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Validation of Simulation Models for Mass Flow Rate of Maize Grain Through Horizontal Circular Orifices

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Abstract: The mass flow rate (MFR) of maize grain is essential in determining appropriate size of orifice for flow control. There are several simulation models for MFR that have been developed. However, there is need for a reliable simulation model for MFR of maize grain through horizontal circular orifices. In this paper, the Beverloo, British Code of Practice (BCP) and Tudor simulation models for MFR were validated. The experimental results used in validation were obtained by discharging 12.0 kg of maize grain (Hybrid 614 variety) through horizontal circular orifices with diameters ranging from 0.040 m to 0.056 m. The time taken for the grain to flow through the orifices was recorded and MFR determined. The moisture content of the maize grain used was 11.4%, wet basis. The actual MFR ranged from 720 kg/h to 1735 kg/h, 650 kg/h to 2006 kg/h for Beverloo, 851 kg/h to 2378 kg/h for BCP and 867 kg/h to 2010 kg/h for Tudor model. The data analysis showed that none of the simulation models results best fitted the experimental. Therefore, New model was established based on MATLAB R2019a curve fitting tool. The New model results corroborated with the experimental. In addition, the models performance evaluation results showed that the New model had higher coefficient of determination (R^2 = 0.9965), lower root mean square error ($RMSE$ = 24.8 kg/h), lower absolute residual error (ε_r = 0.6%) and higher simulation performance at 10% residual error ($\eta_{sim,10\%}$ = 100%) than Beverloo, BCP and Tudor model. This implied that the New model was more reliable for simulating MFR of maize grain through horizontal circular orifices compared with Beverloo, BCP and Tudor model.

Keywords: Validation, Simulation Models, Mass Flow Rate, Maize Grain, Horizontal Circular Orifices

1. Introduction

The mass flow rate of grain through various sizes, shape and orientations of orifices is essential in determining appropriate orifice size for flow control during grain handling. The flow rate of grain and other granular materials through horizontal orifices has been studied by several researchers [1-5]. The grain flow rate through an orifice is independent of the depth of the grain above the orifice [6, 7]. The flow rate of granular materials through horizontal orifices increase with orifice diameter raised to a power ranging from 2.5 to 3.0 [2, 3].

The main factors that influence the grain flow rate include orifice diameter, orifice shape, vertical fill height, particle size, granular mass cohesion and coefficient of mass friction, grain shape and angularity, cone angle of the base of the container, grain size distribution, wall coefficient of friction and grain angle of repose [8]. The objective of this paper was to validate simulation models for mass flow of maize grain through horizontal circular orifices.

2. Materials and Methods

2.1. Simulation Models Used

The mass flow rate for maize grain through horizontal circular orifices was simulated based Beverloo, British Code of Practice (BCP) and Tudor model. The unit of measurement for mass flow rate was converted to kg/h before the models were used. The Beverloo model is given in equation 1 [1] where, Q_B is Beverloo model mass flow rate of maize grain through horizontal circular orifice (kg/h), C_d is friction or discharge coefficient (dimensionless), ρ_g is bulk density of maize grain (kg/m^3), A_e is effective orifice area (m^2), g is acceleration due to gravity (m/s^2) and D_e is effective hydraulic diameter (m).

$$Q_B = 3600 C_d \rho_g A_e \left(g D_e\right)^{0.5} \quad (1)$$

The effective hydraulic diameter (D_e) was determined based on equation 2 where, D_h is hydraulic diameter of the orifice (m), K_p is the shape factor taking into account inclination of the feed hopper walls and d_g is mean diameter of the maize grain (m).

$$D_e = D_h - K_p d_g \quad (2)$$

The hydraulic diameter (D_h) was considered equal to the diameter of the orifice [9-11]. The effective orifice area (A_e) was evaluated using equation 3.

$$A_e = \frac{\pi D_e^{\,2}}{4} \quad (3)$$

The BCP model is given in equation 4 [12] where, Q_{BCP} is British Code of Practice model mass flow rate of maize grain through horizontal circular orifice (kg/h) and D_o is diameter of the horizontal circular orifice (m).

