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ORIGINAL ARTICLE

Head loss and pressure head in central pivots for citrus irrigation

Pérdida de carga y carga de presión en pivotes centrales para el riego de cítricos

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ABSTRACT: Irrigation of citrus plantations contributes to obtaining profitable harvests and for this, central pivot machines are used, among other techniques. The equations for calculating head loss and pressure head, available for center pivots with full coverage irrigation, do not provide sufficiently accurate results on irrigation machines configured for citrus. The objective of the present study is to develop new mathematical expressions for the calculation of head loss and pressure head in central pivots configured for citrus irrigation. The equations of these two hydraulic parameters are presented, which guarantee sufficient precision, validated by field measurements.

Keywords: citrus, irrigation, centre pivot irrigation, agricultural hydraulics.

RESUMEN: El riego de plantaciones de cítricos contribuye a obtener cosechas rentables y para ello se emplean, entre otras técnicas, las máquinas de pivote central. Las ecuaciones para el cálculo de la pérdida de carga y la carga de presión, disponibles para los pivotes centrales con riego a cobertura completa, no ofrecen resultados suficientemente precisos en las máquinas de riego configuradas para cítricos. El objetivo del presente estudio es desarrollar nuevas expresiones matemáticas para el cálculo de la pérdida de carga y la carga de presión en pivotes centrales configurados para el riego de cítricos. Se presentan las ecuaciones de estos dos parámetros hidráulicos, que garantizan suficiente precisión, validada por mediciones de campo.

Palabras clave: citrus, riego, riego por pívot, hidráulica agrícola.

INTRODUCTION

Irrigation of citrus trees (Citrus spp.) contributes to obtaining profitable harvests since it determines their productive precocity, controls vegetative development, flowering, fruit setting and fruit quality (Albrigo *et al.*, 2019).The central pivot machine is a technique that has been used worldwide for the irrigation of citrus trees for more than 20 years. Several authors made references to its wide use in South Africa Zanini *et al.* (1998), in the northeast of Brazil Coelho *et al.* (2006) and in Zimbabwe Albani & Palentini (2016). In Cuba its use is still incipient; at 2016, a pilot experience was implemented in areas of the “Jiguaní” Agricultural Enterprise, where a machine in use for the irrigation of 32 ha of citrus trees was adapted Fernández-Hung *et al.* (2019) and a new one to foment another 32 ha, was recently installed.

A guide from Valmont Irrigation (2019) refers to two possible locations of spray nozzles for irrigation of citrus groves with center pivot machines: one above and one below the foliage. For phytosanitary reasons and to minimize the reduction in application efficiency due to losses due to evaporation and wind drift, it is preferred to apply irrigation below the tree canopy, just above the root system, in strips of soil representing concentric circular rings (Figure 1).

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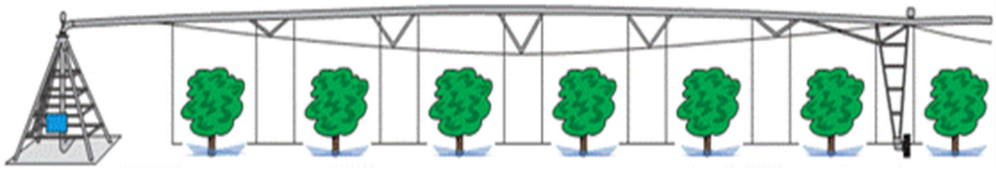

FIGURE 1. Configuration of the central pivots for citrus irrigation.

These particularities mark the differences with respect to the irrigation of other full coverage crops and determine the calculation of the technical-operational parameters of the irrigation machine configured for citrus trees.

A previous study highlighted that the mathematical expressions of the technical-operational parameters that were conceived for the central pivots that irrigate with full coverage, when applied to those configured for citrus irrigation, do not offer sufficiently precise results that contribute to the efficient use of water (Fernández-Hung *et al.*, 2022). The particular arrangement of the spray nozzles also has an impact on the head loss and the distribution of the pressure head that occurs in the main pipe of the irrigation machine. With this, the calculation of the hydraulic variables that determine, for example, the selection of pumping equipment and the nozzles themselves, results in poor reliability.

