RESEARCH ARTICLE OPEN ACCESS

Experimental Investigation Of Solar Powered Sonic Pump

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ABSTRACT
This paper deals with the experimental analysis of a solar powered sonic (resonance) pump for boreholes in Botswana. A model solar powered sonic pump is tested at average resonance frequency of 5.42 Hz when furnished with spring-loaded poppet valves, mainly 1.5″, 2.0″ and 3.0″ valves. The flow rate is measured against the power input and the results indicated that the flow rate correlates to the size of valves and their parameters such as valve spring constant, valve spring preload and valve stroke. Also it is found that the accuracy of the experiments can be improved by setting the pump in resonance through measuring the maximum acceleration.
Keywords – solar power, sonic pump, spring-loaded poppet valves, resonance oscillations.

I. INTRODUCTION

Water is a scars commodity in Botswana and in many African countries and is as an important source for life survival on the planet. Although the sonic pumps were primarily invented and used for many decades in the oil industry of US [1], UK and Russia [2] they could be used for pumping ground water from deep wells. Some researchers achieved 100 m depth of pumping, [2] and employed these pumps for Agricultural applications, [3]. For many years the author is investigating the opportunities of employing sonic pumps for pumping ground water from shallow to deep boreholes in Botswana. Several models and prototypes of sonic pumps were developed and studied to establish the principle of operation [4]. Later the prototype pumps were tested on shallow to medium depth boreholes [5] and found them useful for desert and rural applications since they tolerate up to 40% sand mixed with water [2], which is the case of Botswana's boreholes. Since today electricity is not available in the desert and most of the rural areas of Botswana the author decided to explore the available solar energy in the country. There are many research and industrial developments using solar energy [7], [8], [9] for pumping ground water but none of them has been applied to sonic pumps. Instead these investigations applied to centrifugal submersible pumps directly driven by the PV power through a special control unit. Unfortunately today sonic pumps are not known by the pump specialist and even not listed in the specialized literature for pumping systems. In fact these pumps are very efficient since they operate in resonance and the deeper they pump from the more efficient they become [2]. Therefore the objectives of this study are to redesign the previously designed and constructed sonic pump to be powered by a PV solar energy with relevant electronic equipment through a pack of batteries; conduct experiments and establish the flow rate of the pump versus input power.

II. MATERIALS AND METHODS

A modified model sonic pump established in 2006 by [5] powered by a dual shaft mechanical shaker consisting of two 60-Watt AC motors was used in this study. Four modifications were done to the design of the existing pump which include: Increasing the offset masses of shaker to boost the shaker unbalance to a value of 0.0408 [kg.m]; designing and manufacturing new offset masses and installing them symmetrically with respect to the motor's plane of rotation; selecting and installing a new set of springs for the pump suspension system providing large resonance amplitudes of the oscillating system; making the total oscillating mass of the pump for all valve's installations similar in order to attain comparable resonance frequencies. The modifications also covered the attachments of the three valve sizes mainly 1.5″, 2.0″ and 3.0″ spring-loaded poppet valves being investigated. These are achieved by adding additional masses to the oscillating system to obtain almost the same resonance frequencies. In fact each size of valves consisted of three individual spring-loaded poppet valves having to some extent different mechanical parameters, such as the valve spring stiffness, valve spring preload and the valve stroke. The mechanical parameters of the individual valves are established in the research work [6] and the results are listed in Table1 in an increasing order of the valve's strokes. The reason for this arrangement is that the valve stroke appears to be one of the most important mechanical parameters of the spring-loaded poppet valves, since it affects the valve head losses and therefore influences directly the valve discharge (the pump flow rate). It was found in the study [6] that the higher the valve strokes the lower the valve head losses, due to the increased interior cross section (the valve stroke limiting area) allowing the water flow to pass through with minimum resistance.

Table 1 Summary of the mechanical parameters of spring-loaded poppet valve, [6].

