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Experimental investigation of solar powered diaphragm and helical pumps

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Abstract

For several years, many types of solar powered water pumping systems were evaluated, and in this paper, diaphragm and helical solar photovoltaic (PV) powered water pumping systems are discussed. Data were collected on diaphragm and helical pumps which were powered by different solar PV arrays at multiple pumping depths to determine the pumping performance, efficiency, and reliability of the different systems. The highest diaphragm pump hydraulic efficiency measured was ~48%, and the highest helical pump hydraulic efficiency measured was ~60%. The peak total system efficiency (e.g. solar radiation to pumped water) measured for the diaphragm and helical pumps were ~5% and ~7%, respectively (based on PV modules with ~12% efficiency). The daily water volume of the three-chamber high head diaphragm pump performed better than the dual-chamber high head diaphragm pump (~5 to ~100% depending on PV array input power and pumping depth). Use of a controller was shown to improve the quad diaphragm pump performance below a solar irradiance of 600 W/m^2 (20 m head) to 800 W/m^2 (30 m head). While diaphragm pumps made mostly of plastic demonstrated similar to much better pumping performance than diaphragm pumps made with a high proportion of metal, the metal pumps demonstrated a longer service life (>2 years) than the plastic pumps service life (<2 years). Helical pumps analyzed in this paper were capable of deeper pumping depths and usually demonstrated a longer service life than the diaphragm pumps that were analyzed.
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Keywords: Solar water pumping; Pump; Photovoltaics; Efficiency; Diaphragm pump; Helical pump

1. Introduction

For stand-alone (no utility interconnection) solar water pumping systems, there has been a significant amount of research performed. A model was developed for simulating solar-PV water pumping systems (Odeh et al., 2006), and this reference also includes an excellent literature review of past research on solar water pumping systems. The effect on performance of a solar PV fixed array versus one tracking was analyzed for diaphragm pump systems (Clark and Vick, 1997; Vick and Clark, 2002). There have been comparisons of diesel powered to solar-PV powered centrifugal pump systems (Kamel and Dahl, 2005), and wind powered to solar-PV powered helical pump systems (Clark and Vick, 2008). There have also been field testing in different locations in the world of solar powered diaphragm pumps (Clark, 1994; Vick and Clark, 2007), helical pumps (Vick and Clark, 2005; Foster et al., 2006), and centrifugal pumps (Hamidat et al., 2003).

Fig. 1 shows a typical solar-PV water pumping system containing a PV array, disconnect switches, controller, submersible motor with pump, and storage tank. Specifically, this paper will discuss performance, pump efficiency, and reliability of the pumps/controllers of solar powered diaphragm and helical pumping systems. What we refer to as pump efficiency is frequently referred to as hydraulic

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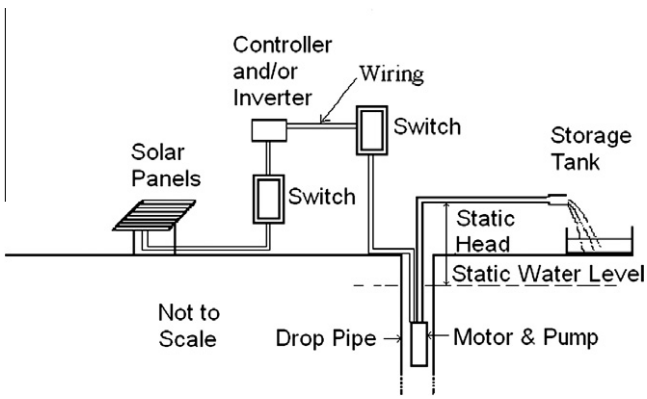


Fig. 1. Schematic of solar-PV water pumping system.

efficiency in the literature. The latitude for the United States Department of Agriculture – Agricultural Research Service Conservation and Production Research Laboratory (CPRL), Bushland, Texas is 35.184° N. From 1996 until the present, the PV arrays during data collection were set to an incidence of 25° during spring/summer and 45° during fall/winter which increases the solar irradiance (W/m^2) and solar insolation (kW h/m^2) compared to a PV array latitude incidence angle of 35° during the year (Vick and Clark, 1996). The average daily water volumes (l/day) and solar insolations (kW h/m^2/day) calculated in this paper for each month were based on irradiance data collected at CPRL over a four year period (1996–1999). The average daily solar insolation measured during this four year period was 6.24 kW h/m^2/day while the solar insolation of a latitude tilt array at this location is 5.78 kW h/m^2/day.

2. Experimental setup and methodology

All of the data depicted in this paper were collected at the CPRL facility which is located 16 km west of Amarillo, Texas and Amarillo is one of the locations in the National Solar Radiation Data Base (Marion and Wilcox, 1994). Measurements collected for the solar water pumping experiments at CPRL were:

1. Solar irradiance (W/m^2) measured at PV array inclination.
2. DC voltage (V) and DC current (A) measured between PV array and pump controller or pump (if no controller).
3. Water pressure (psig) – used for estimating simulated pumping depth and calculation of pump output power.
4. Water volumetric flow rate (l/min).
5. PV module temperature (°C), air temperature (°C) and barometric pressure (mB)

Solar water pumping data were collected in a building containing several underground sumps. The sumps used for solar water pumping testing were 4 m deep with a static water level 1.5 m below ground level and water was recycled in the pumping process. A back pressure valve was used to simulate pumping depths from 20 to 150 m.

