MODULAR AXIAL PISTON PUMPS BRING EFFICIENCIES

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Abstract

Positive displacement, water lubricated, axial piston pump technology has been growing in popularity and by unit size in the SWRO industry for more than 14 years. A "tipping point" exists for this technology to replace the less efficient centrifugal high pressure pumps that have dominated in large scale SWRO systems for more than 30 years. The axial piston pump array requires up to 25% less power than the current SWRO industry's standard centrifugal (turbine) pump and power is the single greatest operating cost in the seawater reverse osmosis process. Modular axial piston pump arrays can be efficiently and economically applied to provide high pressure feed to any size system, including large municipal-scale plants. This concept was originally presented at the IDA biannual conference in 2013, where large train sizes from 7,500-27,000 m3/day (2-7 mgd) were considered. This paper will add to that study by providing total life cycle analyses for train sizes from 1,000-5,700 m3/day (0.26-1.5 mgd). In addition, examples of existing full-scale APP arrays will be provided.

I. Background

The axial piston (AP) pump/motor was invented in 1907 [1] and was the foundational product for the oil hydraulics power and motion industries of today [2]. Today sales of the axial piston pumps and motors make up the largest share of the forty billion dollar oil hydraulics component market[3].

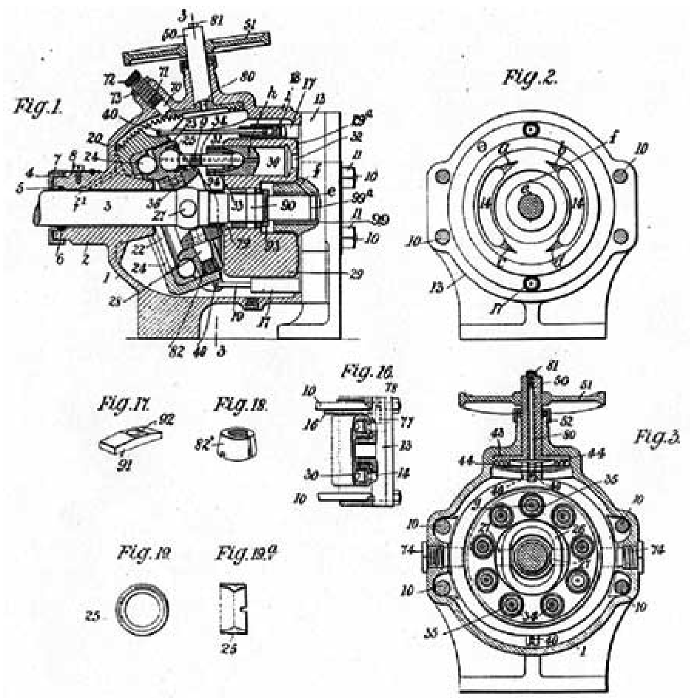

Figure 1. Williams & Janney's Axial Piston Pump and Motor. ca. 1907 [2]

Although the axial piston pump has proven its utility in oil hydraulics for more than 100 years [4], it was not until the invention of modern composite and ceramic materials and precision manufacturing technologies that the unique axial piston design could be used with plain water. In the early 1980's through a public-private partnership with the British Government, a line of axial piston products that used plain water as the lubricating fluid instead of oil was developed. As a result, water lubricated axial piston pumps, motors and other products have been marketed and applied in water hydraulic systems since 1987 [5].

The water lubricated axial piston pump has also been growing in popularity and by unit size in the SWRO industry for more than fourteen years. A "tipping point" exists for this technology to replace the less efficient centrifugal high pressure pumps that have dominated in large scale SWRO systems for more than 30 years. The axial piston pump can be efficiently and economically linked together in parallel to provide high pressure feed to any size system, including large municipal-scale plants.

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[1] Williams and Janney US Patent No. 1,062,071

[2] Tiefenback Water Hydraulics, www.tiefenbach-waterhydraulics.com, Water Hydraulics history page and by kind permission and in co-operation with the Tampere University of Technology (TUT), Finland Prof. Kari T. Koskinen.

[3] Global Industry Analysts, Inc 2010

[4] I. McNeil, Hydraulic Operation and Control of Machines, Thames and Hudson, 1954.

[5] John Need Currie, (Scot-Tech Ltd.), Advances in Water Hydraulics, Proceedings of the 2nd International Symposium on Fluid Control, Sheffield (UK) University, 1988

