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in

Lamaddalena N. (ed.), Bogliotti C. (ed.), Todorovic M. (ed.), Scardigno A. (ed.).
Water saving in Mediterranean agriculture and future research needs [Vol. 1]

Bari : CIHEAM
Options Méditerranéennes : Série B. Etudes et Recherches; n. 56 Vol.I

2007
pages 353-366

MEASUREMENT AND IMPROVEMENT OF THE ENERGY EFFICIENCY AT PUMPING STATIONS

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SUMMARY - Several works have been carried out to optimize the total cost (investment and energy cost) in pumping stations in an attempt to obtain the combination of variable and fixed pumps that would reduce the cost to a minimum. These works take into consideration the theoretical characteristic curves of the pumps that means just considering the pump and engine efficiencies and not the efficiency of other components of the pumping station.
The goal of this work is to develop a pumping station simulation model and describe a methodology to calibrate it with measured data (using optimization techniques) with the objective of determining the best energetic and economic regulation option. This simulation model considers the characteristic curves of the pumps and the regulation of the pumping station. To represent the real behavior of a pumping station, the simulation model should be calibrated with measured data. Developing the pumping station calibrated model permits carrying out an energy cost study and determining the regulation that minimizes this cost. One of the main aspects to consider when carrying out the energy cost analysis is to estimate the discharge distribution through the irrigation season. The optimum regulation will be the option that best fits with the discharge distribution in terms of efficiency. This model will be applied to a pumping station located in Tarazona de La Mancha (Albacete, Spain), obtaining a cost saving of 16.02% by changing the pumping station regulation from the current regulation.

Key words: pumping station, electric energy, pump, efficiency, energy cost, variable speed drive, simulation model.

RESUME *- Plusieurs travaux ont été conduits sur l'optimisation du coût total des stations de pompage (Investissement et coût d'énergie) dans le but d'obtenir une combinaison des pompes fixes et variables qui réduit au minimum le coût. Ces travaux basés seulement sur les courbes caractéristiques théoriques des pompes, prennent en considération l'efficience des pompes et du moteur et non pas de l'efficience des autres composants de la station de pompage.*
L'objective de ce travail, est de développé un modèle de simulation pour les stations de pompage et de décrire une méthodologie de calibration à partir des données mesurées (en utilisant des techniques d'optimisations) dans le but de déterminé la meilleure régulation énergétique et économique.
Ce modèle de simulation examine les courbes caractéristiques des pompes et la régulation du station de pompage. Pour représenter le véritable fonctionnement de la station de pompage, ce modèle doit être nécessairement calibré avec des données mesurées. Le développement d'un modèle de calibration des stations de pompage permet une étude du coût énergétique et les régulations possibles pour minimiser ce coût. Un des aspects principaux à être considéré durant l'analyse du coût énergétique est l'estimation de la distribution des débits durant la saison d'irrigation. La régulation optimale est l'option la plus adaptée avec la distribution des débits en terme d'efficience. Ce model appliqué sur une station de pompage de Tarazona de la Mancha (Albacete, Spain), a résulté une réduction de coût de 16.02% en changeant la régulation de la station de pompage de celle actuelle.

Mots-clés: *Station de pompage, énergie électrique, pompe, efficience, coût d'énergie, pompe à vitesse variable, model de simulation.*

INTRODUCTION

Rational and efficient use of energy is essential for carrying out a sustainable development. In Spain, agriculture requires high energy consumption, mainly for machinery and irrigation, and this consumption is increasing due to the irrigation energy requirements. Electrical energy is the main source of energy in irrigation. Petroleum Liquefied Gases (PLGs) only provide the 24.41% of the total energy requirement in irrigation. It is predicted that 80% of PLG energy will be transformed into electrical consumption in 2012 horizon. Works with the aim of increasing the efficient use of electrical energy should be developed.

Several works have been carried out to optimize the total cost (investment and energy costs) in pumping stations (Moradi-Jalal *et al.,* 2003; Pulido *et al.,* 2003a; Moradi-Jalal *et al.,* 2004;Planells *et al.,* 2005). They attempt to obtain the combination of variable and fixed pumps that reduces costs to a minimum. These works consider the theoretical characteristic curves of the pumps, which means just considering the pump and engine efficiencies and not the efficiency of the other components of the pumping station. With these methodologies, energy saving is mainly obtained by means of the regulation improvement in the pumping station. The proper selection of the pump size does not improve energy saving because the price of the different combination of pump sizes, for the same installed power, is similar (Moradi-Jalal *et al.,* 2003).

In order to develop this work, a pumping station simulation model, which considers the characteristic curves of the pumps and the pumping station regulation is carried out. To represent the real behavior of a pumping station, its simulation model should be calibrated with measured data. Hydraulic model calibration is a two-step process: 1) comparison of measured and calculated flows and pressures; and 2) adjustment of initial parameters of the model, based on theoretical relationships, to improve the fitting of the measured and calculated values (Walski, 1983).