To calculate the head loss in the main pipe of the central pivots, three different approaches have been used: Adding the partial head losses, by stepwise method Kincaid & Heermann (1970); through a friction factor, which can be determined from a theoretical analytical solution Chu & Moe (1972); Seyedzadeh *et al.* (2021), through a complex numerical solution Reddy & Apolayo (1988); Scaloppi & Allen (1993); Anwar, (2000); Valiantzas & Dercas (2005); Tabuada (2014) or as a result of a non-linear regression analysis Keller & Bliesner (1990). The determination of the pressure head along the main pipe is linked to the calculation of the head loss. In the first and third approaches to calculate the head loss, the pressure head at the outlets is obtained directly (Kincaid y Heermann, 1970; Baptista *et al.*, 2019a; 2019b; 2020).Some researchers proposed its calculation based on the head loss distribution factor Chu & Moe (1972); Keller & Bliesner (1990); Scaloppi & Allen (1993); Anwar (2000); Seyedzadeh *et al.* (2021),and others proposed it included in the calculation of the load loss itself (Valiantzas y Dercas, 2005; Tabuada, 2014).

The methods for calculating head loss and pressure head, using friction and distribution factors, consider that irrigation is carried out at complete coverage and, therefore, do not represent the configuration adopted by the central pivots for irrigation of citrus. The method that calculates the pressure loss and pressure load section by section is excessively laborious and the one that uses hydraulic simulation models requires advanced knowledge in using the software. Although these last methods represent any configuration of the irrigation machine and are the most accurate, their adoption in practice is very limited. Therefore, the objective of the present study is to develop two simple and sufficiently precise mathematical expressions to calculate the pressure loss and pressure load distribution in the center pivots configured for citrus irrigation, through regression analysis.

MATERIALS AND METHODS

Determination of head loss

The head loss on the lateral was determined from the so-called friction factor, F, proposed by Chu & Moe, (1972), with the following generic expression:

$$F = \frac{(h_O - h_R)}{h_m} \quad (1)$$

where h_o is the pressure load on the pivot (m); h_R, the pressure head at the final end of the lateral and h_m, the fictitious head loss with the flow through to end (m).

The term (h_o - h_R), which represents the head loss on the lateral, is obtained from (1) for which the variable F is required, which was determined through a regression analysis with the STATGRAPHICS statistical package. For this, using Buckingham's P theorem, the variables involved in the analysis were defined and organized in the following dimensionless numbers P: $P_1 = F$; $P_2 = N$ y $P_3 = Q\ (n\ D)^{-1}$. The functional relationship between these terms is expressed mathematically as:

$$\mathcal{F}(\Pi_1, \Pi_2, \Pi_3) = \mathcal{F}\left(F,\ N,\ \frac{Q}{v\,D}\right) = 0 \quad (2)$$

where from:

$$F = \frac{(h_O - h_R)}{h_m} = f\left(N, \frac{Q}{vD}\right) \quad (3)$$

where N is the number of emitters (dimensionless); Q, the inlet flow rate to the machine (L s^{-1}); D, inner diameter of the lateral (mm) and n, the water kinematic viscosity at 20°C (10^{-6} m^2 s^{-1}).

The values of the hydraulic variables h_o, h_R and h_m, were obtained using the numerical hydraulic simulation model implemented in the EPANET 2 software. For this, a type 3^2 factorial design was conceived; that is, two factors with three levels each Melo *et al.* (2020), as presented in the following table:

TABLE 1. Factorial design configuration

Factors	Low level	Medium level	Nivel alto
N	64	132	270
$\frac{Q}{\nu\ D}$	$6.2 \cdot 10^4$	$1.2 \cdot 10^5$	$1.8 \cdot 10^5$

Figure 2 shows, as an example, one of the three numerical simulation models of irrigation pivots that correspond to each level of the factorial design: low, medium and high, as well as its equivalent model with total flow to final end.

These models represent three machines with lengths R = 200, 404 and 818 m, resulting from the number of emitters N = 64, 132 and 270, respectively, and their analysis diagram can be seen in Figure 3.

Determination of pressure load distribution

The pressure head distribution along the main pipe was calculated using the distribution factor, H, which was also proposed by Chu & Moe, (1972):

$$H = \frac{(h_r - h_R)}{(h_o - h_R)} \tag{4}$$

where h_r, is the pressure head at the points on the main pipe, located at distances r from the pivot (m) and (h_o - h_R) is the same parameter as in (1).

