System of mathematical equations to predict wear rate on circular-cone orifice of pesticide spray nozzles

Akshay Kumar Singh[1*], Yogesh Chandra Bhatt[2], Kishor Dhande[3], Sachin Vilas Wandkar[2], Nishant M Stanley[1]

(1. *Division of Agricultural Engineering, Indian Institute of Agricultural Engineering, New Delhi 110012, India*;
2. *Department of Farm machinery and Engineering, College of Technology and Engineering, Udaipur 313001, India*;
3. *Department of Farm Power and machinery, Konkan Krishi Vidyapeeth, Dapoli 415712, India*)

Abstract: A simple system of mathematical equations was developed to predict wear rate on the circular-cone orifice (CCO) plates of hollow-cone type pesticide spray nozzles. Geometrical and physical properties of CCOs, abrasiveness of spray solutions, time of usage and change in discharge rate were taken into considerations as observable parameters to predict wear. The developed equations were also validated by conducting a long rum wear test on CCO plates made of plastic (P), stainless steel (S) and ceramic (C) materials. Tests conducted on the wear test rig (WTR) by investigating each material at three different spray pressures 350, 700 and 1000 kPa, respectively. Strong coefficient of determination (R^2>0.96) between experimental and calculated values revealed that the developed system is suitable to predict wear rates for all the CCO plates with minor variations. The CCO plates made of ceramic at spray pressure 350 kPa (C-350) have shown longest worn-out life as compared to C-700 and C-1000, respectively. P-350 and S-350 have reported effective working of 40 h and 60 h, respectively. CCO plates of ceramic have shown least wear rate due to minimum value of wear coefficient (C_w = 0.006) followed by stainless steel (C_w=0.013) and plastic (C_w= 0.016), respectively. The validation of equations has also revealed that the use of CCO plates of ceramic material may not only enhance the component reliability of a sprayer or any atomization device but also ensure a precise quantity of pesticide spray due to comparatively least wear rate on orifice.

Keywords: Circular-cone orifice (CCO) plates, mathematical equations, spray pressure, wear rate, wear coefficient (C_w)
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1 Introduction

Chemical pesticide application is being considered as the quickest and effective approach among various strategies available to protect agricultural crops[1]. Pests, weeds and diseases cause nearly 40% losses (highest by insects followed by pathogens and weeds) of standing crop in the field[5]. Hence, pesticide application has become an integral part of agricultural produce which often follows unscientific pattern and overdose levels in India[12]. Excessive dosages of pesticide solutions above recommended level not only increase the cost of production but also play havoc to environment[3,20]. Since spraying of pesticide solution is most common practice around the plant canopy by means of available atomising devices, role of spray nozzles becomes crucial in order to apply a precise quantity of chemical. Quantity of pesticide applied per unit area (L ha^{-1}) is governed by two major factors i.e. discharge rate and time of coverage[13]. Therefore, it is essential that nozzles should emit finer droplets of pesticide solution with no/minor variations in discharge rate throughout spraying operation. However, such spray nozzles fail to maintain discharge rate with allowable variations due to wear on spray emitting orifices.

Wear on orifice plates is referred as the deterioration of orifice material either through abrasion or corrosion. Today, material of construction of available nozzles such as, plastic, nylon, stainless steel, ceramic etc., is corrosion resistive rather than decay of orifice material by abrasion of pressurised spray solution. Selection of spray nozzles is categorised on the basis of requirement of droplet sizes and its distribution, spray pattern, spray angle and the amount of overlap required[14]. In addition, a desirable droplet size and spectrum is essential to ensure the uniformity and complete coverage, respectively during spray application[7]. In-spite of having many other factors that influence above mentioned selection criterion of nozzles, physical properties and material of construction plays a crucial role[9,18]. Wear on orifice results failure of nozzles to maintain an accurate quantity of spray solution essentially due to change of area of the orifice. Differentiating final and initial weights of nozzles is the simplest and commonly used technique to measure wear rate which require sophisticated instruments with skills. Moreover, deposition of foreign materials from spray solution in pores of orifice plate, if occurs, due to mechanical abrasion, the wear rate may not be measured accurately.