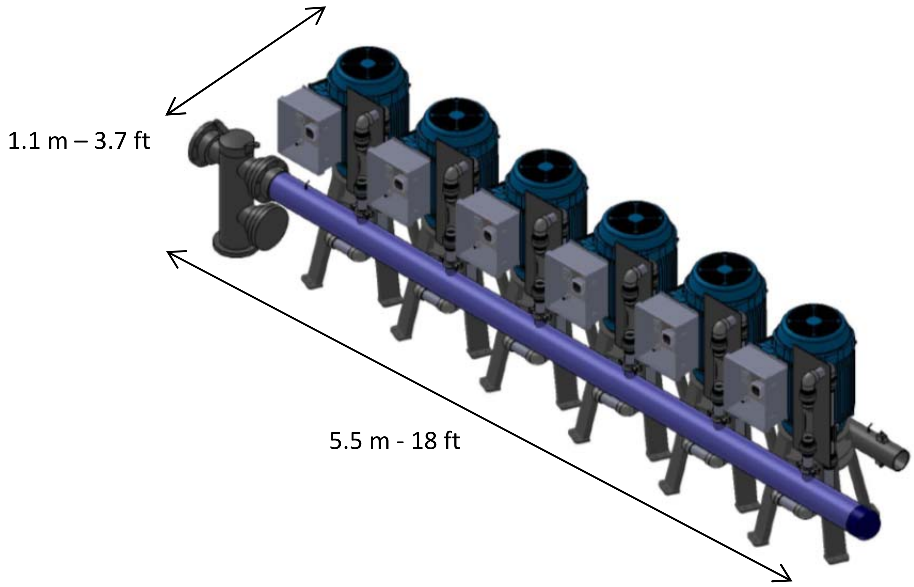


Figure 2. Six Pump Array Provides up to 257 m3/hr (1,134 gpm) at 90% Efficiency

This kind of modular application in pumping systems was pioneered by Energy Recovery, Inc. and modular Pressure Exchanger (PX) arrays are now the standard for energy recovery in SWRO. Many parallels can be drawn between the modern axial piston pump and isobaric pressure exchangers because both operate on the same revolutionary technology platform of water lubricated bearings. When ceramic is used, these bearings can provide maintenance free operation for tens of thousands of hours. Furthermore, both devices employ a positive displacement axial piston design that results in very high efficiencies and virtually pulsation free flow. The progression in size of the axial piston pump has also been similar to the PX. The initial commercial PX units in 1995 produced only 9 m3/hr (40 gpm) and were therefore only considered suitable for smaller scale systems. But as the size of the individual PX units grew and their reliability in modular arrays was proven the technology became an industry standard applicable to the largest systems in the world. Similarly the modern water lubricated axial piston pump has grown in size from its original introduction into the SWRO market in 2000 with maximum capacities of approximately 10.2 m3/hr (45 gpm) to capacities up to 78 m3/hr (343 gpm) available today. Through its progression the water lubricated axial piston pump has also proven its compatibility in modular array applications.

The axial piston pump array requires up to 25% less power than the current SWRO industry's standard centrifugal (turbine) pump. Power is the single greatest operating cost in the seawater reverse osmosis process.