The flow meters used in the diaphragm pump experiments had an accuracy of +/−0.1 l/min while those used for helical pump experiments had an accuracy of +/−0.5 l/min. The water flow rate was calibrated before and after each experiment at three or more pumping depths. The pyranometer used for irradiance measurement on each experiment had a typical accuracy of +/−3%, and was calibrated once per year with a more accurate pyranometer (accuracy +/−1%). The DC voltage and current were measured with transducers with an accuracy of +/−0.5 V and +/−0.1 A, respectively. The PV module temperature and air temperature were measured with a T-type thermocouple and a resistance thermometer respectively (accuracy of +/−1 °C). The water pressure was measured with transducers with an accuracy of +/−1 psig (pressure <100 psig) and +/−3 psig (pressure >100 psig). Data averages were recorded every minute on a datalogger, and the data were then downloaded to a computer. The data were processed with a computer program which binned the data at different irradiance levels (e.g. 100, 200,..., 1400 W/m^2). The standard deviation of each measured variable was also calculated for each irradiance bin. Using the amount of time and average flow rate in each irradiance bin, the water volume (WV) pumped for each month could be calculated

$$\mathrm{WV}_i = \Sigma(\Delta t_n * Q_n) \tag{1}$$

where WV_i is the total volume of water for each month i (l), Δt_n is total time for each nth irradiance bin (min), Q_n is average volumetric flow rate for each nth irradiance bin (l/min), and $n = 1$ represents irradiance level of 100 W/m^2, $n = 2$ is 200 W/m^2, etc.

The average DWV for each month was calculated by

$$\mathrm{DWV}_i = \mathrm{WV}_i / D_i \tag{2}$$

where DWV_i is average DWV for each month i (l/day), D_i is number of days for each month i (days).

The solar insolation for each month was calculated by

$$E_i = \sum[\Delta t_n * n * 100 * (1\ \mathrm{h}/60\ \mathrm{min})]/(1000\ \mathrm{W/kW}) \tag{3}$$

where E_i is solar insolation for each month i (kW h/m^2).

The average daily insolation for each month can also be calculated

$$\mathrm{DI}_i = E_i / D_i \tag{4}$$

where DI_i is daily insolation for each month i (kW h/m^2/day).

The power to pump water at a specific head[1] and irradiance is obtained by the following equation

$$\mathrm{Pw}_n = \mathrm{head}_n * Q_n * (\mathrm{min}/60\ \mathrm{s}) * (\mathrm{m}^3/1000\ \mathrm{l}) * g * \rho_{H20} \tag{5}$$

[1] The head loss due to pipe friction was neglected due to low flow rates.

where Pw_n is the power to pump water at a specific head at nth irradiance bin (kg m^2/s^3 = W), head$_n$ is static pumping depth + pressure to overcome back pressure valve[2] at nth irradiance bin (m), g is gravity (9.8 m/s^2), and ρ_{H20} is the density of water (1000 kg/m^3).

If the head is not the desired head at a certain irradiance bin, Q_n is reduced/increased by factor (head actual/head required). The power from the PV array was calculated by

$$Ppv_n = V_n * I_n \tag{6}$$

where Ppv_n is the DC power from PV array for nth irradiance bin (W), V_n is voltage from PV array for nth irradiance bin (V), and I_n is the current from PV array for nth irradiance bin (A).

Pump efficiency for each irradiance bin can now be calculated by

$$PE_n = Pw_n/Ppv_n * 100\% \tag{7}$$

where PE_n is pump efficiency at nth irradiance bin.

System efficiency (e.g. total efficiency) can also be calculated for each irradiance bin by

$$SE_n = Pw_n/(n * 100) * 100\% \tag{8}$$

where SE_n is system efficiency at nth irradiance bin.

3. Solar powered diaphragm pumps

Diaphragm pumps are positive displacement pumps, and have the characteristic of low flow for shallow to moderate heads that require low power (<200 W). Diaphragm pumps currently come in three types – low head/low flow, high head, and high flow. At CPRL we have documented lifetimes over 6 years for low head/low flow diaphragm pumps as long as the 30 m head was not exceeded (Vick and Clark, 2002). One diaphragm pump manufacturer (Sun Pumps[3]) recommends that the pumps be pulled from the well after two years and retrofitted with new parts, and another diaphragm pump manufacturer (SHURflo) recommends the retrofit occur once per year. Solar powered diaphragm pump motors are powered by direct current (DC) electricity at voltages from 12 to 40 V. DC voltages above 50 V can damage these pump motors and pump controllers, so higher voltages should be avoided. Currently high head diaphragm pumps have a maximum pumping depth of 70 m, and the maximum flow rate of the high flow (often referred to as "quad" due to four-chamber piston arrangement) diaphragm pumps is ~16 l/min. For this paper, similar type diaphragm pumps were tested at CPRL side-by-side so the PV arrays were exposed to the same atmospheric conditions (e.g. irradiance, PV module temperature, precipitation, etc.). After the performance testing, the pumps were tested at the maximum rated pumping depth until failure (or the performance decreased substantially) to determine the lifetime of the pumps.

3.1. Performance evaluation of diaphragm pumps

The CPRL diaphragm pump performance testing in this paper occurred over the 2006–2010 period. The high head and high flow diaphragm pumps were powered by either two Solarex 53 W/12 V multi-crystalline PV modules (e.g. ~100 W PV array power rating for each experiment) or with a single BP Solar 160 W/24 V multi-crystalline PV module. Controllers were used in the high head diaphragm pump comparisons, but only one controller was used on one of the high flow diaphragm pump comparisons. The main purposes of the controllers are to adjust the PV array voltage and/or current to improve pumping performance at lower irradiance levels, and to restrict voltage and/or current from PV array to protect the DC pump motor. In the early 1990's some solar powered diaphragm pumps tested at CPRL had short lifetimes due to not having a controller that could restrict the electrical power to the pump motor. The high head diaphragm pumps selected for this study were chosen since they were rated at a much deeper pumping depth (70 m) than had been previously tested at CPRL. A pumping depth of 30 m was a major restriction on the application of earlier diaphragm pumps, so having good performance and reliability at deeper pumping depths would be an important achievement. The high flow (quad) diaphragm pumps were selected since the flow rate was much higher than solar powered diaphragm pumps previously tested at CPRL.

