rate.

Thus, the fitted model for the ventilation rate in the vent pipe can be specified as:

$$lnQ = b_0 + b_1D + b_2Vwind + b_3SPT + b_4Hum + b_5SCR + b_6Temp \tag{4}$$

Results and discussion

Model output and summary statistics

The output of the regression analysis based on Eq. (4) is presented in Table 4.

Table 4 shows the estimates of the regression coefficients, *b*, their standard errors and the p-values associated with the t-test statistic on whether the coefficients are significantly different from zero. Also shown in the table are the individual coefficient of determination, R_j^2, for each variable representing the percentage of the changes in the dependent variable that can be explained by the inclusion of the respective independent variable in the model. The individual variance inflation factors are also indicated.

It is seen from the table that the diameter of the vent pipe (*D*) has the greatest influence on the ventilation rate (Q), accounting for 52.68% of changes in lnQ. With b = 0.0116, a unit or 1 mm change in diameter leads to 0.0116 change in lnQ if all other factors are held constant. Generally, if a variable Z is related to a variable X in a linear regression model such that $\ln Z = b_0 + b_j X$, then a unit change in X leads to a change of b_j in lnZ which is approximately equal to a percentage change of b_j in Z (Simon 2003). Thus, a 1 mm increase in diameter leads to approximately 1.16% change in Q if all other factors are held constant. This implies that increasing the diameter by 50 mm, say from 100 mm to 150 mm or 150 mm to 200 mm, leads to a 50 × 1.16% or 58% increase in the ventilation rate if all other factors are held constant. Similarly, a unit (m/s) increase in the external wind speed (*Vwind*), which is the second most influential factor, leads to an increase of 28.7% in the ventilation rate. *Vwind* accounts for 25.19% of the changes in Q. It is seen that the effect of temperature changes makes the least contribution ($R^2 = 0.03\%$) to the explanation of changes in Q. This confirms earlier findings that the action of wind on top of the vent pipe (Bernoulli's principle) is more important than thermal induced ventilation (Mara 1984).

On the other hand, the multidirectional design (*SPT = 1*), in which windows or openings are provided in all sides of the superstructure, significantly reduces the ventilation rate by 32.3% of the rate in an equivalent standard superstructure if all other factors remain constant. This factor accounted for 6.8% of the changes in Q. Similarly, the installation of insect screens in windows (*SCR*) reduced the ventilation rate by 6.8% but accounted for only 0.3% of the changes in the ventilation rate through the vent pipe. It should be noted that, all the above inferences are subject to the standard errors indicated in Table 4 for the various predictors. For instance, the standard error for the coefficient of the variable *SPT* is 0.017. This implies that, the multidirectional superstructure design reduces the ventilation rate by 32.3% ± 1.7%.

Overall, the regression model is statistically significant (F = 850.45; p = 0.000). The model had an adjusted coefficient of multiple determination, R^2, of 91.44%, which means that the model explains 91.44% of the changes in the ventilation rate. Also, the predicted R^2 of 91.22% signifies that the model will explain that percentage of changes in the ventilation rate when a new set of data that were not included in the development of the model are used to predict an unknown ventilation rate.

Model validation and predictions

From the model output shown in Table 4, the values of the intercept and coefficients of the variables, rounded to three decimal places, are substituted in Eq. 4 to obtain the following model equation:

$$\begin{aligned} lnQ = 0.226 + 0.012D + 0.287Vwind - 0.323SPT \\ + 0.010Hum - 0.068SCR + 0.028Temp \end{aligned} \tag{5}$$

The model was validated with 96 observations by comparing the predicted ventilation rates with those that were observed in the field for each set of predictors or independent variables. The dependent variable, which was log-transformed prior to analysis, was converted back to the original variable, Q. In Table 5, a 95% confidence interval and a 95% prediction interval are shown for the predicted Q for selected sample sets of predictors. The confidence interval is the range within which the mean Q for each set of predictors repeated for a number of times is expected to lie. On the other hand, the prediction interval specifies the range within which the Q for a set of predictors observed only once is expected to lie. Due to a higher uncertainty associated with a single observation of a set of predictors, the prediction interval is always wider than the confidence interval (Wiles 2013). Since each set of predictors used for the validation was observed only once, the prediction interval forms the basis for assessing the validity of the model. Out of 96 sets of predictors, 92 had the observed Q falling within the respective prediction intervals. Four observed Qs fell outside the prediction interval. Thus, 96% of the observations fell within the predicted intervals, which indicates a high level of reliability.