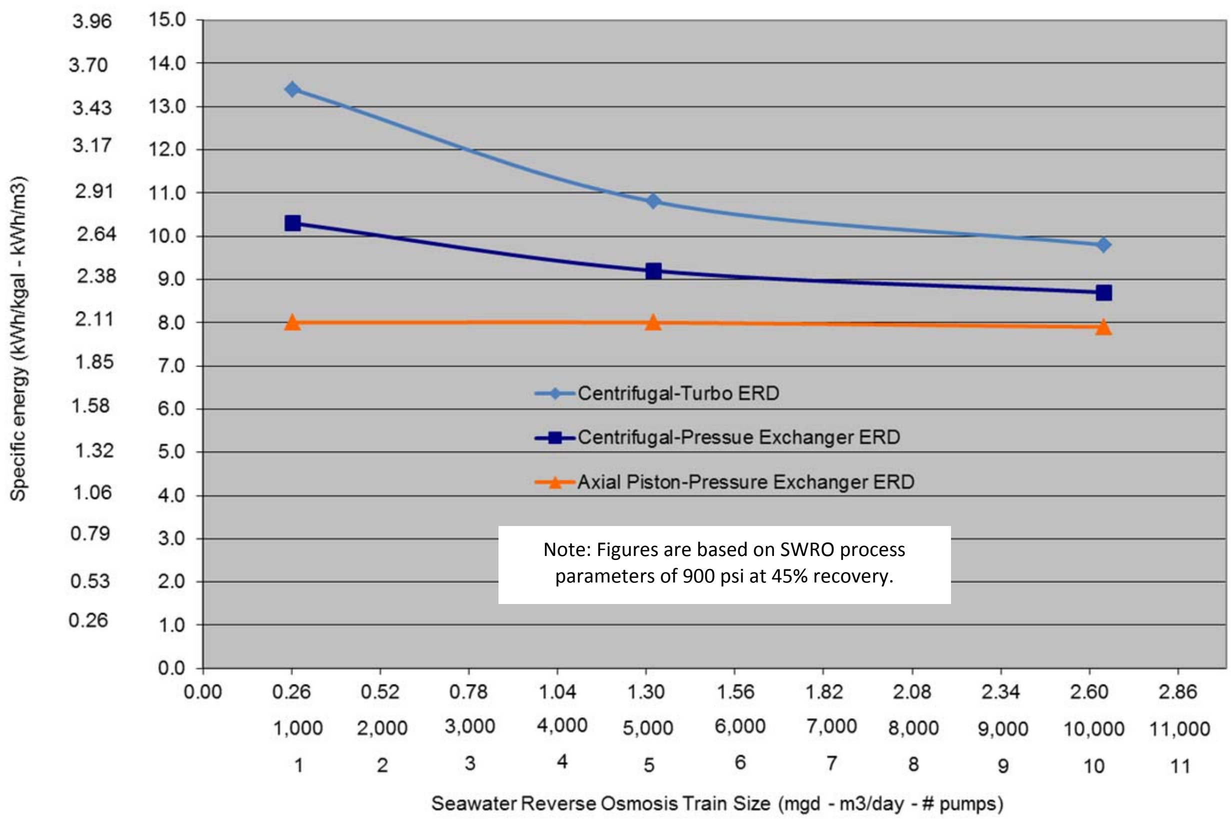


Figure 3. Specific Energy Consumption for AP and CF Pumps vs system Size

The efficiency advantage of the AP pumping system shown in Figure 3 represents the largest single gain in desalination efficiency in 30 years. It should be noted that Turbo and Pelton technologies require a 100% feed flow main high pressure pump, which when combined with the AP pump requires higher capital costs and energy consumption compared to an equivalent Axial Piston-Pressure Exchanger system ie. It is not currently practical to combine Turbos and Pelton wheels with axial piston pumps. Looking at the X-axis one can see that as the train size increases axial piston pumps are added onto a pumping array. For example, a 4,000 m3/day (1.1 MGD) train would require four AP pumps running in parallel to produce 174 m3/hr (767 gpm) at a specific energy of 2.1 kWh/m3 (8.0 kWh/kgal). In Figure 3 one can see how the CF pump systems energy consumption improves as the plant size increase. This is because CF pump efficiency improves as flow rate increases. This fact diminishes the AP efficiency advantage as the CF pump size increases.

II. Twenty Year Life Cycle Analysis

A comparative study was conducted to evaluate the AP modular pumping system at various flows to the life cycle cost of typical centrifugal pumps used in the SWRO industry. Leading centrifugal pump manufacturers were considered including FEDCO, Energy Recovery Inc., KSB and Sulzer and the following flow rates and pump types were used in the study:

Table 1. Centrifugal Pump Flow Rates and Types

Pump Flow Rate	Pump Type
42 m3/hr - 186 gpm	Centrifugal, “Canned”, 42 stages 21/21
159 m3/hr - 701 gpm	Centrifugal, “Canned”, 15 stages
211 m3/hr - 927gpm	Centrifugal, “Canned”, 14 stages
318 m3/hr - 1400 gpm	Centrifugal, “Canned”, 8 stages
568 m3/hr - 2500 gpm	Horizontal Ring Section, 3 stages
1136 m3/hr - 5000 gpm	Split Case, 3 stages

The study includes the evaluation of the high pressure pump system capital and operating expenses in order to determine the 20 year life cycle costs of each alternative. Preliminary capital cost evaluation not only includes the pump manufacturing, but also the following installation and support equipment associated with a high pressure pump system:

- Variable Frequency Drive (VFD) or Soft Start/RVS
- Electric Service Cable and Cable Installation
- Electrical Connectors
- Pump and Skid Install
- Motor, Drive, and Coupling Installation
- Pump Alignment
- Delivery Check Valve
- Relief Valve
- Delivery Pipework

2.1 System Performance Parameters

Certain SWRO operating parameters impact the overall performance of a given system. Table 2 provides a set of parameters as a basis for comparing the performance and subsequent operating costs for each pumping system at six different flow rates. Although we are focusing on the specific performance of the high pressure pumping system some parameters assume that the pumps are working in combination with an isobaric energy recovery system.

Table 2. System Performance Parameters and Assumption

Description	Units	42 m3/hr		159 m3/hr		211 m3/hr		318 m3/hr		568 m3/hr		1136 m3/hr		Axial Piston	
Pump type	Stages	42 (21/21)		15		14		8		Seg-ring 3		Split-case 3		PD	
VFD efficiency	%	97.0%		97.0%		97.0%		97.0%		97.0%		97.0%		n/a (1)	
Motor efficiency	%	95.8%		95.8%		95.5%		96.0%		96.0%		96.0%		90.0%	
Net pump efficiency	%	77.5%		79.9%		82.8%		81.5%		83.0%		84.5%		95.0%	
Centrifugal (CF) slide wear rate (% eff loss/yr)	%/yr	0.3%		0.3%		0.3%		0.3%		0.3%		0.3%		n/a	
Pump Flow rate	m3/hr - gpm	42	186	159	701	211	927	318	1,400	568	2,500	1,136	5,000	equal to CF	
Permeate flow rate (assumes isobaric)	m3/day - mgd	1,006	0.3	3,790	1.0	5,012	1.3	7,570	2.0	13,517	3.6	27,034	7.1	equal to CF	
Suction pressure	bar - psi	2.1	30	2.1	30	2.1	30	2.1	30	2.1	30	2.1	30	2.1	30
Discharge pressure	bar - psi	62.1	900	62.1	900	62.1	900	62.1	900	62.1	900	62.1	900	62.1	900
Power centrifugal (year 1)	kW	100		366		469		715		1,254		2,463		see AP power	
Power axial piston (AP)	kW	87		310		410		640		1,144		2,287		<---------	

1. Applied 97% VFD to 42 m^3/hr system.

Table 3. Cost Parameters and Assumptions

Cost Parameter Description	Unit	Value
Electric power (year 1)	$/kWh	0.15
Annual power cost increase	%	2%
Online factor	%	95%
Discount rate	%	5%
Plant operating period	years	20

2.2 CF Cost Parameters

The twenty year lifecycle costs were analyzed for the six flow rates specified in Table 1. Budgetary quotations were obtained from each manufacturer to determine the capital cost for each pump and motor package. In addition, quotations and estimates were obtained for the associated components required for installation including VFD's, skids, piping and civil work.