Currently, several methodologies based on optimization techniques have been developed (Dias *et al.,* 2000; Wu *et al.,* 2004), due to the improvement in computational capabilities. These methodologies permit the obtainment of calibration results by optimizing an objective function.

The goal of this work is to develop a pumping station simulation model and its calibration with measured data. It uses optimization techniques to determine the best energetic and economic regulation option. This methodology will be implemented in a pumping station located in the irrigable area of Tarazona de La Mancha (Albacete, Spain).

MATERIALS AND METHODS

The case study

A pumping station that supplies water to an on-demand irrigation network, located in Tarazona de La Mancha (Albacete, Spain), was studied. Water is obtained from five wells in the Hydrogeologic Unit (HU) 08.29, located in the Júcar basin. Underground water is conveyed to a reservoir with a capacity of 23,000 m^3 from which the pumping station, composed of ten 140 HP pumps, conducts the water to the irrigation network. The characteristics of the pumps are shown in *Table 1* and the characteristic curves in Fig. 1.

Table 1. Pump characteristics.

Brand	INDAR®
Type of pump	Submerged electrical pump
Model of pump	345-2
Model of motor	25-30
Discharge ($l\ s^{-1}$)	120
H (m)	74
Power (HP)	140
Frequency (Hz)	50
Speed (r.p.m.)	2900

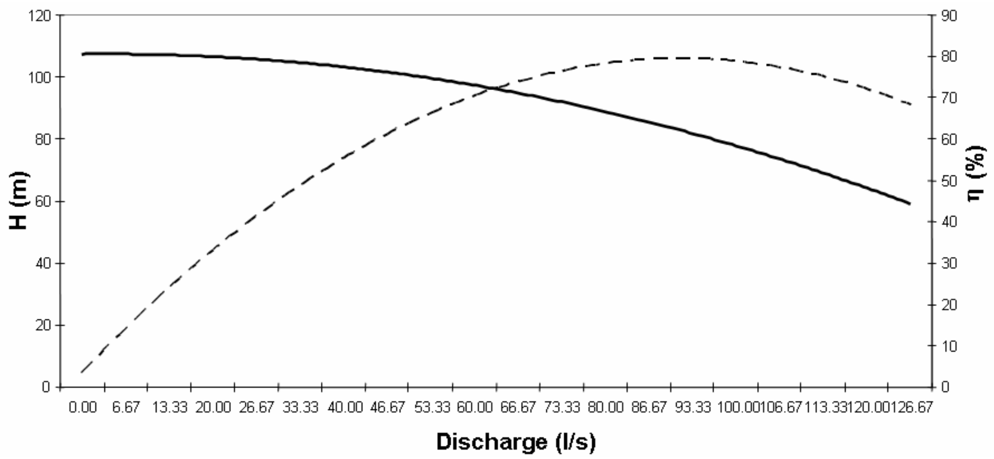

Fig. 1. Characteristic curves Q-H and Q-ηof the pumps

To guarantee a pressure of 45 m in all the hydrants of the network, a head of 62 m (manometric regulation) is applied. The pumping station has two pumps with variable speed drives and the remainders with electronic starters. All pumps are controlled by a Programmable Logic Controller (PLC), which receives data from a pressure transducer located in the pumping station collector. This PLC controls the variable and fixed speed pumps to maintain the set pressure (62 m). Permanent solid-set sprinkler irrigation systems are used for 95% of the area, the rest being irrigated by drip irrigation systems.

In this case, it is not possible to measure the pumping station discharge directly because each pump discharges water to a collector, and from this collector several pipes distribute the flow in the network. Under these conditions, total discharge can be obtained by measuring the instantaneous discharge of each pump by installing a flow meter, or by using the electrical parameters of the pumps to determine the power-discharge curve for the pumping station. In this study, the second methodology was carried out because of its simplicity and precision. Electrical and hydraulic parameters were measured:

- Electrical parameters. Current and voltage readings for each pump were measured to obtain power and the power factor. Two portable supply network analyzers, placed upstream of each variable speed drive, and a set network analyzer (measurement error lower than 1.5%), located next to the low voltage switch, were used to measure all pumping station electrical parameters.
- Hydraulic parameters. Discharge and pressure was controlled at the pumping station by measuring the discharge at each pump with a portable ultrasonic flow meter (measurement error lower than 2.5%) and the head with a pressure transducer and a data logger (measurement error lower than 1%). Discharge in the variable speed pumps were measured continuously and for the fixed pumps discharge was measured every two weeks to control the variability in the discharge of these pumps, which was negligible. Pressure at the pumping station was measured every minute.