$$Q_{BCP} = 3600 C_d \rho_g g^{0.5} \left(D_o - K_p d_g\right)^{2.5} \quad (4)$$

The Tudor model is given in equation 5 [13] where, Q_T is Tudor model mass flow rate of maize grain through horizontal circular orifice (kg/h), δ is the ratio of height dome of the maize grain to diameter of the orifice and μ is sliding coefficient of friction.

$$Q_T = 3600\left(\frac{\pi\sqrt{2}}{6}\right)\rho_g \left(\delta g\right)^{0.5} D_o^{\,2.5} \left(1-\mu\right)^{0.5} \quad (5)$$

2.2. Input Parameters of the Simulation Models

The minimum diameter of the horizontal circular orifice for maize grain to flow without jamming was evaluated based on equation 6 [14] where, R_c is critical ratio of minimum diameter of the horizontal circular orifice (D_o) to mean diameter of the maize grain (d_g). In flow regime where probability of grain jamming is zero, the value of $R_c \geq 6$ [14].

$$D_o = R_c d_g \quad (6)$$

The three major characteristic dimensions namely: length, width and thickness of 100 randomly selected maize grain were measured using a digital vernier caliper with an accuracy of 0.01 mm and average values determined [15-17].

The geometric mean diameter, arithmetic mean diameter and sphericity (shape factor) of the maize grain were evaluated using equation 7, 8 and 9, respectively [16, 18, 19]. In these equations, *GMD* is geometric mean diameter (m), *a* is mean length of the maize grain (m), *b* is mean width of the maize grain (m), *c* is mean thickness of the maize grain (m), *AMD* is arithmetic mean diameter (m) and φ is sphericity or shape factor (dimensionless).

$$GMD = \left(abc\right)^{\frac{1}{3}} \quad (7)$$

$$AMD = \frac{\left(a+b+c\right)}{3} \quad (8)$$

$$\varphi = \frac{\left(abc\right)^{\frac{1}{3}}}{a} \quad (9)$$

Table 1 presents the mean values of the characteristics dimensions of hybrid 614 maize grain variety used in the research.

Table 1. Characteristics dimensions of the hybrid 614 maize grain variety.

Mean length (mm)	Mean width (mm)	Mean thickness (mm)	*GMD* (mm)	*AMD* (mm)	Sphericity/Shape factor (%)
12.41	10.50	4.96	8.52	9.14	68.7

The *GMD* and *AM*D obtained as in Table 1 were modified based on the shape factor to 5.85 mm and 6.28 mm, respectively. These values were used to determine the minimum diameter of horizontal circular orifice for maize grain to flow without jamming. Therefore, the minimum orifice diameters for the grain to flow without jamming using modified *GMD* and *AMD* were 0.035 m and 0.038 m, respectively. The critical ratio (R_c) was 6. However, in this research the minimum horizontal circular orifice diameter used was 0.040 m.

The constant parameters for Beverloo model included friction or discharge coefficient (C_d) of 0.75 and shape factor (K_p) of 1.4 [1]. K_p was an average of values ranging from 1.3 to 1.5 [20]. In the BCP model, the value of C_d used was 0.58. K_p was taken as 1 since inclination angle of the feed hopper walls with respect to vertical axis was greater than 45° [12]. In the Tudor model, the ratio of dome height of the maize grain to orifice diameter (δ) and sliding coefficient of friction (μ) were 0.3 and 0.36, respectively [13]. The bulk density (ρ_g) of the maize grain computed based on the reported models was 740 kg/m^3 [15, 21, 22]. The mean diameter of the maize grain (d_g) was 0.0085 m. The acceleration due to gravity (g) was 9.81 m/s^2.

2.3. Moisture Content of the Maize Grain Used

The moisture content of the maize grain used was determined by randomly collecting three samples each weighing 25.0 g from the entire sample. The samples were then placed into a constant temperature oven set at 105°C for 24 hours. The samples were removed from the oven and allowed to cool down. The final weight of the dried samples was measured using digital balance (Model: Scout Pro SPU6000, Ohaus Corporation, Pine Brook, NJ USA). The moisture content of the samples was then computed based on equation 10 [23] where, MC is moisture content of the sample (%, wet basis), W_i is initial weight of the sample (g) and W_f is final weight of the sample (g).

$$MC = \left(\frac{W_i - W_f}{W_i} \right) \times 100 \tag{10}$$

The average MC of the maize grain used was found to be 11.4%, wet basis.