The expression for calculating H was obtained through a regression analysis between the dimensionless parameters $P_3 = Q\ (n\ D)^{-1}$, $P_4 = H$ y $P_5 = r/R$, aided by the STATGRAPHICS statistical package, according to the following functional relationship:

$$H = \frac{(h_r - h_R)}{(h_o - h_R)} = f\left(\frac{r}{R}, \frac{Q}{\nu D}\right) \tag{5}$$

where r is the distance from the pivot to each discharge point (m) and R, the length of the machine (m). The variables h_o, h_R and h_m were obtained from the same three previous numerical simulation models.

Validation of the proposed equations

To validate the proposed equations, the mean absolute percentage error, *MAPE*, of the hydraulic head along the main pipe was established as an indicator, which consolidates the pressure head and head loss values. It was calculated as follows:

$$MAPE = \frac{1}{n}\sum\left(\left|\frac{(Y_i - \hat{Y})}{Y_i}\right|\right) 100\% \tag{6}$$

where Y_i is the measured pressure head value, $\hat{Y}$, the estimated value and n is the number of measurements. If the resulting value of $MAPE \leq 1 \ldots 2\%$, then the proposed expressions are sufficiently precise to model the head loss and pressure head that occurs in the main pipe of the irrigation machine.

The measurements were carried out on the central pivot machine that was recently installed in areas of the "Jiguaní" Agricultural Enterprise, planned for irrigation of 32 hectares of citrus trees that will be foment (Figure 4).

FIGURE 2. Example of center pivot model in EPANET 2 software.

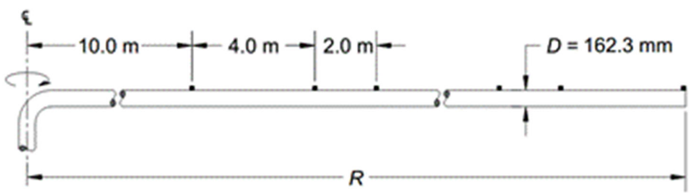

FIGURE 3. Analysis scheme for central pivots modelling.

FIGURE 4. Center pivot machine for citrus irrigation.

RESULTS AND DISCUSSION

Head loss

Table 2 shows the values of *F* calculated from the hydraulic variables h_o, h_R and h_m, which were obtained with the numerical simulation model implemented in EPANET 2 software. It is observed that, in the range analyzed ($64 \leq N \leq 270$), *F* is only a function of *N* and not of the dimensionless number $Q\ (n\ D)^{-1}$. This normally occurs in pressurized flow through pipes, with highs Reynolds numbers, R_e. Keep in mind that $Q\ (n\ D)^{-1} \propto R_e$.

TABLE 2. Calculated values of *F*

N	$Q\ (n\ D)^{-1}$		
	$6.2 \cdot 10^4$	$1.2 \cdot 10^5$	$1.8 \cdot 10^5$
64	0.553	0.553	0.553
132	0.550	0.550	0.550
270	0.549	0.549	0.549

To explain the functional relationship between *F* and *N*, the mathematical model shown below was adopted:

$$F = 0.548 + \frac{0.322}{N} \quad (7)$$

With the following fundamental statistical parameters:

- Correlation coefficient, R: 0.98
- Coefficient of determination, R^2: 96.1%
- Standard error of the estimate: 0.000367
- Mean absolute error: 0.000299

The R^2 statistic indicates that the model as fitted explains 96.1% of the variability in F. The correlation coefficient equals 0.98, indicating a relatively strong relationship between the variables. The standard error of the estimate shows the standard deviation of the residuals to be 0.000367. This value can be used to construct prediction limits for new observations.

In the proposed model, it is observed that when $N \Rightarrow \infty$, $F = 0.548$. This is precisely the value of *F* for the velocity exponent equal to 1.852 for Hazen-Williams's head losses equation, shown in Figure 5 as a horizontal line (F Ch&M). In the figure itself, it can be seen that the new values of *F* are greater than $F_{Ch\&M} = 0.548$ and lower than those obtained by Keller & Bliesner (1990) (F K&B), in curvilinear way.