Bossini valves	1.5″			2.0″			3.0″		
	No.1	No.2	No.3	No. 1	No. 2	No. 3	No. 1	No. 2	No. 3
Inlet port diameter, [mm]	43	43	43	55	55	55	80	80	80
Valve body mass, [kg]	0.58	0.59	0.59	1.41	1.12	1.11	2.01	2.01	2.01
Valve mass, [gram]	20	20	20	30	31	30	113	113	114
Valve stroke, [mm]	6.6	7.2	7.7	13	13.7	14.4	17.8	18.2	19.2
Valve spring constant, [N/m]	128	123	123	164.3	146.3	134.6	383.6	328.5	401.9
Valve spring preload, [N]	1.45	1.57	1.34	1.29	1.39	1.48	4.17	3.56	4.20

Figure 1 shows the front view of the model sonic pump employed in this study along with the solar power supply unit.

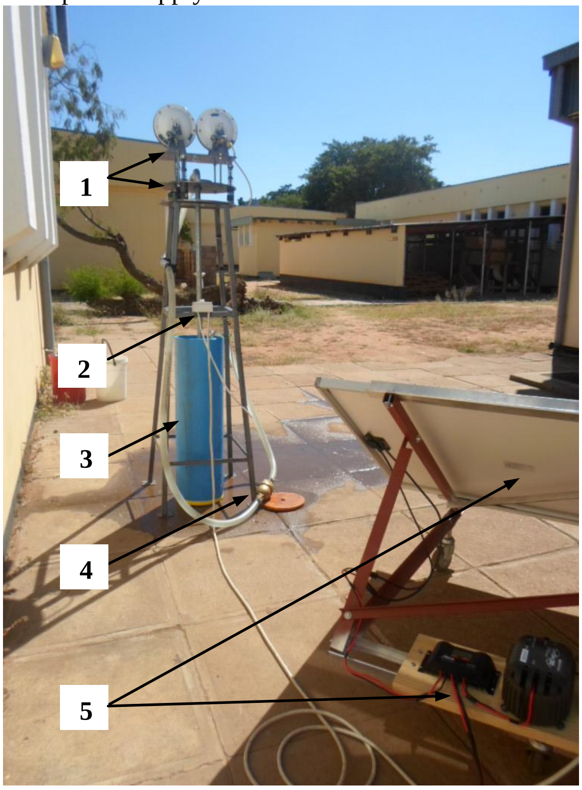

Fig. 1 Shows the experimental setup of the Sonic Pump as front viewed, where: 1 is the shaker with the spring suspension system, 2 motor speed controller, 3 the well, 4 water meter, 5 solar power supply unit.

The most important part of the pump is the mechanical shaker along with the spring suspension system to which the pipe-valve system is attached. A close view of the shaker, the spring suspension system and the oscillating system of the sonic pump are shown in Fig. 2. The shaker with the offset masses and the additional mass attached to the oscillating plate are designated for easy understanding of the design. The shaker consists of two 60-Watt AC motors having rotating stators to which unbalanced offset masses are symmetrically attached on each side of the motors. The motors have non-rotating rotors fixed to the supporting base of the shaker to which the power supply cables, reversing switches and capacitors are attached.

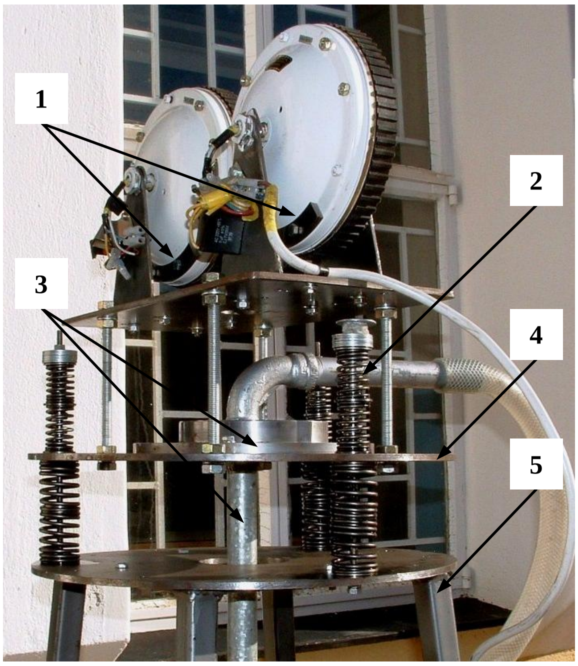

Fig.2. Sonic pump assembly: 1-offset unbalanced masses of the shaker attached to the AC motors, 2-spring suspension system, 3-oscillating pipes with the additional mass connected to the oscillating plate 4, 5-support stand of the pump fixed to a solid foundation.