The droplet size distribution (DSD) is irrespective of the materials of the orifice plate in new nozzles having same capacity and becomes dependent of materials as the wear rate on orifice plates advances with time[9,10]. Experimental investigations to study effects of wear rate on discharge rate, spray distribution

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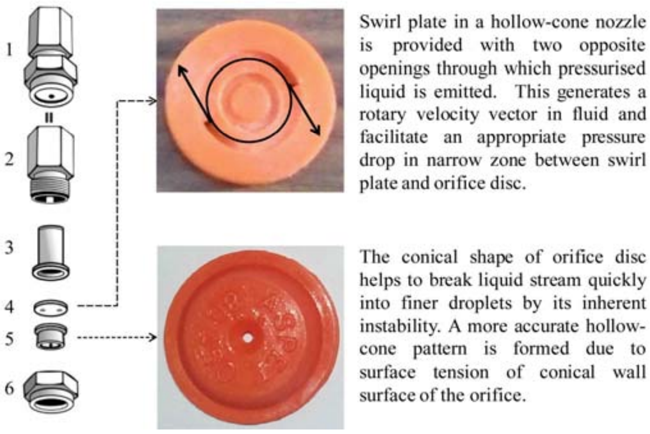
Biographies: Yogesh Chandra Bhatt, Vice President (Activity Council), Indian Society of Agricultural Engineers, Email: DRYCBHATT@hotmail.com.
***Corresponding author: Akshay Kumar Singh**, PhD Research Scholar, Division of Agricultural Engineering, Indian Agricultural Research Institute, Pusa Campus, New Delhi 110012, India. (+91-8619016943), Email: KUMARAKSHAY938@gmail.com.

pattern and droplet size spectrum have attempted by many researchers worldwide[9,16,19]. Whereas, very few researches are available that quantify the wear rate percentage as tool to determine the useful life of nozzles[8,15,17]. In actual, annual use of pesticide sprayers is limited, hence merely the time of usage cannot help to predict wear rate on orifice plates. Study of wear rate on orifice plate of a nozzle that comprises materials of construction, operating spray pressures, discharge rates and abrasive properties of the spray solution is new in India[15]. A spray nozzle is assumed to be worn-out if the discharge rate from its orifice exceeds 15% of the initial discharge rate when operated under desired spray pressure[8]. This clearly indicates that the change in discharge rate with respect to the time of usage can be used as a functional parameter to predict wear on the orifice of a nozzle.

Hollow-cone nozzles are generally used for pesticide spray applications in agriculture which have following advantages over other types: (a) produces finer droplets due to rotary velocity component from axial trajectory of swirl plate, (b) appropriate pressure drop at orifice exit and (c) quick disintegration of liquid droplets[7]. Figure 1 is provided with a schematic diagram of dismantled view of hollow-cone nozzle and the geometrical advantages of circular-cone orifice (CCO) disc and swirl plate. CCO plates of hollow-cone nozzles are most suitable for pesticide spray as they produce finer droplets and used with whirl devices which results an appropriate pressure drop[4,7].



1. Hollow-cone nozzle 2. Nozzle body 3. Sealing gasket 4. Swirl plate 5. Circular Orifice disc 6. Nozzle cap

Figure 1 Geometrical advantages of a hollow-cone nozzle

Nozzles having brass, plastic, nylon, stainless steel etc. as CCO plates materials are commonly used in agrochemical spraying[13,17]. Whereas, the use of CCO plates made of ceramic material has recently marketed in India. With the view to above studies done so far, a system of simple mathematical equations was developed to predict wear rate on CCO plates of hollow-cone nozzles. The developed system of equations consider physical properties of orifice material, abrasiveness of spray solutions, time of usage and change in discharge rate of nozzles as observable parameters to predict rate of wear. The developed equations were also verified by means of a long run wear test on CCO plates of three different materials, as follows: plastic, stainless steel and ceramic, respectively. Each plate material with three replications was mounted on wear test rig (WTR) at three different spray pressures of 350, 700 and 1000 kPa, respectively.