A performance comparison will be shown between two solar powered high head diaphragm pumps manufactured by two different companies: SHURflo Model 9325 (Cypress, California) and Sun Pumps Model SDS-D-228 (Safford, Arizona). The SHURflo pump had a three-chamber piston/diaphragm arrangement while the Sun Pumps had a dual-chamber piston/diaphragm arrangement. Two different PV power arrays were tested (100 and 160 W) on both pumps, but only the performance of the 160 W PV array will be shown. Data were collected at four pumping depths (20, 30, 50, and 70 m) for both pumps, but only the 20 and 70 m data will be shown. The controller used on the SHURflo pump was SHURflo Model 902-100 (LCB-G0). This is similar to controller used on SHURflo Model 9325 diaphragm pump in Protogeropoulos and Pearce, 2000, but it was Model 902-200 (LCB-G), and difference was this controller came in enclosure and had an on/off switch. The controller used on Sun Pumps pump was Sun Pumps Model PCA-30-M1 which came in enclosure and had both on/off switch and a float switch.

Referring to Fig. 2, the DC power is approximately the same for both high head diaphragm pumps until certain PV array power levels are attained, and at that point the controllers restrict the power going to the pumps. At the same

[2] Convert pressure to head in meters with following ratios, .1022 m/kP or 0.704 m/psi.

[3] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture. The authors do not have any vested interest in any company with trade names cited in this paper.

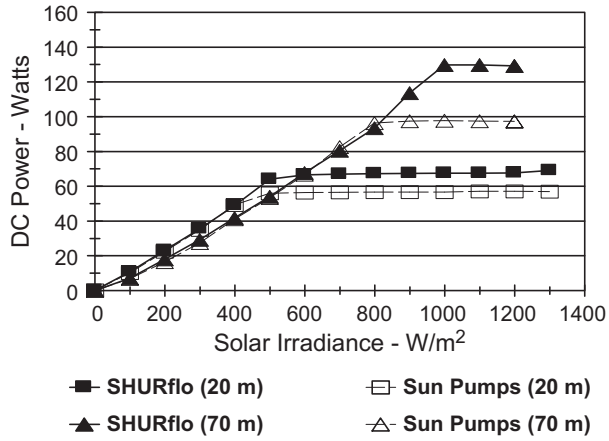


Fig. 2. DC power of high head diaphragm pumps at 20 and 70 m heads for a 160 W PV array.

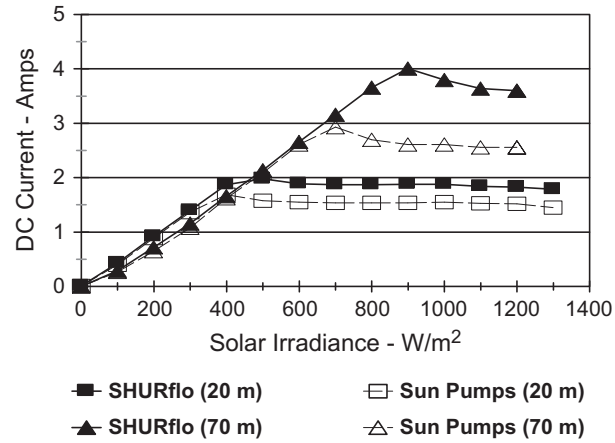


Fig. 4. DC current of high head diaphragm pumps at 20 and 70 m heads for a 160 W PV array.

pumping depth, the controller used with the SHURflo diaphragm pump allowed a higher DC power level than the Sun Pumps controller. The voltage and current measured for both diaphragm pumps at the two different loads or heads are shown in Figs. 3 and 4 respectively. The same voltage (~25 V) is maintained by both controllers until a specific DC power is reached, and the voltage is allowed to increase to about 36 V. When that higher voltage is reached, the current is restricted on both controllers which results in a constant DC power for higher solar irradiance levels. In Fig. 5 the flow rates are seen to maximize at the same irradiance that the voltage and current reached their maximum in Figs. 3 and 4. At a 20 m head, the flow rate of the SHURflo diaphragm pump was higher than that of the Sun Pumps diaphragm pump at solar irradiances >100 W/m^2 which indicated an advantage of the three over the dual-chamber arrangement. However, at a 70 m head the improvement was not observed until a higher irradiance (600 W/m^2) was attained. In Fig. 6 the maximum pump efficiency of the SHURflo diaphragm pump was ~50% higher than the Sun Pumps diaphragm pump for a 20 m

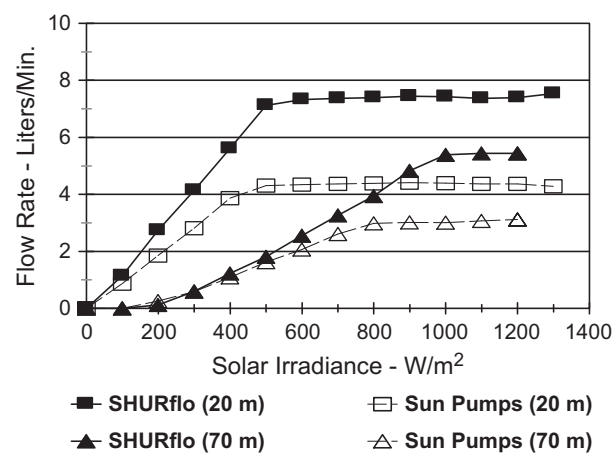


Fig. 5. Flow rate of high head diaphragm pumps at 20 and 70 m heads for a 160 W PV array.

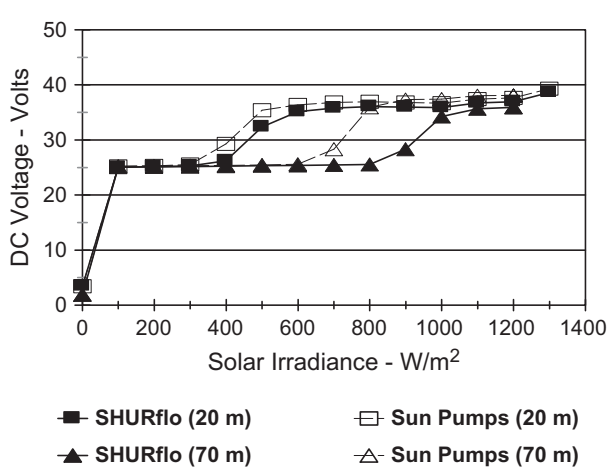


Fig. 3. DC voltage of high head diaphragm pumps at 20 and 70 m heads for a 160 W PV array.