Table 4. Centrifugal Pump Twenty Year Lifecycle Cost Parameters and Assumptions

Capitol Equipment Description			42 m3/hr	159 m3/hr	211 m3/hr	318 m3/hr	568 m3/hr	1136 m3/hr
Pump and motor			$ 31,589	$ 80,228	$ 93,466	$ 195,000	$ 361,100	$ 426,400
VFD			$ 4,860	$ 16,300	$ 23,400	$ 54,000	$ 100,000	$ 200,000
Service Cable			$ 500	$ 725	$ 1,000	$ 1,000	$ 1,500	$ 2,500
Cable Install			$ 500	$ 725	$ 1,000	$ 1,000	$ 5,000	$ 5,000
Connectors			$ 75	$ 250	$ 250	$ 250	$ 750	$ 750
Pump Skid Install			$ 500	$ 1,500	$ 1,500	$ 10,000	$ 15,000	$ 15,000
Motor Install			$ -	$ -	$ -	$ -	$ 5,000	$ 5,000
Drive Install			$ 500	$ 2,000	$ 5,000	$ 5,000	$ 10,000	$ 10,000
Coupling Install			$ -	$ -	$ -	$ 1,000	$ 5,000	$ 5,000
Allignment			$ -	$ -	$ -	$ 5,000	$ 5,000	$ 5,000
Delivery Check Valve			$ 1,516	$ 5,000	$ 8,000	$ 15,000	$ 25,000	$ 35,000
Delivery Pipework			$ -	$ -	$ -	$ -	$ 35,000	$ 45,000
Extra Civils, Pad, Steel			$ -	$ 5,000	$ 8,000	$ 10,000	$ 15,000	$ 25,000
Total 20 year CF Installation and CAPEX			$ 40,000	$ 112,000	$ 142,000	$ 297,000	$ 583,000	$ 780,000
Spare Part/Consumable Desciption	Qty		42 m3/hr	159 m3/hr	211 m3/hr	318 m3/hr	568 m3/hr	1136 m3/hr
Mechanical Seals	2		$ 3,850	$ 6,300	$ 6,300	$ 2,000	$ 2,500	$ 5,000
Oil	lot		$ 100	$ 100	$ 100	$ 500	$ 750	$ 1,000
Coupling	1		$ 250	$ 250	$ 250	$ 500	$ 2,000	$ 3,000
10 year rebuild @ 50% Pump Capex	1		$ 11,000	$ 27,700	$ 31,700	$ 75,000	$ 141,600	$ 140,300
15 year rebuild @ 50% Pump Capex	1		$ 11,000	$ 27,700	$ 31,700	$ 75,000	$ 141,600	$ 140,300
Total CF 20 year spares/consumable costs			$ 26,000	$ 62,000	$ 70,000	$ 153,000	$ 288,000	$ 290,000
Labor Description	Hours	$/hr	42 m3/hr	42 m3/hr	211 m3/hr	318 m3/hr	568 m3/hr	1136 m3/hr
General operation and maintenance (hrs/wk)	1	$ 25	$ 26,000	$ 26,000	$ 26,000	$ 26,000	$ 26,000	$ 26,000
Rebuild 10 year	40	$ 150	$ 6,000	$ 6,000	$ 6,000	$ 6,000	$ 9,000	$ 12,000
Rebuild 15 year	40	$ 150	$ 6,000	$ 6,000	$ 6,000	$ 6,000	$ 9,000	$ 12,000
Total CF 20 year O&M labor			$ 38,000	$ 38,000	$ 38,000	$ 38,000	$ 44,000	$ 50,000
Energy costs			42 m3/hr	42 m3/hr	211 m3/hr	318 m3/hr	568 m3/hr	1136 m3/hr
Lifecycle energy costs			$ 3,094,000	$ 11,309,000	$ 14,486,000	$ 22,102,000	$ 38,755,000	$ 76,134,000

All currencies are in US$. It's assumed that the 10 year CF rebuild recovers some of the slide wear efficiency loss back to 3 years new and that the 15 year rebuild provides no benefit to efficiency.

2.3 AP Cost Parameters

The twenty year lifecycle costs for the AP system were also analyzed at the flow rates specified in Table 1. Pump and spare parts budget estimates were obtained using axial piston pump manufacturer's published pricing as of July-2014. In addition, quotations and engineering estimates were obtained for the associated components required for installation including switch gear, skids, piping and civil work.