Once power is measured for different discharge-pressure conditions, the pumping station efficiency can be determined. By measuring the power and the pressure, the discharge can be obtained. This method is more accurate than adding the hydrant flow meter measurements because they are difficult to obtain and also due to the cumulative effect of measurement error of each of the flow meters. Pumping station data could only be collected during 2004.

Development of pumping stations simulation model

The pumping station simulation model developed in this work reproduces the behavior of all the pumps that compose the pumping station for different types of regulation. This model was implemented in Microsoft® Excel and considers the characteristic curves of the pumps (Q-H and Q-η). The model is run considering both, the discharge interval of 1 l s^{-1} and the required pressure for each discharge. This pressure will be a constant value in case of manometric pumping station regulation, or it will follow the demand curve in case of mano-flowmetric regulation. Using affinity laws for those pumps controlled by variable speed drivers, and the working point (Q-H) for fixed pumps, the pumping station efficiency for each demanded flow can be obtained. This model is useful for establishing the best working condition of the pumping station, for evaluating its efficiency, and for studying the effect of the pumps aging on the pumping station behavior.

In this work, the proposed model will be used for studying several kinds of regulations of the pumping station. Thus, it can be determined which is the best regulation option for the pumping station of Tarazona de La Mancha. The obtained results can be applied to other pumping stations with similar working conditions. In order to obtain an accurate result, the pumping station model has to be calibrated with measured data.

General methodology for carrying out the calibration of hydraulic models

Hydraulic model calibration is a two-step process: first, comparison of measured and calculated flows and pressures; and second, adjustment of initial parameters of the model, based on theoretical relationships, to improve the fitting of the measured and calculated values (Walski, 1983).

Current network facilities may not be the same as those projected. Thus, in the calibration process of pumping stations, several aspects should be considered such as pump and engine aching; efficiency of cables, pumping pipes, and controllers; and failures when acquiring pumping station data.

The steps for carrying out the calibration process are as follows (García-Serra, 1988):

1. Data acquisition. One of the most important steps to obtain a useful hydraulic model is to carry out a proper measurement of the topologic and hydraulic data. These data can be obtained from the pumping station project, definitive building maps, and by checking the pumping station conditions in field.

2. Inserting data into the model. To obtain an accurate model, as many data as are available should be inserted. However, some simplifications can be considered in order to ease the development of the model.

3. Provisional running of the model. As a first step, the model should be run using just the pump and motor efficiencies. Thus, the hydraulic characteristics of the system, relative to these efficiencies and for some specific working conditions, can be obtained.

4. Pumping station data measurement. To study the real behavior of the pumping station, accurate data should be measured. For calibrating hydraulic systems, the main hydraulic parameters to measure are flow and pressure. Frequent and accurate data collection can be obtained with current instruments that permit storage and easy management of data. Electrical parameters are measured to obtain the total efficiency of the pumping station.

5. Adjustment and calibration of the model. Parameters that should be considered in the calibration process are the pipe head losses, cable efficiency, variable speed drive efficiency, and the efficiency of the other components of the pumping station.

Calibration procedures can be divided into experimental and optimization procedures (Batista *et al.,* 2000; Abadía, 2003; Wu *et al.,* 2004): 1) Experimental procedures are based on test-error methodology, which means changing calibration parameters for obtaining the values that have the best adjustment to those measured. This procedure requires calibration in a working condition and validation for other working conditions; 2) Optimization techniques use no lineal optimization methods, considering different parameters as variables, for minimizing the difference of the measured data and the theoretical results of the model (Días *et al.,* 2000).

In this work, an optimization methodology (no lineal optimization) has been applied to calibrate the simulation model (implemented in Microsoft® Excel) of a pumping station located in Tarazona de La Mancha (Albacete, Spain).

Methodology for calibrating pumping stations

A simulation model of pumping stations reproduces the pump behavior for a specific network demand. An evaluation of the effect that different demands can cause on the pumping station behavior, without doing it in the real pumping station, can be performed.

To make the pumping station model more useful and accurate, it has to be calibrated with measured Q-H data. An optimization calibration method can be developed following these steps:

- Data acquisition. Type (characteristic curves) and number of installed pumps, number of variable and fixed speed pumps, and the pumping station regulation are considered.

- Inserting data in the model. The model has been implemented in Microsoft® Excel, introducing the standard characteristic curves and the regulation pressure (manometric regulation at 62 m in the case study). The model differentiates between the pumps that work with variable speed and those that work with fixed speed. To run the model with standard data only pump and engine efficiencies are considered and not the rest of the components of the pumping station efficiency [Eq. (1)].

$$\eta_t = \eta_p \cdot k = \eta_b \cdot \eta_m \cdot \eta_c \cdot \eta_v \cdot \eta_l \quad (1)$$

where:

η_t: total pumping station efficiency
k: calibration adjustment coefficient
η_p: pump efficiency
η_m: motor efficiency
η_c: cables efficiency
η_v: variable speed drive efficiency
η_l: efficiency related to head losses in pump pipes.