Note also that with a wide variation of *N* there is a small change in *F*. Therefore, following the same reasoning as (Keller & Bliesner 1990), who proposed a constant value of $F_{K\&B} = 0.555$, alternatively to (7) one can use the value of $F = 0.551$ with a margin of error of ± 0.3%. If the value of $F_{K\&B} = 0.555$ were used, a maximum error of 1% would be made.

Thus, for center pivots configured for citrus irrigation, using the Hazen-Williams equation, given that the normal flow conditions in the equipment are within their validity limits, the head loss equation, H_F, in the lateral is the following:

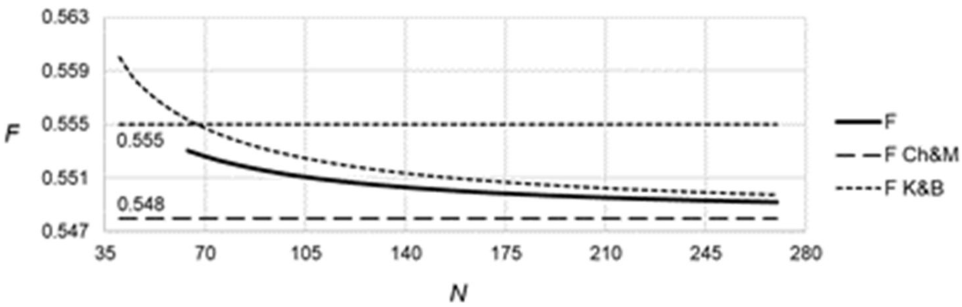

FIGURE 5. *F* variation with *N*.

$$H_F = F \ \ 1.217 \cdot 10^{10} \frac{R \ Q_e{}^{1.852}}{C^{1.852} D^{4.87}} \pm \Delta Z \qquad (8)$$

If it is considered that F = 0.551 and C = 120 … 130, then:

$$H_F = 9 \cdot 10^5 R \frac{Q_e{}^{1.852}}{D^{4.87}} \pm \Delta Z \qquad (9)$$

where F is the friction factor (dimensionless); C, Hazen-Williams's roughness coefficient; R, the total length (m); Q_e, the effective capacity machine (L s^{-1}); D, the inner diameter of the pipe (mm) and DZ, the maximum position head difference, positive or negative (m).

Pressure load distribution

Table 3 shows a selection of 1,407 H values calculated from the hydraulic variables h_o, h_R and h_r, which were also obtained with the numerical hydraulic simulation model implemented in EPANET 2 software.

The multiple regression analysis that was carried out to define the influence of the three independent variables, r/R, N y Q $(n \ D)^{-1}$ on the dependent parameter H, resulted that the last two do not have a statistically significant impact, for a confidence level equal to or greater than 95%. As a consequence, for the range of values analyzed, H is only dependent on r/R.

Thus, from a polynomial regression analysis, which involves r/R and powers of r/R, it was determined that the maximum appropriate order of the adjustment polynomial is 6; However, based on a regression model selection analysis, an order 5 model was adopted that has the same adjusted coefficient of determination, R^2_{adj}, up to the thousandth significant figure, where H is a function of the variables, $\frac{r}{R}$, $\left(\frac{r}{R}\right)^2$, …, $\left(\frac{r}{R}\right)^5$. Thus, for a confidence level equal to or greater than 95%, the resulting best-fit polynomial is:

$$H = 1 - 1.82\left(\frac{r}{R}\right) + 1.13\left(\frac{r}{R}\right)^3 - 0.31\left(\frac{r}{R}\right)^5 \qquad (10)$$

With the following fundamental statistical parameters:

- Correlation coefficient, R: 1.0000
- Coefficient of determination, R^2: 99.9997%
- Adjusted coefficient of determination, $R^2{}_{adj}$: 99.9997%
- Standard error of the estimate: 0.000516

Rewriting (9), it turns out:

$$H = 1 - 1.82\left[\left(\frac{r}{R}\right) - 0.62\left(\frac{r}{R}\right)^3 + 0.17\left(\frac{r}{R}\right)^5\right] \qquad (11)$$

It is obtained that (11) is similar to the following form of the equation proposed by Chu & Moe, (1972), with small discrepancies in coefficients of independent variables:

$$H = 1 - 1.88\left[\left(\frac{r}{R}\right) - 0.6\overline{6}\left(\frac{r}{R}\right)^3 + 0.20\left(\frac{r}{R}\right)^5\right] \qquad (12)$$

The maximum difference between results of both equations is 15 mm, which represents -5.2% error.