2.4. Validation of the Simulation Models

An algorithm was developed using python programming language and used to determine the MFR of maize grain through horizontal circular orifices. The validation of the models involved comparing simulated and actual mass flow rate results. Figure 1 shows section view (a) and actual experimental system (b) used to collect data for the models validation. The height of the experimental system was 0.570 m. The diameters of the top and bottom circular sections of the experimental system were 0.365 m and 0.210 m, respectively, as indicated in Figure 1 (a).

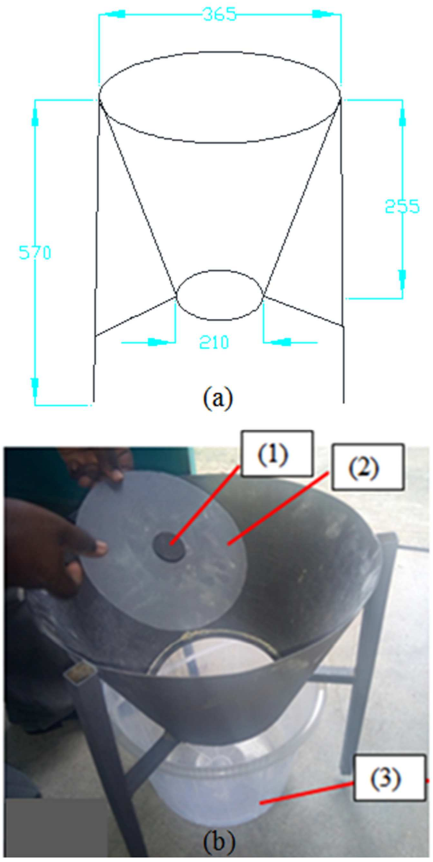

Figure 1. Section view (a) and actual experimental system (b) used to collect data for validation.

Key: (1) is horizontal circular orifice, (2) is circular cover plate to lower section of the system, and (3) is container for collecting discharged maize grain

The experiment involved placing the circular cover plate with an orifice diameter 0.040 m at the lower section of the experimental system as shown in Figure 1 (b). An empty container was placed at the bottom of the experimental system directly below the orifice. The orifice was covered and the system loaded with 12.0 kg of hybrid 614 maize grain variety. The grain was discharged through the orifice and at same time a stop watch was started. The time taken for the grain to be discharged from the experimental system and weight of the grain discharged were measured and recorded.

Similar experiments using orifice diameters ranging from 0.042 m to 0.056 m at interval of 0.002 m were carried out. Three replications were carried out in each experiment. The mass flow rate of maize grain was determined based on equation 11 where, MFR is maize grain mass flow rate through horizontal circular orifice (kg/h), m_g is mass of maize grain discharged through horizontal circular orifice (kg) and t_g is time taken for maize grain to be discharged (s).

$$MFR = 3600 \frac{\mathrm{m_g}}{\mathrm{t_g}} \tag{11}$$

2.5. Evaluation of the Simulation Models

The evaluation of the simulation models for mass flow rate involved determination of coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error ($RMSE$) between the simulated and experimental mass flow rates. The higher the value of R^2 and lower the values of $RMSE$ the better the goodness of fit [24, 25]. The reduced chi-square (χ^2) was evaluated based on equation 12 [26, 27] where, $\psi_{exp,i}$ is experimental value, $\psi_{sim,i}$ is simulated value, N_o is number of observations and N_c is number of constants in the model.

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(\psi_{\exp,i} - \psi_{sim,i} \right)^2}{N_o - N_c} \tag{12}$$

The root mean square error was determined using equation 13 [26, 27] where, $RMSE$ is root mean square error.