- Provisional running of the model. The model can be run considering the standard data and the regulation of the pumping station. Theoretical results of the pump station behavior will be obtained.

- Pumping station data measurement. Measured data were flow, pressure and electrical parameters. The flow in the variable speed pumps was measured continuously, but in the fixed pumps it was only necessary to measure flow sometimes during the irrigation seasons in order to evaluate its variability. This is due to the fact that for a manometric regulation, fixed pumps will work always in the same working point. Electrical parameters were measured every 10 minutes during the whole irrigation season. However, to obtain the Q-η curve in an accurate way for the variable speed pumps, flow, pressure, and electrical data every 10 seconds, during some days, were measured. During the whole irrigation season, discharge for the variable speed pumps was measured every 10 minutes.

- Adjustment and calibration of the model. To calibrate the pumping station model, each of the pumps was calibrated independently by minimizing the difference between measured efficiency and theoretical efficiency for each flow. To obtain the pumping station efficiency for all the discharges, each pump was calibrated and the model was run considering the pumping station regulation conditions.

For carrying out the calibration process, Solver tool, included in Microsoft® Excel, was used. Flows from 0 to 120 $l\ s^{-1}$ were used for calibrating each pump. The difference between the theoretical and measured value of the efficiency, for each flow value, was minimized by means of the k value [Eq. (1)]. Thus, the objective function is:

$$\left[\frac{\left(k_{Q1}\cdot\eta_{b_{Q1}}-\eta_{tm_{Q1}}\right)^2+\left(k_{Q2}\cdot\eta_{b_{Q2}}-\eta_{tm_{Q2}}\right)^2+...+\left(k_{Qi}\cdot\eta_{b_{Qi}}-\eta_{tm_{Qi}}\right)^2}{n}\right]^{0,5} \quad (2)$$

where:
η_{bQi}: theoretical pump efficiency for Q_i flow
η_{tmQi}: total efficiency measured for Q_i flow
n: number of flow values for carrying out the calibration process.

In this case, the number of flow values for carrying out the calibration process (n) was 18 for each variable speed pump.

The coefficient k for each flow was calculated [Eq. (2)] by minimizing the difference between theoretical and measured data. Therefore, it is possible to study its relation with flow that means studying the relation of the rest of the components of the efficiency with flow.

Application of the pumping station calibrated model

Developing the pumping station calibrated model permits carrying out an energy cost study and determining the regulation that minimizes the energy cost.

Different algorithms for minimizing the pumping stations total cost (investment and operation costs) have been developed (Moradi-Jalal *et al.,* 2003; Pulido *et al.,* 2003a; Moradi-Jalal *et al.,* 2004; Planells *et al.,* 2005). However, none of them considers the calibrated pump curves. With these methodologies, cost saving is mainly obtained by improving the energy efficiency and not by minimizing the investment cost (Moradi-Jalal *et al.,* 2003). Because of that, and because in this work a real pumping station is analyzed (pumps are already chosen), the energy cost saving by means of pumping station regulation improvement is mainly studied.

To carry out an energy cost study for different kind of regulations, the following aspects should be considered:

- Discharge distribution through out the irrigation season.
- Pumping station efficiency for each demanded discharge and for each regulation type.
- Energy cost (€/kWh).

The determination of discharge distribution through out the irrigation season has been the subject of several works, considering different methodologies from simple soil moisture balance (Lamaddalena, 1997; Khadra, 2004), to complex forecasting tools as neuronal networks (Pulido *et al.,* 2003b). In this work, discharge distribution was obtained by measuring electrical data in the pumping station every 10 minutes. These electrical data were related to flow data by means of the total pumping station efficiency, by measuring power, and by considering a manometric regulation at 62 m.

In order to obtain the discharge histogram, intervals of discharge of 10 l s^{-1} were considered. The monthly histogram, and the one for the whole irrigation season, can be obtained.

Considering the discharge during the whole irrigation season and the pumping station efficiency, absorbed power can be calculated [Eq. (3)].

$$\overline{N_{abs}}=\sum_{i=1}^{n}\frac{9.81\cdot Q_i\cdot H_i}{\eta_i}f_i=\sum_{i=1}^{n}(N_{Qi}\cdot f_i) \quad (3)$$

where:
Q_i: average discharge for every discharge interval i (m^3 s^{-1})
H_i: average pressure for every discharge interval i (m)
η_i: average efficiency for every discharge interval i (decimal)
f_i: frequency of every discharge i in the irrigation season.