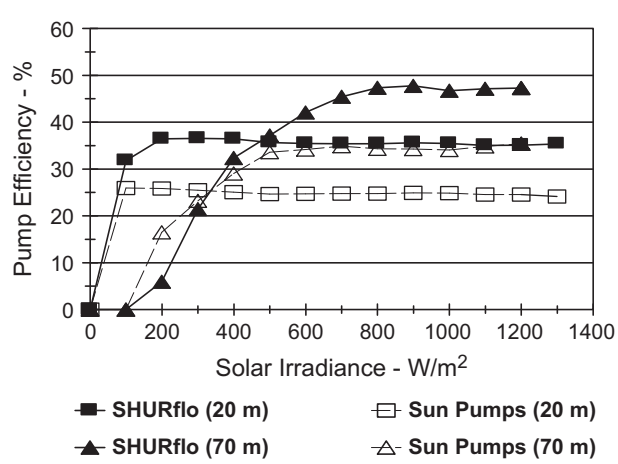


Fig. 6. Pump efficiency of high head diaphragm pumps at 20 and 70 m heads for 160 W PV array.

head, but ~30% for a 70 m head. Although not shown, the 50 m pumping depth achieved the highest maximum pump efficiency of 48% for SHURflo diaphragm pump (very close to efficiency shown in Protogeropoulos and Pearce, 2000).

Two quad (high flow/low head) diaphragm pumps were also tested at two PV array power settings (100 and 160 W), but again only the 160 W data are shown. The manufacturer of one of the quad pumps (Robison Model BL40Q, Weatherford, Oklahoma) asked CPRL to test their diaphragm pump without a controller (although this manufacturer has own controller) while the other quad pump (Sun Pumps Model SDS-Q-128) was tested with the same controller that was used in the high head Sun Pumps Model SDS-D-228 diaphragm pump testing. Both quad pumps had a maximum design pumping head of 30 m, so the pumps were evaluated at 20 and 30 m heads. The DC power measurements for both pumps and pumping depths are shown in Fig. 7. The DC Power of the Robison quad pump is always less than that of the Sun Pumps quad pump below an irradiance level of 600 W/m^2 at a 20 m head and below an irradiance level of 800 W/m^2 at a 30 m head. In Figs. 8 and 9 the voltage and current measured on both diaphragm pumps at the two pumping depths are shown. At a 20 m head, the measured voltage of the Robison quad pump (with no controller) is approximately half that of the Sun Pumps quad (with a controller) for solar irradiance below 400 W/m^2, and the Robison quad pump voltage begins to increase at this solar irradiance until 600 W/m^2 is attained and for higher solar irradiances the voltages are approximately the same. At a 30 m head, the Robison quad pump voltage is half that of the Sun Pumps quad pump below solar irradiance of 600 W/m^2 and the Robison quad pump voltage is a few volts higher than that of Sun Pumps quad pump above a solar irradiance of 800 W/m^2. The current is constant for both quad pumps at both pumping depths up to an irradiance level of 700 W/m^2. At a 20 m head, for irradiance levels above 700 W/m^2,the current of the Robison quad pump increases to 3.5 A while

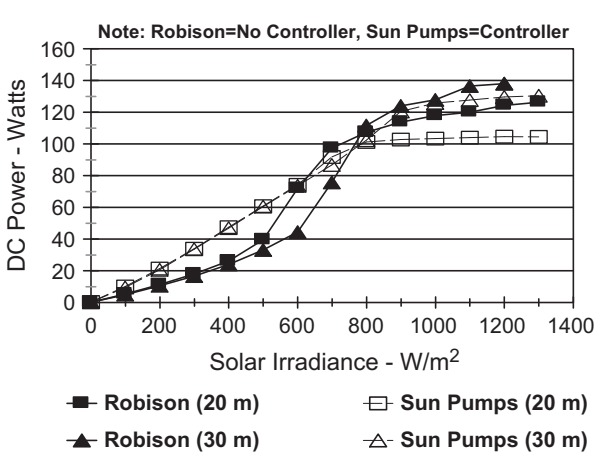


Fig. 7. DC power of high flow diaphragm pumps at 20 and 30 m heads for a 160 W PV array.

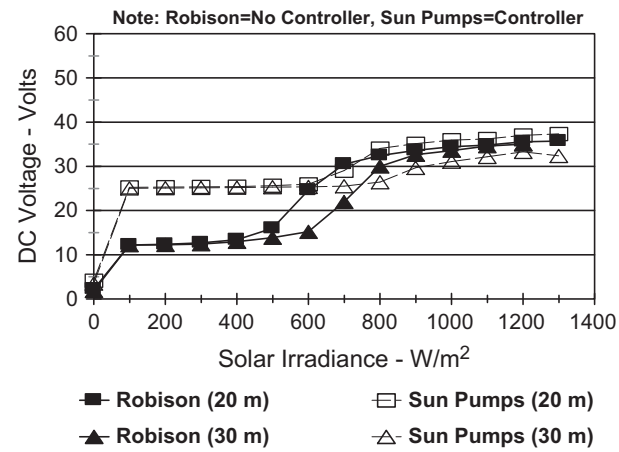


Fig. 8. DC voltage of high flow diaphragm pumps at 20 and 30 m heads for a 160 W PV array.