The stators rotate in opposite directions thanks to the inverted synchronous belts used as spur gears. The unbalanced offset masses are attached in such a way so as the shaker is fully balanced in the horizontal direction, but generates unidirectional inertial forces acting in the direction of the pipe-valve oscillating system. The total oscillating mass of the pump consists of the masses of shaker, oscillating plate, the pipes and valves attached to the pipe system. In this design only one valve is used since the depth of pumping is small. When the oscillating system is set in resonance then the total oscillating mass attains maximum displacements, velocities and accelerations. According to [4] pumping is achieved whenever the oscillating system is subjected to acceleration greater than the gravitational one (g=9.81 m/s^2). The larger the maximum acceleration the greater the flow rate and the pressure developed by the pump. But extremely high accelerations can be destructive to the pipe system since the inertial forces acting at the point of attachment to the oscillating plate become enormous. This requires stronger pipe material and the use of flanged connections in the pipe system, which makes the design expensive. The recommended submersion depth of the foot valves under the water level in the well is about 3-4 m [2]. For depth of pumping up to 30 m one foot valve is required. To maximize the flow rate when pumping from deep wells and at high operating frequencies (20-50 Hz) the number of valves is increased in order to reduce the load on individual valves [2], [4]. The shaker of the model pump tested in this study generates maximum acceleration of $\boldsymbol{a}_{max} \approx 3\times g$ m/s^2, where g=9.81 m/s^2 is the gravitational acceleration.

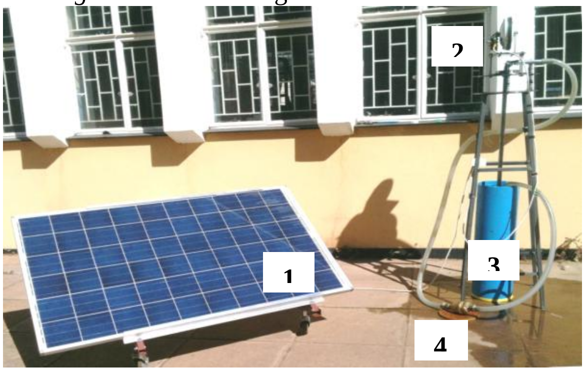

Fig. 3 Side view of the solar powered sonic pump where: 1- solar panel 230W-80V, 2 – shaker and the spring system, 3- the well, 4 – the water meter type C-PHB 3122 of 2.5 m^3/h metering capacity.

The maximum acceleration affects significantly the pressure developed and the flow rate of the pump and if measured or calculated it may be used to predict the flow rate and the pressure of the pump [4]. Fig. 3 show the side view of the model pump along with the solar panel arrangement. As seen from the figure the water from the well is elevated to a height of 1.75 m and then passing through the water meter is returning back to the well. This allows reusing the same water and avoiding the unnecessary spillage around the pump during experiments.

The valves used in this study are shown in Fig. 4; where two out of three 1.5″ valves are shown since the third one is already installed in the pump. The rest of the two groups of 2.0″ and 3.0″ spring-loaded poppet valves are shown in increased order.

Fig. 4 shows the spring-loaded poppet valves and the corresponding extension pipes used to set the same depth of pumping of 1.75m by all the valves.

To eliminate the effect of resonance frequency of the oscillating system upon the valve performance, additional masses are added to the oscillating pipe-valve assemblies. The masses for the three groups of valves and the corresponding resonance frequencies are listed in the table 2 below.

Table 2 Summary of masses added to the oscillating system to achieve comparable resonance frequencies.