Energy cost (€/kWh) is established by contract between the electrical company and the irrigation society (*Table 2*). For each discharge interval (Q_i), an average energy cost is assigned depending on the proportion that this discharge is inside every tariff period during the whole irrigation season [Eq. (4)].

Table 2. Prices of installed and consumed power.

Period*	1	2	3	4	5	6
Installed power (€/kW year)	10.84	5.43	3.98	3.98	3.98	1.81
Consumed power (Cent€/kWh)	9.0909	8.0073	7.6364	6.9171	6.2615	4.2342

*The time interval of each period has a monthly variation.

$$C_i = \frac{\sum_{j=1}^{6} (t_{ij} \cdot C_j)}{\sum_{j=1}^{6} t_{ij}} \quad (4)$$

where:
C_i=average cost of kWh for the discharge interval i (€/kWh), t_{ij}=time that discharge i occurs in the tariff period j, C_j=energy cost in the tariff period j.

Thus, the annual energy cost (E) is expressed as follows:

$$E_i = \sum_{i=1}^{n} N_{Qi} \cdot f_i \cdot t_i \cdot C_i \quad (5)$$

where:
N_{Qi}=the total absorbed power by pumping station for every discharge i.

For each kind of regulation, and considering the discharge distribution during the irrigation season, energy consumption and its cost can be compared. That way, the regulation that best minimizes the energy cost can be established.

RESULTS AND DISCUSSION

Calibration of the pumping station model

Curve Q-η calculation for variable speed pumps considering measured data

By analyzing measured data, the Q-η_t curve for variable speed pumps is obtained (Fig. 2). This curve include all the components of the efficiency [Eq. (1)]. The adjustment to a curve is carried out by means of Statgraphics® 5.0 for different adjustment degree (*Table 3*).

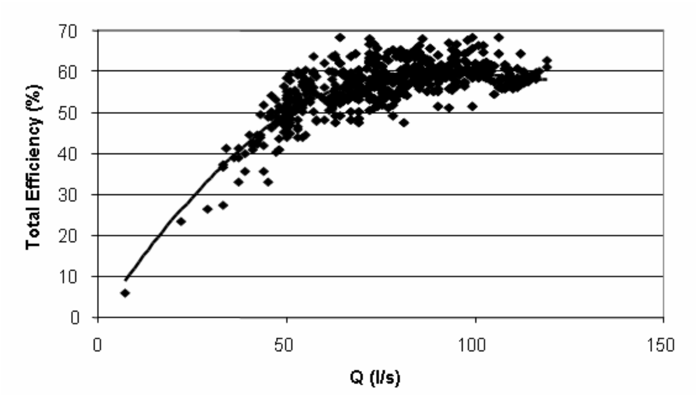

Fig. 2. Measured efficiency curve of the variable speed pumps

Table 3. Adjustment to different polynomials of the efficiency curve for the variable speed pumps.

Polynomial	R^2 (%)	Residuals average	SD residuals	Significance
$\eta_b = -0{,}0063Q^2 + 1{,}1654Q + 6{,}8336$	62,95	2,93	3,89	99%
$\eta_b = 0{,}00006Q^3 - 0{,}0195Q^2 + 2{,}0916Q - 13{,}2388$	64,92	2,86	3,79	99%

Residuals are similar for all adjustments, so adjustment to a second degree polynomial is correct. With this curve, the Q-H curve, and the fixed pumps working points, the pumping station behavior can be analyzed using the simulation model.

Calibration of the curve Q-η_t for variable speed pumps

Theoretical pump efficiency (η_p) is always higher than the total measured efficiency (η_t) because last one considers the rest of the components of the efficiency (Fig. 3). Results of the calibration, considering Eq. (1), are shown in *Table 4*.

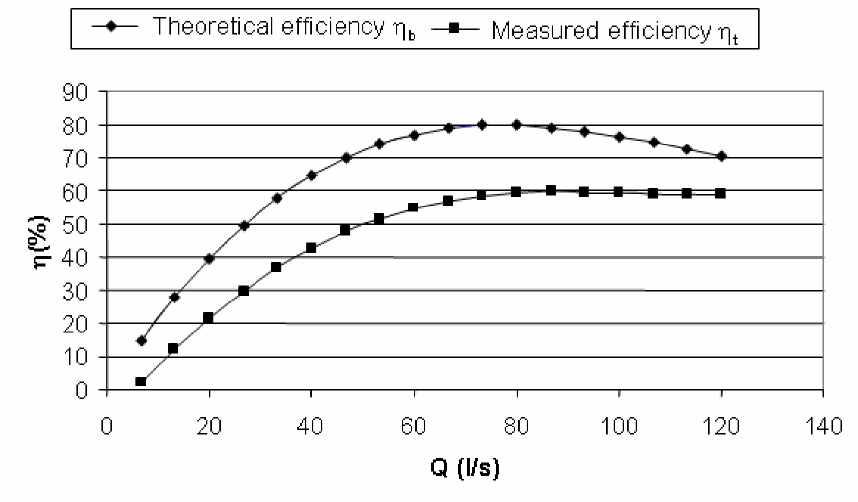

Fig. 3. Comparison between theoretical and measured efficiency curves of the variable speed pumps.