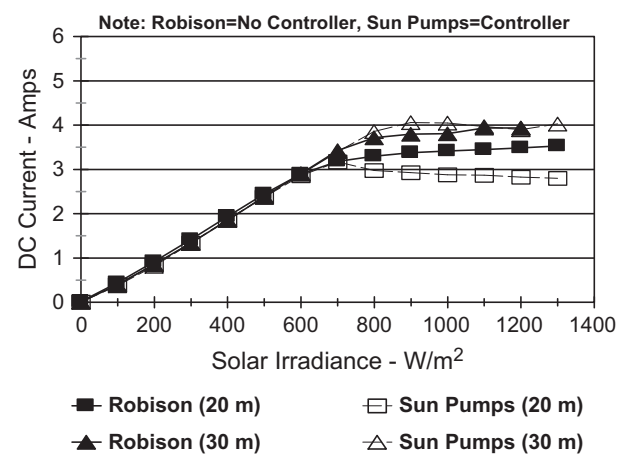


Fig. 9. DC current of high flow diaphragm pumps at 20 and 30 m heads for a 160 W PV array.

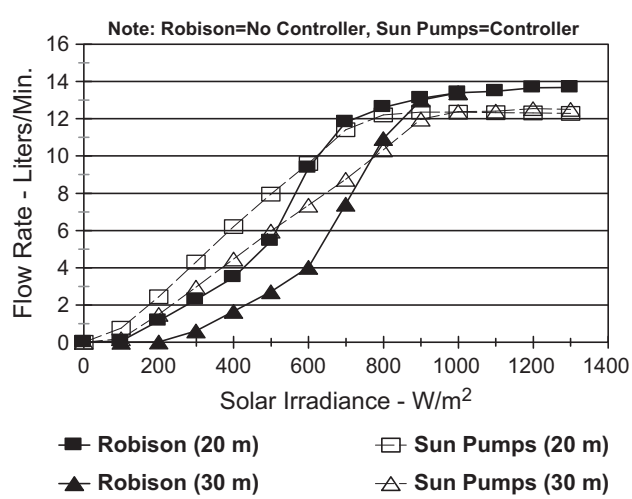


Fig. 10. Flow rate of high flow diaphragm pumps at 20 and 30 m heads for a 160 W PV array.

that of the Sun Pumps quad pump is restricted below 3.1 A. At a 30 m head and for irradiance levels above 700 W/m^2, the current of both quad pumps are within +/−0.1 A of each other and the maximum current is ~4 A. In Figs. 10 and 11 the flow rate and pumping efficiency for the two quad pumps at the two pumping depths are shown. Not surprisingly, based on measured power of the two quad pumps in Fig. 7, the flow rate is higher for the Sun Pumps quad pump for irradiance levels less than 600 and 800 W/m^2 (20 and 30 m heads, respectively), but the Robison quad pump had a higher flow rate for irradiance levels above 900 W/m^2. At a 20 m head, the pumping efficiency of the Sun Pumps quad pump is better at only the very lowest irradiance levels (100 and 200 W/m^2), and the pumping efficiencies are identical for both quad pumps at all other irradiance levels. At a 30 m head, the pumping efficiency of the Sun Pumps quad pump is higher below an irradiance level at 700 W/m^2, and the pumping efficiencies of both quad pumps are approximately the same above this irradiance level. If the Robison pump had been tested with a controller, the flow rate and pumping efficiency would likely have been the same or possibly better than that of the Sun Pumps quad pump.

3.2. Reliability evaluation of diaphragm pumps

The SHURflo Model 9325 high head pump's failure occurred after 1.33 years of testing, and the Robison Model BL40Q quad pump's failure occurred at 0.75 years. The SHURflo high head pump very probably would have had a longer lifetime if it had been operated at a lower head (e.g. after performance testing the pumps were tested at the maximum design head until failure). The high head Sun Pumps Model SDS-D-228 pump failure occurred after 2.4 years (over half of that time the pumping lift was set at a 70 m head). All three of these diaphragm pumps failed due to worn diaphragm seals. The Sun Pumps Model SDS-Q-128 quad pump never failed after 1.95 years of testing, but testing was concluded in July, 2010 when two 160 W/24 V PV modules were mistakenly connected in series (e.g. ~70 V and 320 W) to the controller and resulted in controller failure. Prior testing of this diaphragm pump was at PV power settings of 100 and 160 W with a voltage range of 25–40 V. The Sun Pumps diaphragm pumps have demonstrated better reliability/lifetime than the SHURflo and Robison diaphragm pumps, and the main obvious difference was that the Sun Pumps diaphragm pumps were manufactured with a significant amount of metal while the SHURflo and Robison diaphragm pumps were manufactured mainly of plastic. The weight of the Sun Pumps diaphragm pumps were two to three times that of the SHURflo and Robison pumps (i.e. for comparable types), so it is possible that the higher weight contributed to longer reliability/lifetime by reducing movement of pump during pumping action. However, the exact reason for difference in lifetime between the two types of pumps is not known. We believe future design efforts of high head and high flow diaphragm pumps should concentrate on improving diaphragm seals, or modifying piston action to increase lifetime of pumps. Also, for the SHURflo high head pump, a redesign of the electrical cable plug would be an improvement (two of electrical cable plugs had to be replaced during the testing).

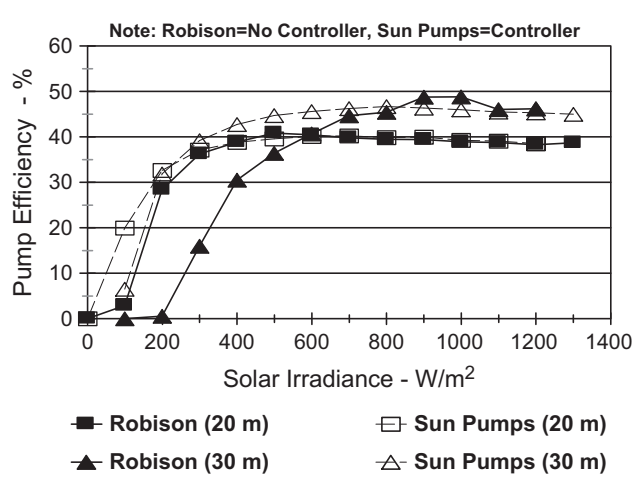


Fig. 11. Pump efficiency of high flow diaphragm pumps at 20 and 30 m heads for a 160 W PV array.