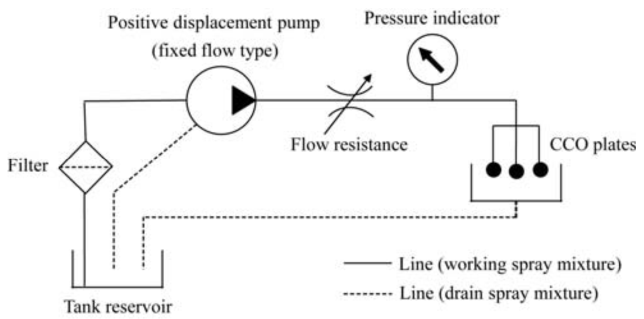
2 Materials and methods

Commercially available and supplied hollow-cone spray nozzles with plastic, stainless steel and ceramic as orifice plate materials were chosen from *ASPEE Agricultural Research and Development Foundation* (Figure 2). Out of ten sets of CCO plates of each material, three were selected for wear test on WTR after preliminary examination of initial flow rates, spray angle and swath on Patternator. Each material with three replications was tested under three spray pressures of 350, 700 and 1000 kPa, respectively. In the study, the notations P(X), S(X) and C(X) were used for the orifice materials of plastic, stainless steel and ceramic, respectively and (X = 350, 700, 1000 kPa). For example, if an orifice plate of stainless steel is tested under spray pressure of 350 kPa that refers to the S(350) and so on. As per the procedure of measuring wear rate, china clay as an abrasive material was mixed with clean water in WTR having proportion of 60 grams per liter[2]. Two-third volume of tank capacity of WTR was filled with the test spray solution as per the guidelines provided by the *Indian Standards*[6].

Plastic Ceramic Stainless steel

Figure 2 Circular-cone orifice plates having different materials

Wear test rig (WTR) was equipped with mainly five functional components as shown in process layout diagram of Figure 3a. Test solution mixed with china clay was lifted by means of a positive displacement pump with capacity of 27 L min^{-1}. Spray pressure in delivery line was maintained by an analogue type pressure gauge and regulator. By-pass flow of test mixture was drained into the reservoir which provided hydraulic agitation to test mixture and facilitated continuous suspension of china clay particles in spray solution. It is recommended to replace the spray test mixture after certain intervals during wear test[11]. As per the guidelines provided by *ASAE standard*[2], quality of abrasive material mixed in spray solution is affected due to continuous discharge through nozzles which essentially depends on the following three factors: (a) quantity of nozzles, (b) discharge rate through nozzles, and (c) volume of mixture.



a. Layout of WTR with functional components

b. Discharge through CCO plates during test

Figure 3 Wear Test Rig (WTR)

Three CCO plates of same material and discharge rate were mounted on WTR at a time (Figure 3b). All CCO plates were sprayed with clean water for 15 min during preliminary examination[6]. Variations in discharge rate were measured after every five hour interval during wear test for CCO plates made of plastic and stainless steel, whereas, in case of ceramic material, same variations were measured after every 20 hours due to precise measurement of discharge rate. Wear test was stopped as the discharge rate through CCO plates was exceeded 15% of the initial discharge rate, the limit at which a CCO plate is assumed to be worn-out[8].