Table 4. Calibration results for different discharge values.

Q (l s^{-1})	η_bTheoretical	η_tMeasured	K	$(\text{Difference})^2$
6,67	14,81	2,11	0,14	1,44892E-06
13,33	28,06	12,34	0,44	6,89038E-08
20,00	39,57	21,53	0,54	1,15057E-07
26,67	49,43	29,66	0,60	1,78834E-07
33,33	57,71	36,72	0,64	6,3651E-08
40,00	64,51	42,74	0,66	1,31764E-07
46,67	69,92	47,73	0,68	2,4612E-08
53,33	74,04	51,75	0,70	4,05403E-08
60,00	76,97	54,84	0,71	3,02049E-09
66,67	78,83	57,09	0,72	2,16252E-08
73,33	79,75	58,59	0,73	8,3749E-08
80,00	79,82	59,45	0,74	2,50737E-07
86,67	79,20	59,78	0,75	3,46928E-08
93,33	78,01	59,72	0,77	1,41034E-08
100,00	76,40	59,43	0,78	5,90557E-10
106,67	74,50	59,07	0,79	5,90366E-09
113,33	72,47	58,84	0,81	6,2077E-08
120,00	70,46	58,92	0,84	1,63284E-08

The evolution of the calibration coefficient k is ascending with flow (Fig. 4). This shows that the rest of components of efficiency are increasing with flow. That is logical because the motor and variable speed drive efficiencies are maximum when they work for nominal revolutions. Bad pump efficiency for flow between 90-120 l s^{-1} is made up for good motor and variable speed drive efficiencies.

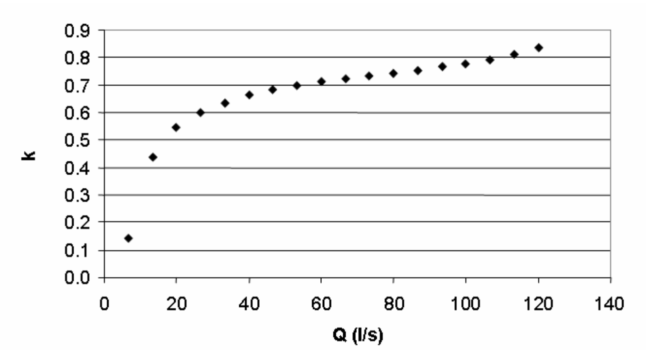

Fig. 4. Evolution of the calibration coefficient "k" with discharge.

Working point for fixed pumps

From measured data, it can be deduced that fixed pumps works always in the same working point for the regulation pressure (62 m),with a flow around 120 l s^{-1} (*Tables 5 and 6*).

Table 5. Discharge and pressure measurements for the 2, 3, 4 and 5 pumps.

	Pump 2				Pump 3				Pump 4				Pump 5			
	%	Q (l/s)	H (bar)	P (kW)	?%	Q (l/s)	H (bar)	P (kW)	%	Q (l/s)	H (bar)	P (kW)	%	Q (l/s)	H (bar)	P (kW)
Average	66.0	121.7	6.2	111.9	58.6	98.4	6.2	102.4	68.1	124.9	6.2	111.3	65.2	122.1	6.2	112.3
Max	67.7	125.0	6.3	112.0	60.0	99.0	6.4	102.6	69.9	129.0	6.3	111.6	66.1	125.5	6.3	112.5
Min	64.5	120.0	6.1	111.6	57.6	98.0	6.1	102.2	66.3	124.0	6.1	111.2	64.2	121.2	6.1	112.1
SD	0.9	1.4	0.0	0.1	0.6	0.5	0.1	0.1	0.8	1.1	0.1	0.1	0.7	0.6	0.1	0.1
CV	1.4	1.2	0.7	0.1	1.0	0.5	0.8	0.1	1.2	0.9	0.9	0.1	1.1	0.5	0.9	0.1