Valve size [inch]	Valve mass with pipes [kg]	Mass added to pipes [kg]	Total mass of valve assembly [kg]	Total Oscill-ating mass [kg]	Reso-nance Frequ-ency [Hz]
1.5″	3.219	3.455	6.674	25.214	5.42
2.0″	4.295	2.428	6.723	25.263	5.41
3.0″	5.916	0.691	6.607	25.147	5.43

As shown in Fig. 2 a special spring assembly is designed to achieve large amplitudes for the same resonance frequency regardless of the masses of the valve and pipe arrangements. The total stiffness of the spring suspension system is set to be K=29227 N/m to obtain an average shaker speed of n≈325 rev/min corresponding to a resonance frequency f=5.42 Hz, assumed to be the same for all valves. The photovoltaic power supply unit consisted of a polycrystalline solar panel, 230W 80V 8.3A; charge controller, DC-AC inverter and a Power and Energy Monitor 2000 MU of 3750VA and 15A AC power and current capacity respectively. The above equipment is mounted on the support frame of the solar panel for mobility and easy tracking the sun during experiments. In addition to this equipment two silver-calcium batteries connected in parallel are employed to maintain a stable power supply.

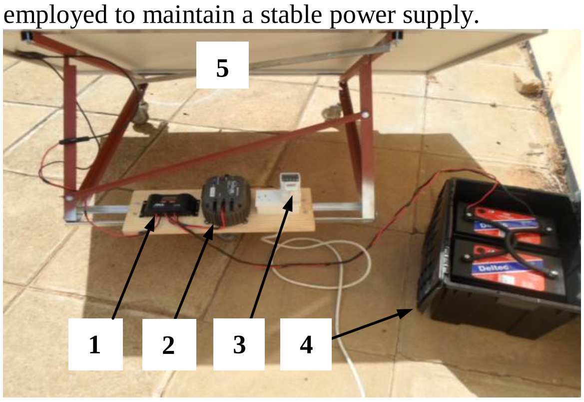

Fig. 5 Solar power supply equipment: **1 -** charge controller PR3030; **2** - DC-AC inverter 12V-240V, 300W, 50Hz; **3 -** power & energy monitor, **4 -** battery pack 2×12V, 185Ah each, **5-** is the back side of solar panel as installed on a support frame & caster wheels.

Fig. 5 shows a close view of the power supply equipment viewed from the back side of the solar panel mounted on caster wheels and the battery pack consisting of two batteries connected in parallel.

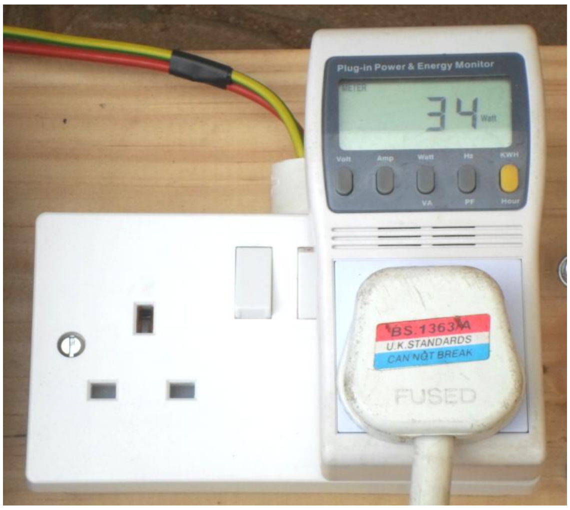

Fig. 6 Power and energy monitor 2000MU of 3.75kW AC power and 15A electric current capacity.

Fig. 6 shows a close view of the power & energy monitor used in the experiments. It measures voltage, amps, watts, volt-amps, hertz and the power factor in the AC grid. In our study we measure predominantly the power consumption of the pump at different power settings when assessing the flow rate of the pump. In addition to that we also measure the voltage and the frequency of the AC power supply to be sure that they comply with the parameters of the motors when operated from the industrial grid. These assure that motors operate under a correct voltage and frequency (50Hz).

I. EXPERIMENTAL RESULTS

There are 216 runs carried out during experiments at six levels of power setups for nine valves repeated four times per valve before the average flow rate of a particular size of valve is identified. The flow rate of each run was measured for 5min and after that average flow rate is calculated per minute. The trials and average results for the 38W power setup of the three sizes of valves are shown in Table 3. It should be mention that the results listed in this table stand for one point only of each size of valve graphs. After that graphs are plotted for the flow rates of each valve from a particular size versus the input power varying from 22W to 38W.