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(\psi_{\exp,i} - \psi_{sim,i} \right)^2 \right]^{\frac{1}{2}} \tag{13}$$

The repeatability of the experimental data was evaluated by determination of the mean and standard errors of the data. The absolute residual error was computed using equation 14. [28, 29] where, ε_r is absolute residual error (%).

$$\varepsilon_r = 100 \left| \frac{\psi_{sim,i} - \psi_{\exp,i}}{\psi_{\exp,i}} \right| \tag{14}$$

The simulation performance of the models at μ_i (%) residual error interval was evaluated based on equation 15 [28, 29] where, $\eta_{sim,\mu\%}$ is simulation performance at μ_i (%) residual error interval (%), β_i is number of data within the μ_i (%) residual error interval and β_t is total trial data.

$$\eta_{sim,\mu\%} = \frac{\beta_i}{\beta_t} \times 100 \qquad (15)$$

3. Results and Discussions

The actual mass flow rate (MFR) of maize grain through horizontal circular orifices with diameters increased from 0.040 m to 0.056 m ranged from 720 kg/h to 1735 kg/h, 650 kg/h to 2006 kg/h for Beverloo, 851 kg/h to 2378 kg/h for British code of Practice (BCP) and 867 kg/h to 2010 kg/h for Tudor model. Figure 2 shows the actual, Beverloo, BCP and Tudor model MFR of maize grain through horizontal circular orifices.

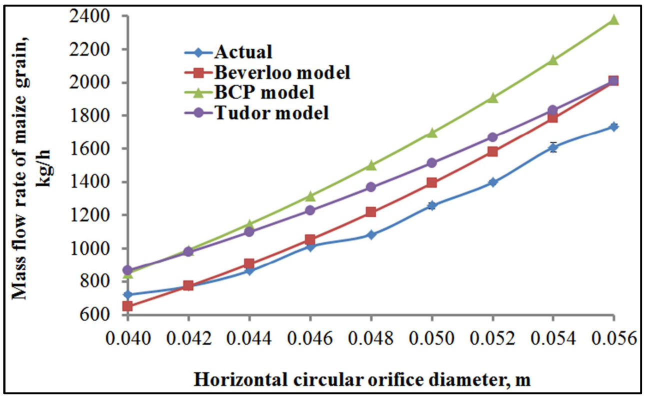

Figure 2. *Actual and simulation models mass flow rates of maize grain through horizontal circular orifices.*

The actual and the simulation models MFR increased with increased in the orifice diameters (Figure 2). The Beverloo model MFR plot was close to the actual for orifice diameters ranging from 0.040 m to 0.046 m. However, the two plots tend to deviate gradually from 43 kg/h at orifice diameter of 0.046 m to 271 kg/h at orifice diameter of 0.056 m. This indicated that the Beverloo model was suitable for simulation of MFR of maize grain for orifices diameters ranging from 0.040 m to 0.046 m and inapplicable for orifice diameters greater than 0.046 m.

The BCP model MFR and actual plots did not have similar trends. The deviation between the two plots increased from 131 kg/h to 643 kg/h as the orifice diameters were increased from 0.040 m to 0.056 m. In addition, the deviation (387 ± 52 kg/h) of the BCP model MFR plot from the actual was higher compared with that between Beverloo and actual (117 ± 27 kg/h), and Tudor and actual (236 ± 13 kg/h). This showed that BCP model overestimated MFR of maize grain more than Beverloo and Tudor model. This observation could be explained by the fact that BCP model was applied for the flow rate of granular materials through orifices of undefined shapes [12].

The Tudor model and actual MFR plots showed similar trends. The deviation between the two plots was considerably inconsistent with the lowest of 147 kg/h observed at orifice diameter of 0.040 m and the highest of 282 kg/h at orifice diameter of 0.048 m.

The Beverloo and Tudor model MFR plots did not have similar trends. The deviation between two plots decreased gradually from 217 kg/h to 4 kg/h as the orifice diameters increased from 0.040 m to 0.056 m. The two plots tend to converged at orifice diameter of 0.056 m. This observation could be due to the introduction of correction factor in the Tudor model [13].