Table 6. Discharge and pressure

	Pump 6				Pump 7				Pump 8			
	%	Q (l/s)	H (bar)	P (kW)	%	Q (l/s)	H (bar)	P (kW)	%	Q (l/s)	H (bar)	P (kW)
Average	59.8	111.4	6.1	112.2	65.5	119.8	6.2	111.5	65.6	128.1	5.9	113.1
Max	61.1	114.0	6.2	112.7	66.2	120.0	6.3	111.7	66.5	129.0	6.0	113.7
Min	58.6	109.0	6.0	111.8	64.7	119.0	6.1	111.3	64.8	127.0	5.8	112.5
SD	0.5	1.0	0.0	0.2	0.4	0.4	0.0	0.1	0.4	0.7	0.0	0.2
CV	0.9	0.9	0.6	0.1	0.6	0.3	0.5	0.1	0.6	0.6	0.6	0.2

Relation between theoretical and measured data for fix speed pumps are shown in Fig. 5 (Q-H points) and in Fig. 6 (Q-η points). Majority of the pumps fit with the theoretical curve, but B3 and B6, do not. This can be due to ageing of these pumps, water losses in pumping pipes, or head losses in single elements between pump and the collector. In this case, is so common to find water losses in the join between the pump and the pumping pipe. Fixing the join make pumps work in the proper working point.

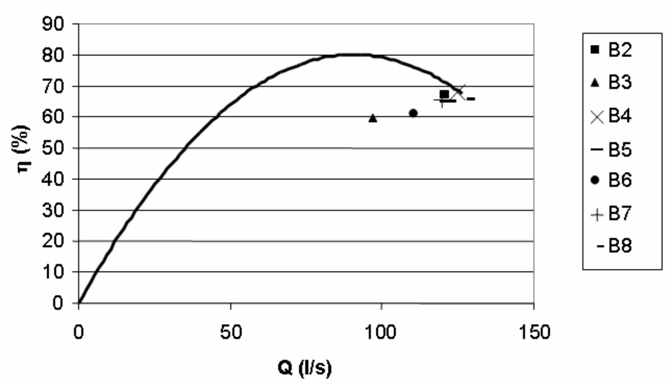

Fig. 5. Measured working points of the fix pumps and theoretical Q-H curve.

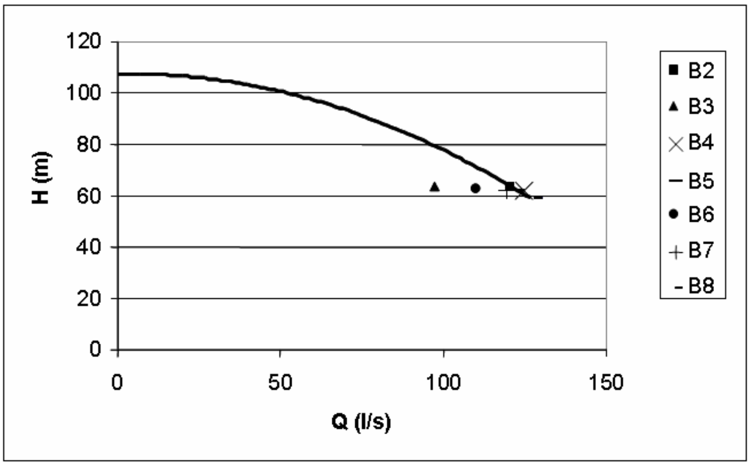

Fig. 6. Efficiency point of each fix pump and theoretical q-η curve.

Results of energy study using calibrated pump curves

Fig. 7 shows the Q-η_t curve of the pumping station using calibrated curves of each pump and considering current regulation (two variable speed pumps working simultaneously and the rest with fix speed). Several studies have concluded that the best regulation is using two variable speed pumps working sequentially (Planells *et al.*, 2005). Therefore, with calibrated pump curves model considering this kind of regulation is developed too. A comparison between both types of regulation can be shown in Fig. 8. With this second option, an efficiency improvement for low flows is shown.

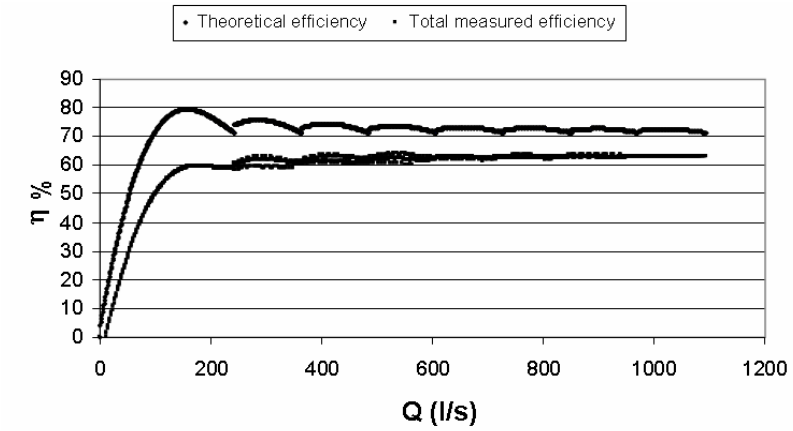

Fig. 7. Theoretical and measured efficiency for different discharges.