4. Solar powered helical pumps

Solar powered helical pumps are positive displacement pumps, similar to the diaphragm pumps discussed in previous section, but instead of pumping water with pulsing diaphragm, a helical shaped metal rod rotates in a thick rubber tube and the progressive cavity created results in water being pumped. Helical pumps typically are used for deeper pumping depths or for higher DWV requirements than those used on diaphragm pumps, and therefore usually require a higher PV array power rating. The helical pump which was analyzed in this report used BP Solar 160 W/24 V modules (e.g. same type modules used by diaphragm pumps in Figs. 2–6). The PV array power ratings ranged from 320 to 640 W, and the heads varied from 50 to 150 m. Most of the solar powered testing at CPRL was with Grundfos (Bjerringbro, Denmark) helical pumps, but we also have performed some testing of Lorentz (Ulzburg, Germany) HR07-2 helical pump (Vick and Clark, 2009). Grundfos currently makes three different types of helical pumps: 3SQF (high head/lowest flow), 6SQF (medium to high head/medium flow), and 11SQF (lowest head/highest flow). Grundfos helical pump motors (<1.5 kW) can be powered with DC or single phase alternating current (AC), and the voltage can vary from 35 to 300 V. The Grundfos helical pumps use a controller imbedded in the pump/motor casing. In 2006 an updated controller was installed on all Grundfos pumps which improved pumping performance significantly, and all data shown in this paper was with this updated controller. Some of the functions in

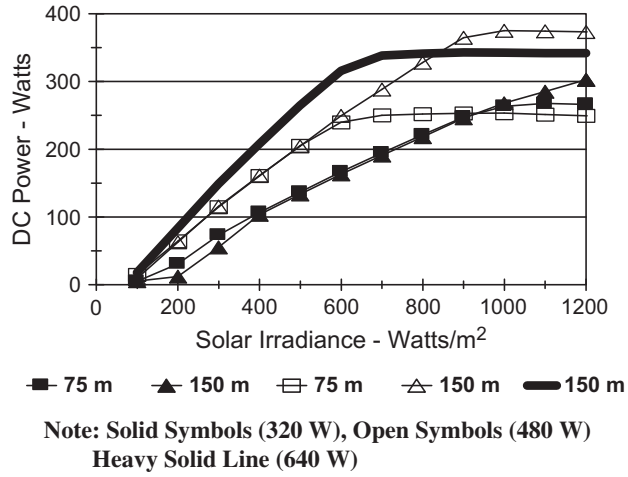


Fig. 12. DC Power of 3SQF-3 helical pump at 75 and 150 m heads for three PV arrays (320, 480, and 640 W).

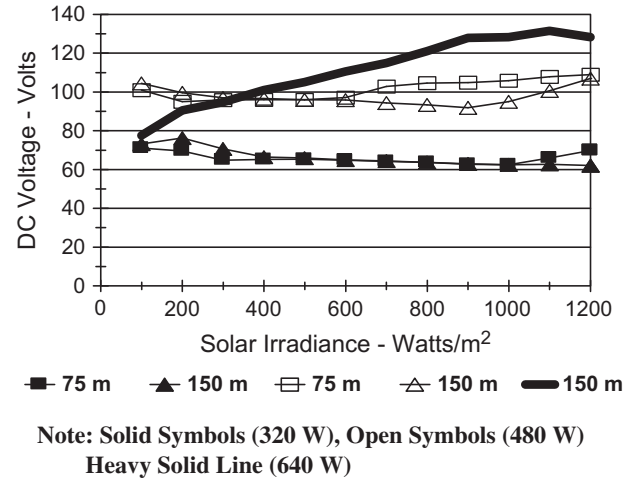


Fig. 13. DC voltage of 3SQF-3 helical pump at 75 and 150 m heads for three PV arrays (320, 480, and 640 W).

this controller are: check the input power to determine if it is AC or DC (if AC the power is rectified to DC for the DC helical pump motor[4]), adjusts voltage and current so optimum power output (e.g. maximum power point tracker), disconnects power supply if voltage too high, and determines if water level in well is below pump intake and if so disconnects power supply to keep pump from being damaged. An above ground controller can also be used to display errors for diagnosing why the helical pump is not operating correctly. In late 2009 another improvement was made to the Grundfos helical pump motor by increasing the pump rotor speed from 3000 to 3600 rpm (estimated by Grundfos to increase flow rate by 20% at same pumping head), but the data shown in this report were collected prior to this modification.

4.1. Performance evaluation of helical pumps

Although we have tested all three types of helical pumps manufactured by Grundfos (3SQF, 6SQF, and 11SQF), we selected the Model 3SQF-3 helical pump for analysis since the flow rate and daily water volumes are similar to that of diaphragm pumps (albeit at higher heads). The DC Power for two heads (75 and 150 m) and three different PV array power ratings (320, 480, and 640 W) are shown in Fig. 12. The helical pump controller restricts the power to ~250 W at a 75 m head, and ~350 W at a 150 m head. The DC voltages and currents of the 3SQF-3 helical pump for the different heads and power ratings are shown in Figs. 13 and 14. The voltage is fairly constant for the 320 W (~65 V) and 480 W (~100 V) PV arrays which is logical since they represent two and three 24 V rated modules in series respectively (optimum voltage output for these modules is ~35 V). The voltage of the 640 W PV array increases linearly from 90 to 130 V. The change in current with respect