Table 5. Axial Piston Pump Twenty Year Lifecycle Cost Parameters and Assumptions

		m3/hr	42	159	211	318	568	1136
Capitol Equipment Description		Unit cost	# Units 1	# Units: 4	# Units: 5	# Units 8	# Units: 13	# Units: 26
Axial piston pump (196 gpm max flow)		$ 27,880	$ 27,880	$ 111,520	$ 139,400	$ 223,040	$ 362,440	$ 724,880
Motor		$ 7,000	$ 7,000	$ 28,000	$ 35,000	$ 56,000	$ 91,000	$ 182,000
DOL starters		$ 4,500	$ 4,500	$ 18,000	$ 22,500	$ 36,000	$ 58,500	$ 117,000
MCC Surcharge		$ 1,500	$ 1,500	$ 6,000	$ 7,500	$ 12,000	$ 19,500	$ 39,000
Check Valves		$ 1,500	$ 1,500	$ 6,000	$ 7,500	$ 12,000	$ 19,500	$ 39,000
Relief valve (rupture disc)		$ 600	$ 600	$ 2,400	$ 3,000	$ 4,800	$ 7,800	$ 15,600
Victaulic high pressure		$ 75	$ 75	$ 300	$ 375	$ 600	$ 975	$ 1,950
Victaulic low pressure		$ 50	$ 50	$ 200	$ 250	$ 400	$ 650	$ 1,300
LP Flow Meters		$ 150	$ 150	$ 600	$ 750	$ 1,200	$ 1,950	$ 3,900
Pump base		$ 500	$ 500	$ 2,000	$ 2,500	$ 4,000	$ 6,500	$ 13,000
Base install		$ 400	$ 400	$ 1,600	$ 2,000	$ 3,200	$ 5,200	$ 10,400
Manifolds		$ 1,500	$ 1,500	$ 6,000	$ 7,500	$ 12,000	$ 19,500	$ 39,000
Total 20 year AP Installation and CAPEX		$ 46,000	$ 46,000	$ 183,000	$ 228,000	$ 365,000	$ 594,000	$ 1,187,000
Spare parts/consumables descript	Unit cost	/pmp/yr	# Units 1	# Units: 4	# Units: 5	# Units 8	# Units: 13	# Units: 26
Piston set	$ 3,700	33%	$ 24,420	$ 97,680	$ 122,100	$ 195,360	$ 317,460	$ 634,920
Valve and port plate set	$ 2,400	20%	$ 9,600	$ 38,400	$ 48,000	$ 76,800	$ 124,800	$ 249,600
Cylinder block	$ 8,000	20%	$ 32,000	$ 128,000	$ 160,000	$ 256,000	$ 416,000	$ 832,000
Swash plate	$ 2,500	20%	$ 10,000	$ 40,000	$ 50,000	$ 80,000	$ 130,000	$ 260,000
Shaft seal	$ 900	20%	$ 3,600	$ 14,400	$ 18,000	$ 28,800	$ 46,800	$ 93,600
Special tools	$ 1,300	n/a	$ 2,600	$ 2,600	$ 2,600	$ 2,600	$ 2,600	$ 2,600
Total 20 year AP spares/consumable costs			$ 82,000	$ 321,000	$ 401,000	$ 640,000	$ 1,038,000	$ 2,073,000
Labor Description	Hours	Rate $/hr	# Units 1	# Units: 4	# Units: 5	# Units 8	# Units: 13	# Units: 26
General maintenance hrs/wk	1	$ 25	$ 26,000	$ 26,000	$ 26,000	$ 26,000	$ 26,000	$ 26,000
Annual rebuild (hours/pmp)	2	$ 25	$ 1,000	$ 4,000	$ 5,000	$ 8,000	$ 13,000	$ 26,000
Total AP 20 year O&M labor			$ 27,000	$ 30,000	$ 31,000	$ 34,000	$ 39,000	$ 52,000
Energy costs			# Units 1	# Units: 4	# Units: 5	# Units 8	# Units: 13	# Units: 26
Total life cycle energy			$ 2,557,000	$ 9,638,000	$ 12,746,000	$ 19,249,000	$ 34,373,000	$ 68,747,000
Savings			# Units 1	# Units: 4	# Units: 5	# Units 8	# Units: 13	# Units: 26
Average annual energy savings			$ 27,000	$ 84,000	$ 87,000	$ 143,000	$ 219,000	$ 369,000
Average annual life cycle savings			$ 24,000	$ 67,000	$ 67,000	$ 115,000	$ 181,000	$ 260,000

2.4 Twenty Year Life Cycle Costs

Looking at Figure four below, CF energy costs on average consume 98% of their total twenty year life cycle costs. Energy consumed by the high pressure pump typically consumes as much as 50% of the total operating cost to produce water within the overall SWRO process [6]. Therefore, high pressure pumping efficiency is of utmost importance when considering pump technologies and targeting ways to improve the overall efficiency and operating costs for SWRO.

[6] The Affordable Desalination Collaboration 10 MGD Conceptual Case Study, Seacord, Dundorf, MacHarg, American Membranes Technology Association (AMTA) Annual Conference Proceedings 2007.