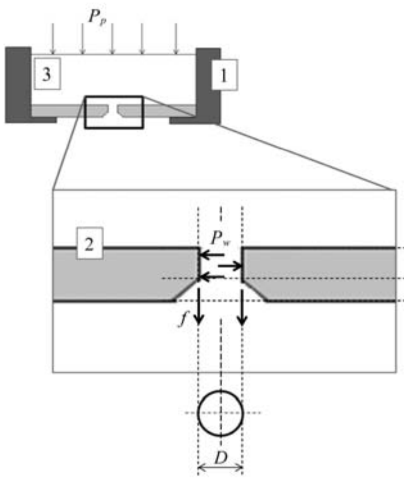
2.1 Development of system of mathematical equations

Development of a system of equations to predict wear rate on CCO plates consists geometrical and material properties of orifice plates, abrasiveness of spray solutions, time of usage and change in discharge rate of nozzles as observable parameters. Zhu et al.[20] developed a mathematical model to predict wear rate on orifice plates that were elliptical in shape. Using above reference, set of mathematical equations were derived that may be useful to predict wear rate on CCO plates with respect to the time of usage of a nozzle. Wear on an orifice plate is the function of following parameters: (a) material of the orifice plate (M_o), (b) spray pressure on orifice wall (P_w), (c) time of usage (t), and (d) abrasiveness of the pesticide solution (A_p)[20].

Mathematically,

$$w=f:[M_o, P_w, t, A_p] \quad (1)$$

As spray solution passes through the wall of the CCO plate, the material deteriorates along the orifice wall and wear on plate takes place. Figure 4 displays a schematic diagram of CCO having diameter 'D' and wall thickness of 'δ'. A normal component of pump pressure (P_p) that acts on the orifice wall is 'P_w' referred as wall pressure. Friction force (f) generates due to the abrasive action of spray liquid on the wall of CCO that results wear on the plate material through walls and consequently increases the area of the CCO with the usage of time. A drop in operating wall pressure is experienced due to increased orifice area which is proportional to the pump pressure (P_p) and inversely proportional to the time of usage (t), respectively.



1. Nozzle tip cover 2. Circular-cone orifice plate 3. Spray liquid

Figure 4 Schematics of circular-cone orifice (Not to scale)

Mathematically,

$$P_w \propto P_p \cdot \frac{1}{t^m} \quad (2)$$

$$P_w = K \cdot P_p \cdot \frac{1}{t^m} \quad (3)$$

where, K is a proportionality constant and 'm' is the arbitrary constant that depends on operating spray pressure and the shape and size characteristics of the orifice plates.

The normal force (F_n) acting on the orifice wall can be given as

$$F_n=P_w \cdot A \quad (4)$$

where, A be the surface area of the orifice plate and can be given as

$$A=\pi \cdot D \cdot \delta \quad (5)$$

Hence, normal force

$$F_n=P_w \cdot \pi \cdot D \cdot \delta \quad (6)$$

The friction force 'f' can be given as, if the coefficient of friction 'μ' between orifice wall and spray liquid is present

$$f=\mu \cdot F_n \quad (7)$$

$$\text{or,} \quad f=\mu \cdot P_w \cdot \pi \cdot D \cdot \delta \quad (8)$$

By placing the value of P_w from the equation (3), we get

$$f = \mu \cdot \pi \cdot \delta \cdot K \cdot P_p \cdot \frac{1}{t^m} \cdot D \quad (9)$$

Because existing friction force 'f' results an increase of orifice area 'A', then the relationship can be given as

$$f = K' \cdot \frac{dA}{dt} \quad (10)$$

where, K' is a proportionality constant.

Now differentiating the equation (5), we get,

$$\frac{dA}{dt} = \pi\left[\delta \cdot \frac{dD}{dt} + D \cdot \frac{d\delta}{dt}\right] \quad (11)$$

Since the wall thickness of the orifice plate is very small, the equation (11) can be re-written as

$$\frac{dA}{dt} = \pi\left[\delta \cdot \frac{dD}{dt}\right] \quad (12)$$

By solving equations (9), (10) and (11) together, we get

$$\left(\frac{dD}{dt}\right) = \left(\frac{\mu \cdot K \cdot P_p}{K'}\right) \cdot \left(\frac{D}{t^m}\right) \quad (13)$$

$$\text{or,} \quad \left(\frac{dD}{D}\right) = C_w \cdot \left(\frac{dt}{t^m}\right) \quad (14)$$

where, C_w is an arbitrary constant that majorly depends on the material of the orifice plate and the frictional characteristics between spray liquid and orifice wall material.