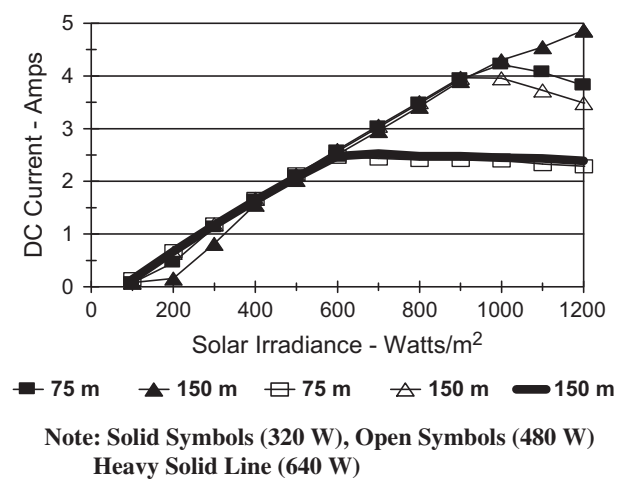


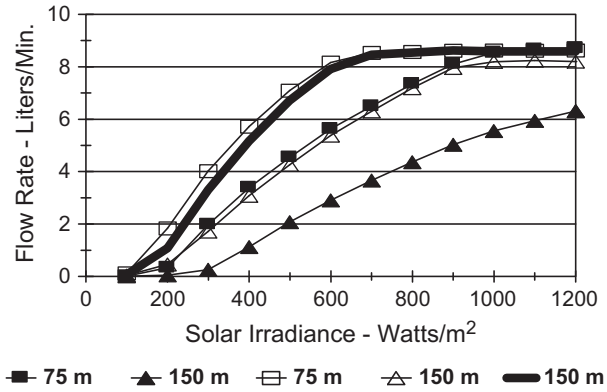
Fig. 14. DC current of 3SQF-3 helical pump at 75 and 150 m heads for three PV arrays (320, 480, and 640 W).

to irradiance is similar to that for the diaphragm pumps. The controller restricts the current at 2.5 A for the 75 m/480 W and 150 m/640 W cases, and the current is restricted at 4 A for the 75 m/320 W and 150 m/480 W cases, but the lower voltage 320 W/150 m case is allowed to increase to 5 A. The flow rate and pump efficiency for the 3SQF-3 helical pump are shown in Figs. 15 and 16. The cut-in irradiance varies from 100 to 300 W/m^2 for both heads and all three PV arrays which is very good for such low power requirements and deep pumping depths. The flow rate is restricted at 8.5 l/min which coincides with DC power and current restrictions in Figs. 12 and 13 respectively. The peak pump efficiency ranged from 40 to 60% with progressively increasing heads and PV power ratings.

4.2. Reliability evaluation of helical pumps

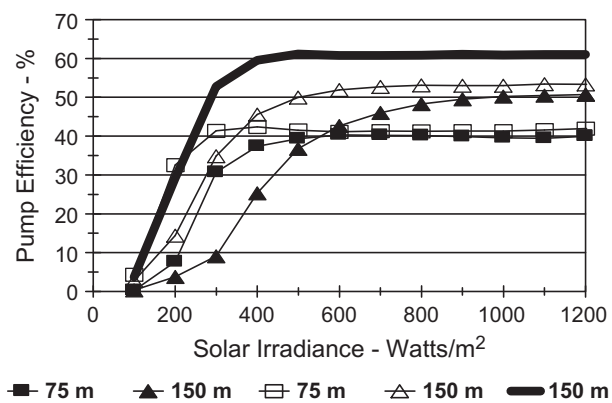
CPRL began continuously testing a Grundfos Model 6SQF-2 (3000 rpm maximum pump motor speed) helical

[4] This feature allows for PV array DC, utility single phase AC, or gas generator single phase AC to power pump motor.



Note: Solid Symbols (320 W), Open Symbols (480 W) Heavy Solid Line (640 W)

Fig. 15. Flow rate of 3SQF-3 helical pump at 75 and 150 m heads for three PV arrays (320, 480, and 640 W).



Note: Solid Symbols (320 W), Open Symbols (480 W) Heavy Solid Line (640 W)

Fig. 16. Pump eff. of 3SQF-3 helical pump at 75 and 150 m heads for three PV arrays (320, 480, and 640 W).

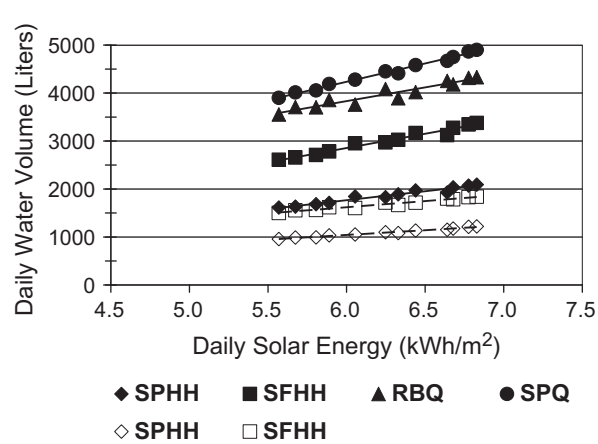
pump in Feb. '04 using three PV array powers (320, 480, and 640 W) at three different heads (50, 75, and 100 m) and concluded that testing in Feb. '07 after 3 years. Very little degradation in the pump occurred over the 3 year period. The Grundfos Model 3SQF-3 (3000 rpm maximum pump motor speed) helical pump was tested for over one year at the maximum design pumping depth of 150 m, and when pump curves were compared at the end of the testing no measurable degradation had occurred. However, the pumps in the CPRL testing were installed in underground sumps, and the same water is pumped continuously, so our experimental setup does not simulate the sediment and other chemicals inside actual wells that can damage pumps. The Grundfos Model 11SQF-2 (3000 rpm maximum pump motor speed) was only tested for 0.2 years although another experiment with the 11SQF-2 (3600 rpm version) began in Sep. '10. All Grundfos helical pumps as of Dec. '09 are being manufactured with a 3600 rpm maximum pump motor speed, so this change may reduce lifetime of these pumps. We did experience reliability problems with a solar powered Lorentz Model HR07-2 helical pump (lifetime of pump 1.25 years), but a Lorentz dealer in our area (American West Windmill & Solar Company, Abernathy, Texas) assured us the lower lifetime was due to quality control problems in manufacturing the pump during that period and not due to problems with pump and controller designs.