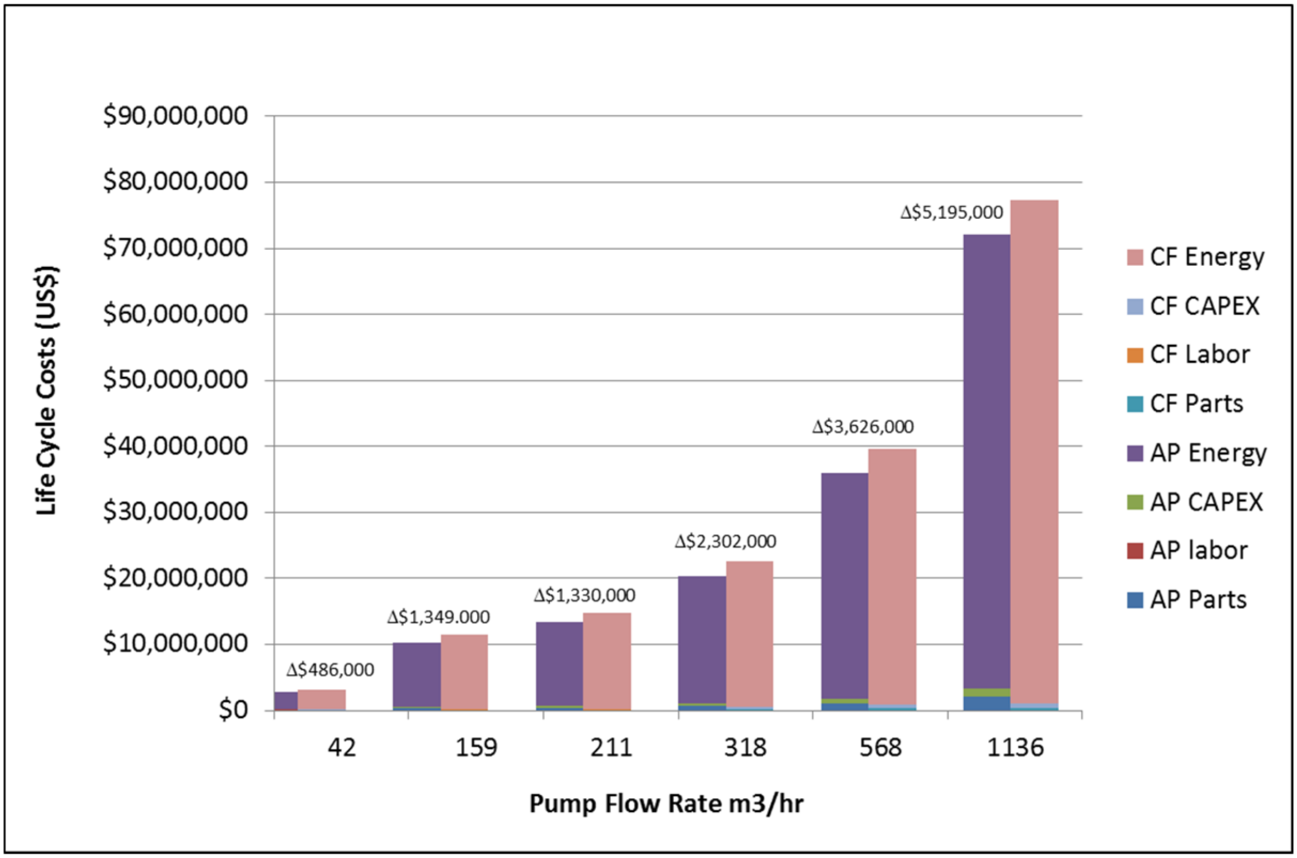


Figure 4. Total Twenty Year Life Cycle Costs

III. Present Worth and Return on Investment (ROI)

Both the Present Value (PV) analysis and Payback Period show that the AP system holds a strong advantage over traditional centrifugal pumps. Even in the extreme case at 1136 m3/hr payback is less than two years.

Table 6. Present Worth Costs and ROI

Present Worth and ROI m3/hr	42	159	211	318	568	1136
CAPEX differential	$ 6,000	$ 71,000	$ 86,000	$ 68,000	$ 11,000	$ 407,000
Percent difference	15%	63%	61%	23%	2%	52%
Average annual life cycle savings	$ 24,000	$ 67,000	$ 67,000	$ 115,000	$ 181,000	$ 260,000
Pay back period (Capex differential/avg annual life cycle savings)	0.3	1.1	1.3	0.6	0.1	1.6
Return on investment (ROI)	400%	94%	78%	169%	1645%	64%
Present Value (PV) of investment	$ 299,000	$ 835,000	$ 835,000	$ 1,433,000	$ 2,256,000	$ 3,240,000

At 568 m3/hr the centrifugal pump manufacturer quoted anomalously high capital costs resulting in nearly equivalent CAPEX costs between the AP and centrifugal systems. Removing this data point from the average analyses, the CAPEX cost for the AP system averaged 43% higher than the CF systems, while yielding an average 0.9 year payback or 105% ROI.

The CAPEX differential represents the initial investment required to achieve the annual power savings from the AP system. The present value of the 20 years savings should always be greater than the initial investment. For example, at 42 m3/hr one has to invest $6,000 to receive a savings over 20 years, which has a present value of $299,000. In other words, it's similar to exchanging $6000 for $299,000 on day one, which is an extremely attractive proposition.

IV. Weight and Dimensions

Below 211 m3/hr the AP pump array averages 30% less floor space, while at 318 m3/hr and above AP pump arrays average 2X more floor space. AP pump arrays when including the motors average 26% more weight. However, the isolated pump weight averages 37% less than the equivalent centrifugal pump. Less weight should correlate to lower cost as the volume of AP pumps being applied in the market place increases.

Table 7. Weight and Dimensional Comparison

CF Weight and Dims	Units		42		159		211		318		568		1136	
Pump weight	kg - lbs		140	309	1,207	2,661	1,462	3,223	1,279	2,820	1,500	3,307	1,991	4,389
Motor weight	kg - lbs		994	2,191	1,880	4,145	1,880	4,145	3,175	7,000	7,600	16,755	5,750	12,676
Base plate	kg - lbs		n/a	n/a	n/a	n/a	included	included	800	1,764	3,000	6,614	1,200	2,646
Grout base plate	kg - lbs		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2,825	6,228	4,708	10,379
Installed weight	kg - lbs		1,134	2,500	3,087	6,806	3,342	7,368	5,254	11,583	14,925	32,904	13,649	30,091
Package dimension	L x W x H, m - ft		5.0x0.8x0.7	16.4x2.8x2.4	4.1x1.1x1.1	13.4x3.6x3.6	4.7x1.1x1.1	15.0x3.7x3.0	5.0x1.2x1.0	16.4x3.9x3.3	4.8x2.0x2.8	15.7x6.6x9.1	4.8x2.0x2.6	15.7x6.6x8.5
Area	m^2 - ft^2		4.0	46	4.5	48	5.2	56	6.0	64	10	104	8.2	104
AP Weight and Dims	**Per AP Module**		**# Units: 1**		**# Units: 4**		**# Units: 5**		**# Units: 8**		**# Units: 13**		**# Units: 26**	
Pump weight (kg - lbs)	91	201	91	201	364	802	455	1,003	728	1,605	1,183	2,608	2,366	5,216
Motor weight (kg - lbs)	757	1,669	757	1,669	3,028	6,676	3,785	8,344	6,056	13,351	9,841	21,695	19,682	43,391
Installed weight (kg - lbs)	948	2,090	948	2,090	3,792	8,360	4,740	10,450	7,584	16,720	12,324	27,169	24,648	54,339
Package dimension (L x W x H, m - ft)	0.9x1.1x1.8	3.0x3.7x6.0	0.9x1.1x1.8	3.0x3.7x6.0	3.6x1.1x1.8	12.0x3.7x6.0	4.5x1.1x1.8	15x3.7x6.0	7.2x1.1x1.8	24.0x3.7x6.0	11.7x1.1x1.8	39x3.7x6	23 x 1.1 x 1.8	78 x 3.7 x 6
Area (m^2 - ft^2)	1.0	11	1.0	11	4.0	48	5.0	56	8	88	13	143	26	286