Table 3 Valve's discharge at power input of 38W.

Valve size	Valve No.	Run 1	Run 2	Run 3	Run 4	Avg. runs	Avg. runs
		l / 5 min				*l* / 5 min	*l* / min
1.5″	1	43.7	43.4	43.7	43.8	43.7	8.73
	2	37.7	38.3	37.2	35.8	37.3	7.45
	3	47.6	47.0	46.8	46.1	46.9	**9.38**
2.0″	1	45.4	46.0	46.9	46.9	46.3	9.26
	2	52.6	53.0	52.2	52.3	52.3	10.5
	3	54.3	54.4	53.7	53.9	54.1	**10.82**
3.0″	1	47.7	47.7	50.1	50.0	49.4	9.88
	2	47.0	47.1	47.4	47.3	47.2	9.44
	3	56.3	56.4	56.	55.8	56.1	**11.23**

The first set of three graphs refers to the 1.5″ valves. These are shown in Fig. 7, from where the flow rate of valve No.1 is found to vary from 6*l*/min to 8.73*l*/min, the flow rate of valve No.2 varied from 6.5*l*/min to 7.45*l*/min and for valve No.3 the variation is from 4.02*l*/min to 9.38*l*/min with the power input varied from 22W to 38W. It should be noted that all the valves are arranged by an increasing stroke as shown in Table 1. Apparently valve No.3 has the highest increase in the average water discharge being 134% when power varied from 22W to 38W.

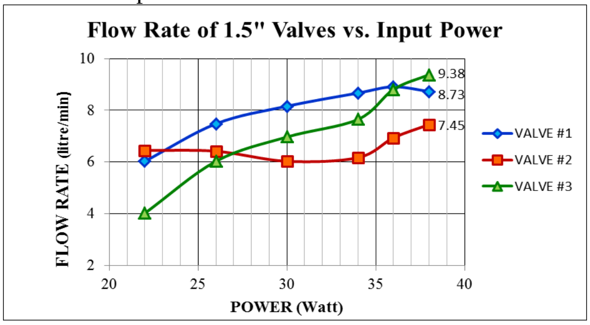

Fig. 7 Average discharge of 1.5″ valves vs. input power

In fact valve No. 3 attained the largest flow rate among the three valves. The reasons being are the influence of the individual valve strokes, valve spring constants and valve spring preloads (Table 1). In this case the valve stroke of 7.7 mm of valve No.3 contributed mostly for the discharge of 9.38*l*/min together with the suitable combination of the valve parameters. The percentage increase of the average discharge of valve No.1 is 45.5% which is noticeably below that of valve No.3 and that of valve No.2 is only 14.6%. The latter result indicates that the parameters of this valve are inappropriately combined to provide a discharge almost unresponsive to the power input. Obviously valves with a combination of their parameters close to these of valve No. 2 should be avoided in practice as being improper for the above range of the power input and maximum acceleration. Possibly at higher accelerations the mass of the valve itself will provide greater inertial force which eventually would play additional roll in the valve performance. This phenomenon needs to be further investigated by varying the maximum acceleration and setting the resonance precisely by measuring the resonance acceleration.

Table 4 Comparison of the 1.5″- valves parameters with the corresponding flow rates.

Valve numbers	No.1	No.2	No.3
Valve stroke, mm	**6.6**	**7.2**	**7.7**
Spring constants, N/m	128	123	123
Spring preloads, N	1.45	1.57	1.34
Max. discharge, *l*/min	**8.73**	**7.45**	**9.38**

In Fig. 7 the trend of water discharge for valves No.2 and No.3 shows that if power is further increased eventually they could perform better. It should be mentioned that this case is the most complicated since there are three points of interception among the flow rates graphs. These points are at 23W regarding the graphs of valves No.1 and No.2, at 27W concerning valve No. 2 and No.3 and at 34W with regard to valve No.1 and No.3 respectively. For a higher power range different valve parameters will be predominant than at the present power range due to the increased influence of the inertial forces acting on the valve. These are very complicated and unpredictable interactions among the valve parameters and are difficult to predict unless experimentally investigated. In this case the most important parameter appears to be the valve stroke which generally helps obtaining the largest flow rate.