By integrating both sides, we get

$$\int_{D=D_o}^{D=D_t} \frac{dD}{D} = \int_{t=0}^{t=t} \frac{dt}{t^m} \quad (15)$$

By solving the above equation (15), we finally get

$$\left(\frac{D_t}{D_o}\right) = e^{\left[C_w \cdot \frac{t^{(1-m)}}{(1-m)}\right]} \quad (16)$$

Since the percentage change in discharge rate has been adopted as one of the best measures to indicate the wear rate, the discharge rate through office plate at any given time 't' can be calculated by multiplying the area (A) of the orifice to the constant discharge velocity (V_f).

So, the discharge rate q_{t_1} and q_{t_2} at time t_1 and t_2, respectively are

$$q_{t_1} = \pi \cdot D_{t_1} \cdot \delta \cdot V_f \quad (17)$$

$$q_{t_2} = \pi \cdot D_{t_2} \cdot \delta \cdot V_f \quad (18)$$

Thus the wear rate (Δw), in per cent can be given as

$$\Delta w = \left(\frac{q_{t_2} - q_{t_1}}{q_{t_1}}\right) \times 100 \quad (19)$$

By solving equation (19) with the help of equation (17) and (18), we get

$$\Delta w = \left(\frac{D_{t_2} - 1}{D_{t_1}}\right) \times 100 \quad (20)$$

We know, that at time $t = 0$, the diameter of the circular orifice plate was D_o. Let the diameter of circular orifice plate after the usage for time 't' becomes D_t. Then, equation 20 can be re-written as

$$\Delta w = \left(\frac{D_t}{D_o} - 1\right) \times 100 \quad (21)$$

By placing the value of (D_t/D_o) from the equation 16, the above expression will be

$$\Delta w = \left[e^{\left(C_w \cdot \frac{t^{(1-m)}}{(1-m)}\right)} - 1 \right] \times 100 \quad (22)$$

The equation (22) represents the percentage wear occurred after the time of usage (t). The arbitrary constants m and C_w depends on material of construction, spray pressure and frictional properties of spray solution. These constants can be determined by solving any two simultaneous equations, that yields form equation (22) for different time intervals, say t_1 and t_2. Mathematically, they can be shown as

$$\Delta w_{t_1} = \left[e^{\left(C_w \cdot \frac{t_1^{(1-m)}}{(1-m)}\right)} - 1 \right] \times 100 \quad (23)$$

$$\Delta w_{t_2} = \left[e^{\left(C_w \cdot \frac{t_2^{(1-m)}}{(1-m)}\right)} - 1 \right] \times 100 \quad (24)$$

By solving above equations (23) and (24) for the constants m and C_w, we finally get

$$m = \left[1 - \frac{\ln\left[\Delta W_{t_1} / \Delta W_{t2}\right]}{\ln\left[t_1 / t_2\right]} \right] \quad (25)$$

$$C_w = \frac{(1-m) \cdot [\Delta W_{t_1}]}{(1-m)} \quad (26)$$

where, $\Delta W_{t_1} = \ln\left(\frac{\Delta w_{t_1}}{100} + 1\right)$ and $\Delta W_{t_2} = \ln\left(\frac{\Delta w_{t_2}}{100} + 1\right)$, respectively.

By using equations (22), (25) and (26), the wear rates on CCO plates were calculated over different time intervals unless discharge rate through orifices were exceeded 15% of initial discharge rate. In order to check acceptability of derived predicting equation, the calculated values of percentage change in discharge rate were compared with the values that were observed during experiment of wear on WTR.