Possibilities exist for improving the AP system's overall weight and dimensions including increasing the individual pump unit size and/or increasing the number of pumps per motor through a double motor shaft configuration. In fact, one manufacturer has recently released an axial piston pump rated at 78 m3/hr (343 gpm). This is almost double the capacity of the AP unit size considered in this study and should help to reduce the space required by the AP pump array.

V. Sensitivity Analyses

Using the standard set of costs and conditions established in Tables 1-5, the figures below show how varying AP net pump efficiency, energy costs, RO feed pressure, CF capital costs and AP spare parts costs impacts the return on investment for the AP system.

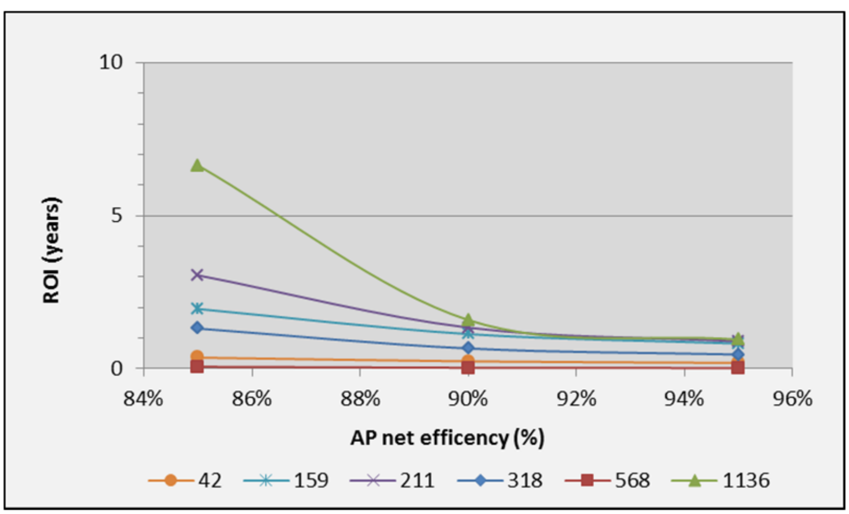


Figure 5. Payback Period Versus AP Efficiency

Only recently has the axial piston pump been more widely applied to the full scale market. Therefore, good historical operating data is unavailable in the literature. One key question is what efficiency will the pumps be able to maintain over time? This is a particularly relevant with water lubricated bearings that can wear and result in a loss in flow and efficiency over time. Scheduled maintenance can recovery the efficiency to like-new performance, but the efficiency between regular service intervals will vary. Therefore the ROI versus a range of average pump efficiencies from 85-95% are plotted in figure 5. The result shows that even at 85% net AP pump efficiency the ROI is still less than 5 years in most cases. On the other hand, there are indications that the AP pump efficiency can reach as high as 94%.

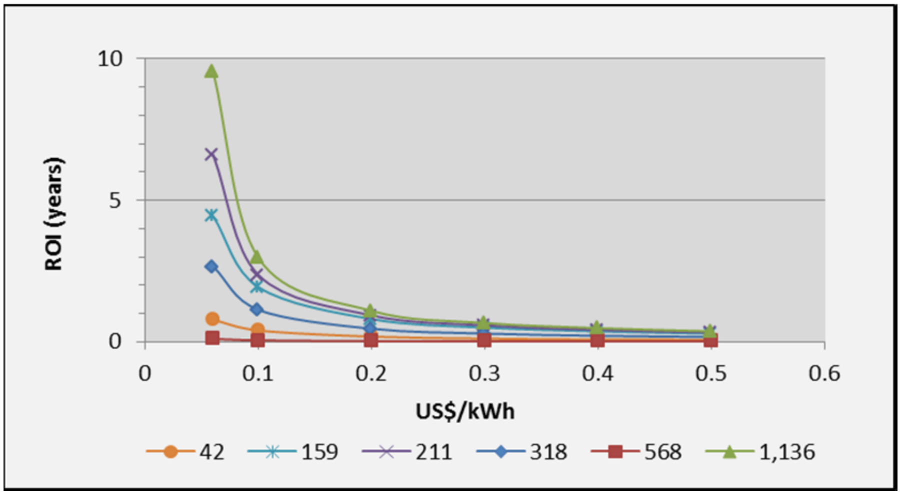


Figure 6. Payback Period Versus Energy Costs

Energy costs obviously play a significant role and give the AP system a decisive advantage where power costs are high. Even at $0.01/kWh the AP system yields a less than five year return on investment over the entire flow range considered. However, at flows beyond 568 m^3/hr, the AP system's diminished efficiency advantage and added spare parts burden pushes the ROI beyond 5 years at $0.06/kWh.