The average test results for the 2″ valves are plotted in Fig. 8 where maximum water discharge is attained at 38W input power. Among the three valves valve No.3 with 14.4 mm stroke delivers 10.82 *l*/min, followed by valve No. 2 having 13.7 mm stroke of 10.51 *l*/min discharge and that of valve No.1 with 13 mm stroke and 9.26 *l*/min water discharge.

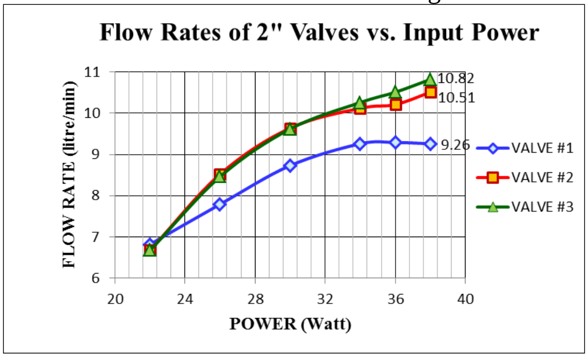

Fig. 8 Average discharge for 2″ valve vs. input power

The effect of the valve stroke on the flow rate appears to be again the most influential parameter but this time it is strongly supported by the proper combination of the valve spring constant and valve spring preload. The combination of these parameters affect the flow rate in a such a way that they help increase the water discharge progressively.

From Table 5 it is observed that the valve spring constant decreases from valve No.1 towards No.3 and therefore reduces the spring force acting on the valve for the same valve displacement. This allows valve No.3 of smallest spring constant to open more than the rest, hence reducing the interior head losses and increasing the flow through the valve body, and the final effect is increased valve discharge.

Table 5 Comparison of the 2″- valves parameters with the corresponding flow rates.

Valve number	No.1	No.2	No.3
Valve stroke, mm	**13**	**13.7**	**14.4**
Spring constants, N/m	164.3	146.3	134.6
Spring preloads, N	1.29	1.39	1.48
Max. discharge, *l*/min	**9.26**	**10.51**	**10.82**

In addition to that considering the data for the valve spring preload it is realized that the latter increases as valve numbers increases. The smalest spring preload affect adversly the valve capacity to close quickly at the end of the sucktion stroke [4] as for valve No.1. This allows some backflow of water to the well, hence reducing the valve discharge and therefore dropping the pump flow rate. These are the reasons why valve No. 3 has the largest discharge as compared to the rest two as seen in Fig. 8 and Table 5.

The average test results for the 3″ valves are shown in Fig. 9 where maximum valve discharge is attained again at 38W power input. Once again valve No. 3 having the largest stroke of 19.2 mm achieves the largest discharge of 11.23 *l*/min followed by valve No.1 of 9.88 *l*/min of stroke of 17.8 mm and the valve No. 2 delivers the least flow rate of 9.44 *l*/min having 18.2 mm stroke. In this graphs the effect of valve stroke is not consistent since the effects of other two parameters influenced the flow rate inversely as in the case of 1.5″ valves shown in Fig. 7 and Table 4.

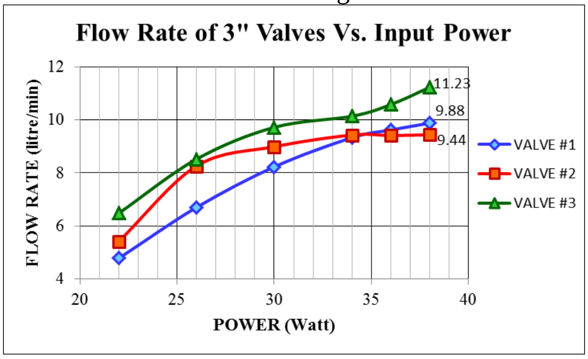

Fig. 9 Average discharge for 3″ valve vs. input power

The effects of the valve spring constant and valve spring preload can be explained analyzing the data in Table 6 for the 3″ valves.