However, the Beverloo and BCP MFR plots had similar trends. This is could be attributed to the fact that the BCP model was developed from Beverloo model [12]. The deviation between the two plots gradually increased from 201 kg/h to 372 kg/h as orifice diameters increased from 0.040 m to 0.056 m.

The Tudor and BCP model MFR had similar trends. The two plots were close between orifice diameters of 0.040 m and 0.042 m but started deviating gradually as the orifice diameters increased from 0.042 m to 0.056 m. The lowest deviation of 14 kg/h was observed at orifice diameter of 0.042 m and the highest of 368 kg/h was at orifice diameter of 0.056 m.

Therefore, the performance of Beverloo, BCP and Tudor models in simulation of mass flow rate of maize grain through horizontal orifice was not satisfactory. Based on MATLAB R2019a curve fitting tool and fitting regression line yielded actual model for maize grain mass flow rate given in equation 16 (R^2 = 0.9965) where, Q_N is New model mass flow rate of maize grain through horizontal circular orifices (kg/h) and *Do* is diameter of horizontal circular orifice (m).

$$Q_N = 1\cdot 903 \times 10^6 D_o^2 - 1\cdot 17 \times 10^5 D_o + 2341 \qquad (16)$$

The MFR of maize grain based on the New model ranged from 706 kg/h to 1757 kg/h for horizontal circular orifice diameters increased from 0.040 m to 0.056 m. Figure 3 shows the actual and New model mass for flow rate of maize grain through horizontal circular orifices.

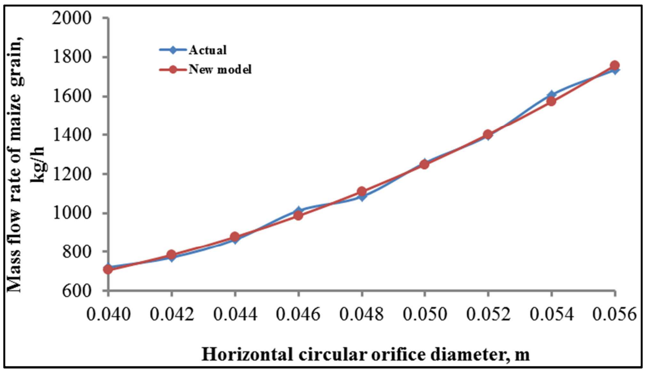

Figure 3. *Actual and New model mass flow rate of maize grain through horizontal circular orifices.*

The actual and New model MFR of maize grain plots had similar trends and close. This implied that the actual MFR results corroborated with that of the New model.

The Student's t-test results showed significant difference (P < 0.05) between the Beverloo model and actual MFR, BCP model and actual MFR, and Tudor model and actual MFR. This indicated that the simulated and actual results of MFR were not in agreement. Thus, the Beverloo, BCP and

Tudor model were not suitable for simulation of MFR of maize grain through horizontal circular orifices.

Further, the Student's t-test results did show existence of significant difference ($P < 0.05$) between Beverloo model and Tudor model MFR, Beverloo model and BCP model MFR, and Tudor model and BCP model MFR. This revealed that the Beverloo, BCP and Tudor MFR results did not agree and hence the models were not compatible.

However, the Student's t-test results did not indicate any significant difference ($P > 0.05$) between the New model and actual MFR. In addition, models evaluation results showed that the New model had higher coefficient of determination ($R^2 = 0.9965$), lower root mean square error ($RMSE = 24.8$ kg/h), lower absolute residual error (ε_r = 0.6%) and higher simulation performance at 10% residual error ($\eta_{sim,10\%}$ = 100%) compared with Beverloo, BCP and Tudor model. This implied that the Q_N model was more reliable for simulation of mass flow rate of maize grain through horizontal circular orifices compared with the Beverloo, BCP and Tudor model.

4. Conclusion

The Beverloo, British Code of Practice and Tudor model mass flow rates (MFR) results were not in agreement with the actual. However, the Beverloo model MFR results were comparable with the actual for orifice diameters ranging from 0.040 m to 0.046 m.

The established New model MFR results corroborated with the actual. This implied that the New model was more reliable for simulating MFR of maize grain through horizontal circular orifices compared with Beveloo, British Code of Practice and Tudor model.

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