3 Results and discussion

Figure 5 displays the wear rate per cent that occurred on CCO plates made of plastic materials at pressures 350, 700 and 1000 kPa, respectively. The discrete points represent the values of wear rates that were observed during experimental investigation and the continuous lines (both solid and dotted) represent the values of wear rates that are calculated from developed predicting equations, respectively. Experimental values of wear rates has shown variations with the calculated values of CCO plates made of plastic for almost first 15 h of test run at spray pressure 350 kPa. Whereas the orifice plates of plastic material have shown relatively less variations between experimental values and calculated values of wear rates per cent at higher spray pressures of 700 and 1000 kPa. This may be due to the conical shape factor of orifice plate at the point of discharge. CCO plates of plastic materials worn-out in 40, 25 and 15 h of usage under spray pressures of 350, 700 and 1000 kPa, respectively.

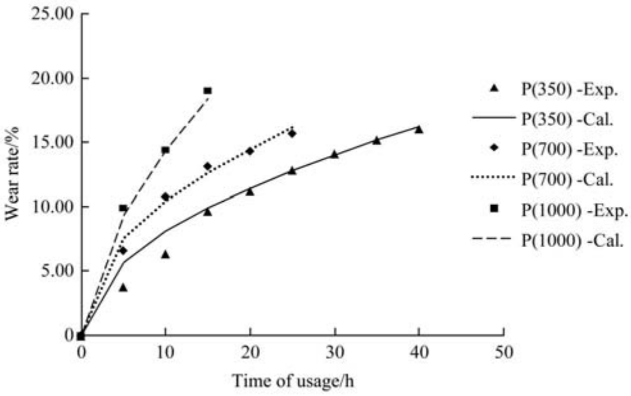


Figure 5 Rate of wear in plastic CCO plates at different pressures (Exp. – experimental values and Cal. – Calculated values)

Figure 6 represents CCO plates made of stainless steel tested at 350, 700 and 1000 kPa of spray pressures, respectively. Orifices were worn-out after 60 h of usage when the spray pressure was 350 kPa. The useful life of usage was reduced to 40 h and 25 h when the spray pressure was of 700 and 1000 kPa, respectively. Initial variation of wear rates between experimental values and calculated values were also observed in stainless steel orifice plates before the discharge from the orifice plate reached to its propinquity of flow at low spray pressure. Useful hours of usage were reported greater for orifice plates of stainless steel material as compared to the orifice plates of plastic material at all spray pressures during wear test on WTR.

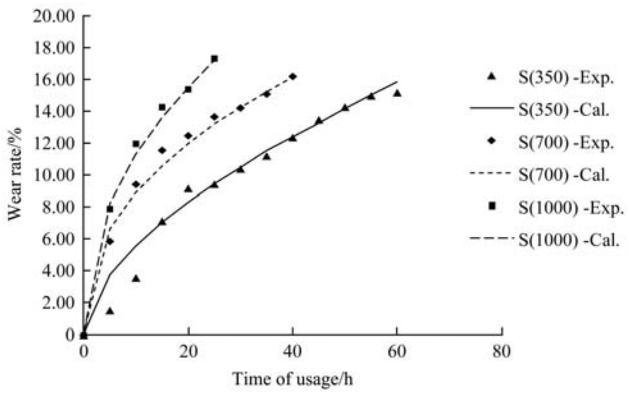


Figure 6 Rate of wear in stainless steel CCO plates at different pressures
(Exp. – experimental values and Cal. – Calculated values)

Figure 7 shows rate of wear percentage, both experimental values and calculated values, of CCO plates made of ceramic materials at spray pressures 350, 700 and 1000 kPa, respectively. Orifice plates of ceramic have shown a very low rates of wear at all spray pressures. The experimental values of wear rates varied from calculated values of their counterparts up to around 160 h at 350 kPa. This phenomenon may be attributed to the favourable spray pressure at which the orifice plates of ceramic material could stand against wear for a longer period of time. Such phenomenons were not observed in orifice plates of ceramic during test pressures 700 and 1000 kPa, respectively. CCO plates made of ceramic were reported maximum wear resistive against tested spray solution as compared to CCO plates made of either plastic or stainless steel at all test pressures 350, 700 and 1000 kPa, respectively.