5. Daily water volume performance of diaphragm and helical pumps

There are two types of pumps powered by solar energy which have been extensively tested and analyzed at CPRL and they are diaphragm (1992–2010) and helical (2004–2011) pump types. CPRL has tested and analyzed the centrifugal pump with different solar PV arrays, but the solar PV modules and controllers used have been discontinued or are not predominantly used any more (Clark et al., 1998; Vick et al., 2003). In this section the DWV is estimated for both diaphragm and helical pumps at different pumping depths (30 and 70 m for diaphragm and 75 and 150 m for helical) with insolation as the independent variable, and the best performing pump is identified. Having insolation as the independent variable may allow the DWV for various solar powered pumps to be accurately estimated at any location in the world, and we are currently investigating this hypothesis.

The DWV of diaphragm pumps for heads of 30 and 70 m are shown in Fig. 17. The nomenclatures for the diaphragm pumps in Fig. 17 are:

- SPHH – Sun Pumps Model SDS-D-228 high head diaphragm pump.
- SFHH – SHURflo Model 9325 high head diaphragm pump.
- RBQ – Robison Model BL40Q high flow (quad) diaphragm pump.
- SPQ – Sun Pumps Model SDS-Q-128 high flow (quad) diaphragm pump.



Note: Solid Symbols (30 m head), Open Symbols (70 m head)

Fig. 17. Daily water volume of diaphragm pumps at 30 and 70 m heads for a 160 W PV array.

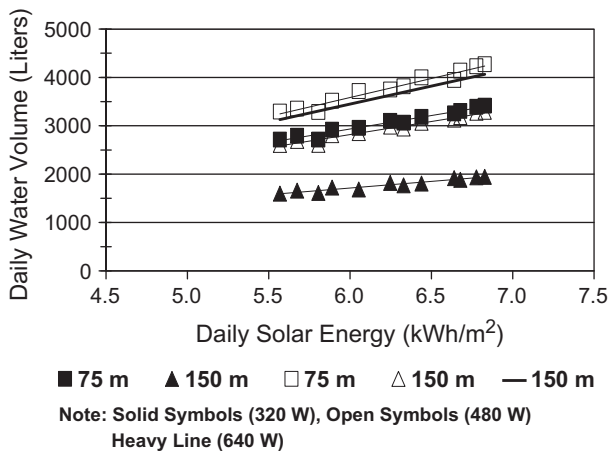


Fig. 18. Daily water volume of 3SQF-3 helical pump at 75 and 150 m heads for PV arrays 320, 480, and 640 W.

The DWV of the diaphragm pumps at a 30 m head varied from 1600 to 4900 l/day. At a 30 m head, the SPQ diaphragm pump had the highest average DWV of the diaphragm pumps, but was only 300 l/day more (10% more) than the RBQ diaphragm pump which was tested without a controller. Also at a 30 m head, the DWV of the SFHH diaphragm pump was approximately twice that of the SPHH diaphragm pump. At a 70 m head the DWV of the diaphragm pumps varied from 1000 to 1800 l/day, and the SFHH diaphragm pump was ~50% higher than the SPHH diaphragm pump. Although not shown, the difference in average DWV was ~5% for these two high head diaphragm pumps with a 100 W PV array for a 70 m head (e.g. 753 l/day for SPHH and 796 l/day for SFHH).

The DWV of the Grundfos Model 3SQF-3 helical pump for the same cases analyzed in Figs. 12–16 are shown in Fig. 18. The DWV for the helical pumps shown varied from approximately 1500–4000 l/day. At a 150 m head, there was a 1173 l/day increase in the average DWV from the 320 W PV array to the 480 W PV array while only a 678 l/day increase in the DWV occurred from the 480 W PV array to the 640 W PV array. This lower improvement in DWV for the same power increase is likely due to the 320 W PV array operating at ~65 V compared to the voltages of ~100 V and ~125 V for the 480 and 640 W PV arrays respectively. According to Grundfos, while their helical pumps can operate in a DC voltage range of 30 to 300 V, they perform better for DC voltages approximately at or above 120 V.

6. Conclusions

In terms of performance, the SHURflo Model 9325 high head diaphragm pump performed better than the Sun Pumps Model SDS-D-228 high head diaphragm pump for two solar PV arrays (100 and 160 W) and four pumping depths (20, 30, 50, and 70 m) with the largest percentage difference occurring at the lower pumping depths and the higher PV power array. Part of this improvement was due to the controller of the Sun Pumps having a lower DC power restriction than that of the SHURflo controller, but the other part of improvement likely due to SHURflo having three pistons/chambers while the Sun Pumps had two. The Sun Pumps high head pump lasted longer (2.4 years) than the SHURflo high head pump (1.33 years), but both pumps had much shorter lifetimes than previous testing with low head/low flow diaphragm pumps (>6 years). The Sun Pumps Model SDS-Q-128 high flow (Quad) pump performed better than the Robison Model BL40Q high flow (Quad) pump, but if the Robison pump had been tested with a controller, the daily water volume would have likely been similar. The Robison high flow pump failed at 0.75 years while the lifetime of the Sun Pumps quad was >1.95 years (e.g. lifetime not determined). Only one manufacturer's helical pumps (Grundfos) were shown in this paper, and the highest head/lowest flow pump (3SQF-3) was analyzed in detail. The peak pump efficiency measured on the helical pump was higher than that measured on the diaphragm pumps (~60% compared to 48%). The Grundfos Model 6SQF-2 helical pump was tested at CPRL over a 3 year period at three different PV array power ratings (320, 480, and 640 W) and three different pumping depths (50, 75, and 100 m), and no decrease in performance was measured. Improving the endurance of diaphragm pumps without requiring 1–2 year servicing (e.g. increase lifetime to level of helical and centrifugal pumps) should significantly improve their usage.

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