Table 6 Comparison of the 3″- valves parameters with their flow rates.

Valve number	No. 1	No. 2	No. 3
Valve Stroke, mm	**17.8**	**18.2**	**19.2**
Spring constant N/m	383.6	328.5	401.9
Spring preload, N	4.17	3.56	4.20
Max. discharge, *l*/min	**9.88**	**9.44**	**11.23**

The relations among the valve parameters and the flow rate for these valves appear to be also complex since there is one point of interception of the graphs of valve No.1 and No.2 at 34W power input. It is evident that the discharge of valve No.2 is larger for than that of valve No.1 for the power range from 22W to 34W, because the spring constant and spring preload are smaller than these of valve No.1. These combination facilitate the valve to opens easily at low power input and hence helps achieving larger discharge. Contrary to this situation when power is larger than 34W then the inertial forces acting on valve No.1 are higher than before and the larger spring constant and preload act efectively towards increasing the discharge, while the softer spring and smaller spring preload of valve No.2 allow some water backflow to the well, hence reducing the valve discharge and therefore the pump flow rate.

II. CONCLUSIONS

This paper presents the experimental analysis carried out on a solar powered sonic pump in terms of flow rate versus the input power and the foot valve parameters. A model sonic pump usually powered from the AC grid was set to operate under solar power and the flow rate was measured against the power input. Three sizes of spring-loaded poppet valves are tested mainly 1.5″, 2.0″ and 3.0″ each size of them consisted of three valves. The input power is varied from 22W to 38W at six levels and the pump is operated at resonance frequency of 5.42, 5.41 and 5.43Hz respectively, corresponding to the sizes of valves and the total mass of the oscillating system (Table 2). The resonance frequency is maintained approximately the same for all the valves by adding additional masses to the oscillating system in order to eliminate the effect of the resonance frequency upon the flow rate. Large amount of experiments were carried out and outstanding results are recorded. It was found that the maximum flow rate of the sonic pump varied from 9.38 *l*/min to 11.23 *l*/min depending upon the size of the valve and the corresponding valve parameters that is the valve stroke, valve spring constant and the valve spring preload. Among the nine valves being tested, three from each size, the valves of the largest stroke generally discharged the highest flow rate. The percentage increase in the flow rate of 1.5″ valves versus power input varies from 46.1% for valve No.1, 15.5% for valve No. 2 to 134% for valve No. 3.

The percentage increase of the flow rate for 2.0″ valves varies from 35.8 % for valve No.1, 57.6% for valve No.2 to 62.2% for valve No.3 suggesting the important contribution of the largest valve stroke to the flow rate.

The percentage increase of the flow rate for the 3.0″ valves varies from 106.7% for valve No. 1, 72.3% for valve No.2 and 73.3% for valve No. 3. For this size of valves the increased stroke did not contributed proportionally to the flow rate. The reason is that the other two valve parameters such as the valve spring constant and the spring preload influenced the flow rate adversely. In addition to these considerations one very important fact is not taken into account, this is setting the pump in exact resonance. Practically for every experiment this is done by increasing the resonance amplitude visually until it looks maximal. Strictly speaking the best way to set the system in exact resonance is to measure the maximum acceleration attained in resonance. Unfortunately at the time of the experiments there was no relevant equipment to measure the resonance acceleration. So for more precise and reliable results in the future it is recommended that the pump to be set in operation by measuring the resonance acceleration. This will guarantee that the results obtained will be comparable and the effect of valve parameters could be studied accurately and reliably. It is also suggested that the depth of pumping be increased to the depth of a real borehole of at least 30 m. These conditions would require employing more powerful shaker and changing the parameters of the oscillating system so that to keep the operating conditions close to the present resonance frequency, amplitudes and accelerations.

III. ACKNOWLEDGEMENTS

This research work became possible thanks to the financial support of the Office of Research and Development (ORD) at the University of Botswana and the Innovation Hub of Botswana (IHB) at Botswana Institution of Engineers (BIE).

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