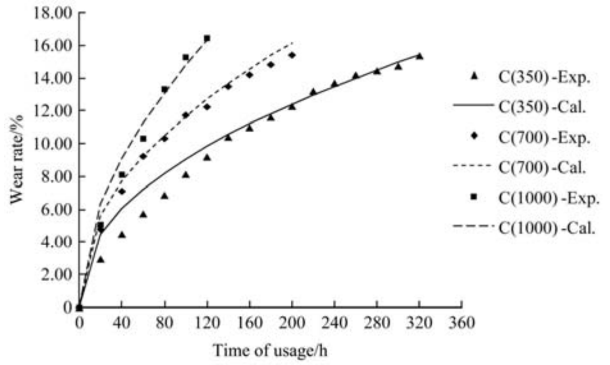


Figure 7 Rate of wear in ceramic CCO plates at different pressures (Exp. – experimental values and Cal. – Calculated values)

The values of arbitrary constants '*m*' and 'C_w' have shown in Table 1. These constants were calculated by solving any two simultaneous equations of wear rate per cent corresponding to their respective time intervals. For example, if experimental values of wear rates (per cent) were reported 9.69% after 20 h of WTR operation, denoted as $\Delta w_{t_{20}}$, and 11.22% after 25 h of WTR operation, denoted as $\Delta w_{t_{25}}$, respectively in CCO plate made of plastic material at 350 kPa of spray pressure. Then the constants '*m*' and 'C_w' can be calculated from equations (25) and (26), respectively (*m*=0.525 and C_w=0.012, respectively).

Table 1 Values of constants *m*, C_w and R^2 for CCO plates made of plastic, stainless steel and ceramic.

	Plastic			Stainless steel			Ceramic		
Spray pressure/kPa	350	700	1000	350	700	1000	350	700	1000
*m**	0.525	0.551	0.427	0.443	0.595	0.570	0.569	0.562	0.494
Average		0.501			0.536			0.542	
C_w*	0.012	0.016	0.021	0.008	0.014	0.017	0.005	0.006	0.007
Average		0.016			0.013			0.006	
R^2	0.997	0.992	0.992	0.985	0.967	0.982	0.989	0.979	0.995

Note: * The constants *m* and C_w were calculated through equation 25 and 26, respectively.

Table 1 has displayed values of the constant *m* and C_w and the coefficient of determination (R^2). From equation (2), the wall pressure on CCO is inversely proportional to the time of usage having power '*m*'. Wear prediction model on elliptical orifice plates, developed by Reichard et al.[11], stated that the increase in discharge rate due to the wear varied approximately with $t^{0.5}$. Similarly, reported average values of '*m*' were 0.501, 0.536 and 0.542 for CCO plates made of plastic, stainless steel and ceramic, respectively. Values of C_w for different plate materials have influenced considerably as the respective constant exhibits frictional characteristics of orifice material. Since C_w shows a proportional relation with wear rate percentage (Δw_t), higher the value of C_w leads to higher wear rate (equation (26)). Hence, CCO plates made of ceramic material has been reported as highest wear resistive having minimum value of C_w (0.006) followed by CCO plates made of stainless steel (C_w=0.013) and plastic (C_w= 0.016), respectively. Values of R^2 showed a strong correlation between wear rates that were observed during experimental investigation and that were calculated by means of predicting equations.

4 Conclusions

The developed system of simple mathematical equations is suitable to predict wear rate on CCO plates of hollow-cone nozzles. Equations uses change in discharge rate as an indicator to predict wear rate and also consists physical parameters of orifice plates made of various materials. Constant C_w is the factor that indicates the wear resistive properties of material, hence termed as wear coefficient (C_w). Therefore, CCO plates of ceramic have shown least wear rate due to minimum value of wear coefficient (C_w = 0.006) followed by stainless steel (C_w=0.013) and plastic (C_w= 0.016), respectively. The validation of equations has also revealed that the use of CCO plates of ceramic material may not only enhance the component reliability of a sprayer or any atomization device but also ensure a precise quantity of pesticide spray due to comparatively least wear rate on orifice.

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