Conclusions

The regression analysis of factors affecting the ventilation rate showed that the diameter of the vent pipe is the most important factor which accounts for 53% of variations in the ventilation rate. Increasing the vent pipe from one standard size to another, i.e., 100–150 mm or 150–200 mm leads to an increase of 58% in ventilation rate, if all other factors are held constant. After vent pipe diameter, the wind speed is the second most important factor accounting for 25% of changes in the ventilation. A unit increase of 1 m/s in the wind speed leads to an increase of 29% in the ventilation rate, if all other factors are held constant. The adoption of the multidirectional design leads to a reduction of 32% in the ventilation rate and accounts for 9% of the variations in the ventilation rate while the installation of insect screens reduces the ventilation rate by 9% and accounts of less than 1% of the variations in the ventilation rate. It follows that where the multidirectional design and use of insect screens are desired, their combined effect of 41% reduction in the ventilation rate could be compensated for by increasing the

Table 5 Sample model validation output

Obser-vation	D	H	SPT	SCR	Vwind	Temp	Hum	Predicted Q	SE	CLIM1	CLIM2	PLIM1	PLIM2	Observed Q	Remark
1	100	250	0	0	0.6	22.93	32.67	12.43	1.04	11.53	13.41	8.71	17.75	14.41	PL
2	100	500	1	0	3.3	29.70	66.33	33.52	1.02	32.29	34.79	23.62	47.56	29.96	PL
3	100	750	1	1	3.2	32.60	63.33	31.69	1.02	30.45	32.98	22.33	44.99	27.69	PL
4	100	1000	1	0	1.0	32.87	61.00	17.95	1.02	17.24	18.68	12.64	25.48	18.37	CL
5	150	250	1	0	3.7	32.43	10.00	41.41	1.03	38.90	44.09	29.08	58.98	47.05	PL
6	150	500	0	0	1.9	31.63	66.33	58.81	1.02	57.07	60.60	41.47	83.40	89.02	>PL
7	150	750	1	0	1.6	26.40	86.67	40.96	1.02	39.50	42.48	28.87	58.12	38.15	PL
8	150	1000	0	1	1.6	26.30	88.00	53.45	1.02	51.45	55.53	37.66	75.86	62.31	PL
9	200	250	1	1	2.0	23.03	87.33	70.88	1.03	67.17	74.79	49.84	100.80	71.22	CL
10	200	500	0	1	1.6	35.30	50.67	84.40	1.02	80.55	88.43	59.40	119.90	57.65	PL
11	200	750	0	1	0.5	26.50	88.00	69.30	1.02	66.05	72.71	48.77	98.47	50.87	PL
12	200	1000	0	0	0.3	26.50	87.00	70.15	1.03	66.68	73.80	49.35	99.72	101.74	>PL

Definition of remarks: CL = Observed Q lies within 95% confidence interval of the predicted Q; PL = Observed Q lies within 95% prediction interval of Q; > PL = Observed Q lies outside (beyond) 95% prediction interval

SE standard error of the predicted Q, *CLIM1, CLIM2* Lower and upper limits of 95% confidence interval of the predicted Q, *PLIM1, PLIM2* lower and upper limits of 95% prediction interval of Q

vent pipe diameter by 50 mm, which will increase the ventilation rate by 58%. Changes in the ambient air temperature was the least significant factor affecting the ventilation rate. This is consistent with earlier findings that thermal induced ventilation is not as important as compared to the action of wind on top of the vent pipe. The regression model developed in this study, with an adjusted coefficient of multiple determination, $R^2 = 91.44\%$, could explain 91.44% of the variations in the ventilation rate. It also had a predicted R^2 of 91.22%.

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Compliance with ethical standards

Conflict of interest The author(s) declare that they have no competing interests.

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