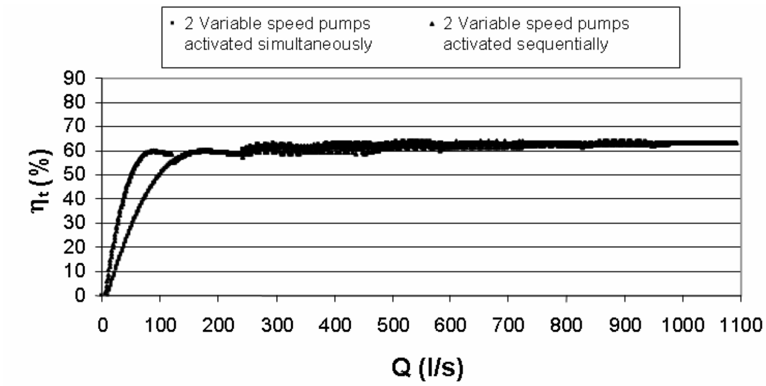

Fig. 8. Comparison between efficiency curves considering an activation of the variable speed pumps in a sequentially and simultaneously way.

To determine the energy consumption in pumping stations, discharge distribution during the whole irrigation season should be considered. In this case, cumulated frequency of discharges is shown in Fig. 9 for every month of the irrigation season and for the whole irrigation season 2004. In Fig. 9 can be shown that low discharges have a higher frequency than high discharges, mainly between 40-90 l s^{-1} (6-10% of maximum discharge). In June, July and August, high discharges are more frequent, but still discharges between 40-90 l s^{-1} are predominant. This is due to pumping station is able to discharge during the whole day, but farmers just irrigate when it is cheaper for them (7.00 pm to 9.00 am).

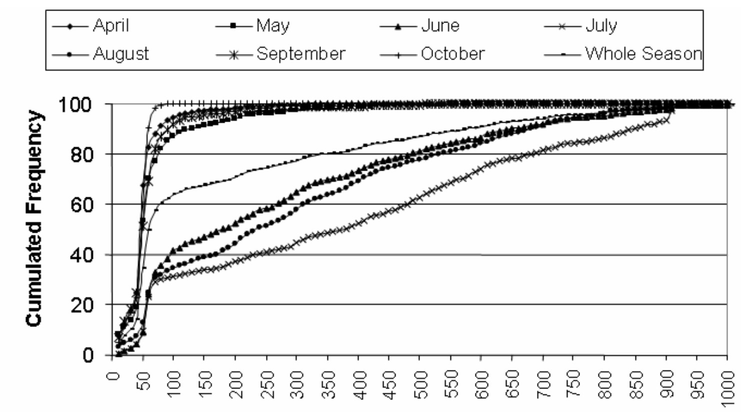

Fig. 9. Cumulated frequency of the discharges for each of the months of the irrigation season.

To determine the economic saving when an alternative pumping station regulation is carried out, it is necessary to obtain the relation between the energy price and discharge [Eq. (4)]. It depends on the electricity rate period in which each discharge is included. Low discharges are associated to a high energy price because there is a higher proportion of this kind of discharges inside the expensive electrical rates.

Considering the discharge distribution, average absorbed power during the whole irrigation season can be calculated for each kind of regulation. Even the regulation considering just one variable speed pump obtains a better result than the current regulation, because it obtains a better efficiency for low discharges. Therefore, it is important obtaining good efficiency for low discharges because are the more frequent and expensive.

Energy analysis results in an energy saving of 14% and economic saving of 16.02% when pumping station is controlled by two variable speed drives working sequentially and not simultaneously. Moradi-Jalal (2003) obtained an energy saving of 32%, but with a pump combination considering several types of pump, which carry lot of maintenance and regulation problems. Pulido *et al.* (2003a) obtained an energy saving of 41% selecting the proper pumps and their regulation.

CONCLUSIONS

This work shows that simple electrical and hydraulic measurements at pumping stations can help to improve their management obtaining, as a result, a high reduction of the energy cost by carrying out a proper regulation.

These measurements permit calculate the discharge distribution through the irrigation season with a higher accuracy than the traditional processes found in the literature, integrating the behavior of the farmers when irrigating their plots. Considering the discharge distribution through out the irrigation season is an essential step to carry out a proper energy study of pumping stations.

In the case study, it can be obtained a cost saving of 16.02% by changing the pumping station regulation from the actual regulation, in which two variable speed pumps work simultaneously, to a regulation considering two variable speed pumps working sequentially.

Acknowledgment

This research work was funded by the Spanish Ministry through the R&D Plan of Science and Technology, and included within the project “Manejo eficiente del agua de riego y la energía en zonas semiaridas (ref AGL2001-1180-C02-01)”.

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