Finally, for center pivot machines configured for citrus irrigation, the equation of pressure head, h_r, at each outlet on the main pipe, located a distance r from the pivot, is as follows:

$$h_r = 9 \cdot 10^5 R \frac{Q_e{}^{1.852}}{D^{4.87}} \left\{1 - 1.82\left[\left(\frac{r}{R}\right) - 0.62\left(\frac{r}{R}\right)^3 + 0.17\left(\frac{r}{R}\right)^5\right]\right\} + h_R \pm \Delta Z_{(R-r)} \qquad (13)$$

Validation of proposed equations

In Figure 6, it can be seen that the hydraulic head measurement points are located on both sides of the curve that represent their calculated values.

TABLE 3. Calculated values of H

N	*Q (n D)* $^{-1}$	*r/R*				
		0.00	**0.25**	**0.50**	**0.75**	**1.00**
64	$6.2 \cdot 10^4$	1.000	0.564	0.223	0.039	0.000
	$1.2 \cdot 10^5$	1.000	0.563	0.222	0.039	0.000
	$1.8 \cdot 10^5$	1.000	0.563	0.222	0.039	0.000
132	$6.2 \cdot 10^4$	1.000	0.562	0.221	0.038	0.000
	$1.2 \cdot 10^5$	1.000	0.562	0.221	0.038	0.000
	$1.8 \cdot 10^5$	1.000	0.562	0.221	0.038	0.000
270	$6.2 \cdot 10^4$	1.000	0.562	0.220	0.037	0.000
	$1.2 \cdot 10^5$	1.000	0.562	0.220	0.037	0.000
	$1.8 \cdot 10^5$	1.000	0.562	0.220	0.037	0.000

The dispersion of these points in relation to the curve is attributed to the differences that may exist in the roughness conditions (Hazen-Williams C-coefficient and unforeseen local head loss) and, fundamentally, to appreciation of the measurement instrument (glycerin manometer), which introduces an error of ±0.51 m. However, the deviations are relatively small. The calculation of the mean absolute percentage error, MAPE, produces a value of 0.49%. This vale is less than 1 … 2%, which indicates that the proposed equations have excellent precision.

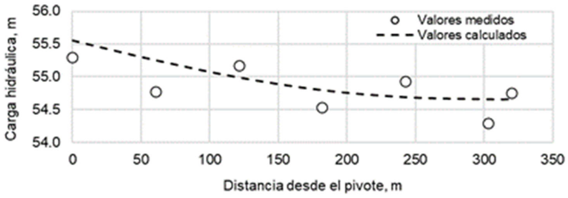

FIGURE 6. Calculated and measured hydraulic head.

Likewise, in the scatter graph presented in Figure 7, correspondence is observed between the calculated and measured hydraulic head values.

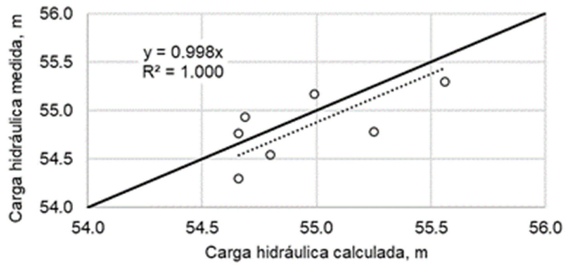

FIGURE 7. Dispersion of calculated and measured hydraulic head values.

CONCLUSIONS

- The development of mathematical expressions is presented to calculate the head loss and the pressure load distribution in central pivots configured for the irrigation of citrus plantations.
- The R^2 statistic indicates that the model as fitted explains 96.1% of the variability in F. The correlation coefficient equals 0.98, indicating a relatively strong relationship.
- In the proposed model, it is observed that when *N* □ ∞, *F* = 0.548. This is precisely the value of *F* for the velocity exponent equal to 1.852
- The calculation of the mean absolute percentage error, MAPE, produces a value of 0.49%. This vale is less than 1 … 2%, which indicates that the proposed equations have excellent precision

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