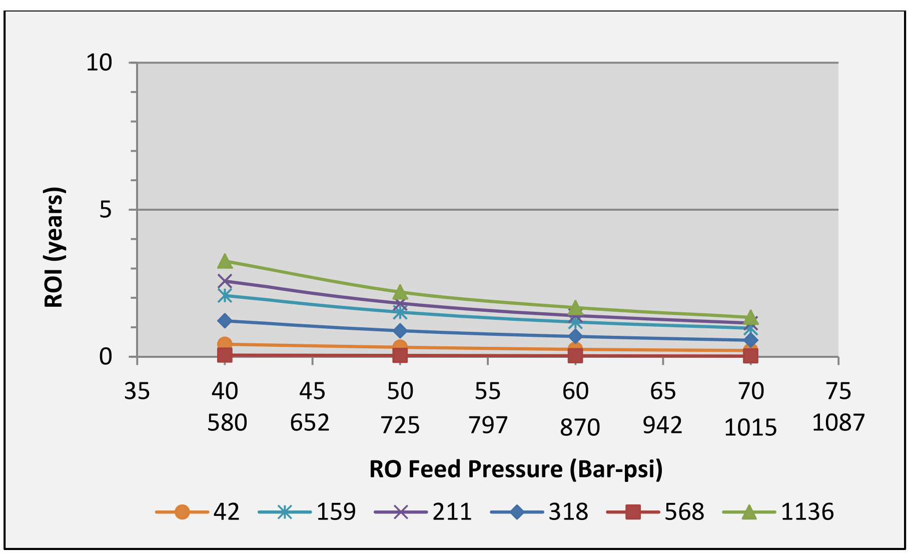


Figure 7. Payback Period Versus RO Feed Pressure

Another important factor that impacts energy consumption and thus the payback period for an energy saving high pressure pump is the RO feed pressure. SWRO feed pressures typically range between 55-70 bar (650-1000 psi) depending on membrane manufacturer, age, condition and other operating conditions. However, membranes continue to improve and feed pressures between 45-55 bar (650-800 psi) are becoming more common. Figure 7 shows how even at very low feed pressures the AP system still provides a quick return when compared to CF pumps. Even at 1,136 m3/hr the AP system yields a 30% return on investment (3.25 year payback) over the CF system at a feed pressure of 40 bar (580 psi).

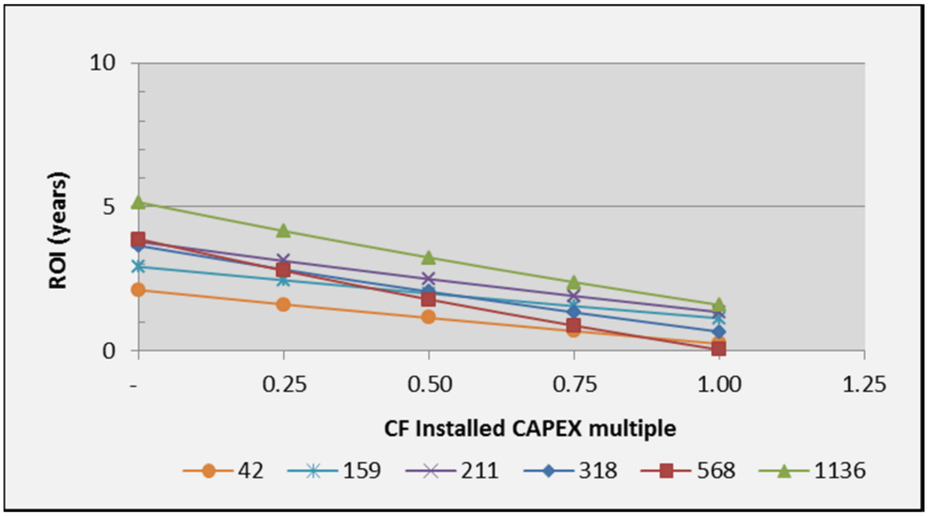


Figure 8. Payback Period Versus CF Installed CAPEX Costs

The estimated installed CAPEX costs were based on engineering estimates and actual quotations from the pump manufacturers and other major component suppliers. Manufacturers' quotations are subject to significant variations from initial budgetary pricing to final/best firm fixed price quotations in addition to volatility in commodity materials pricing. Therefore, we also considered the sensitivity of payback versus the Total 20 year CF Installation and CAPEX costs. In Figure 8 a multiplier of 0-1 was applied to the Total 20 year CF Installation and CAPEX costs and plotted against the payback period on the vertical axis. A multiplier of zero correlates to zero CF Installation and CAPEX costs and a multiplier of one corresponds to the same CAPEX costs given in Tables 4. Looking back to figure 4 we recognized how efficiency directly impacts energy costs, which make up 98% of the total life cycle costs. Figure 8 helps to reinforce the point, showing how the centrifugal systems can have zero CAPEX and install costs and the AP system still yields an average 3.5 year ROI.

It should be noted that over the range of flows considered in this study, on average 28% of the lifecycle energy savings are offset by AP system spare parts replacement expenses. The primary reasons for replacement include wearing of the sliding/bearing surfaces which decrease the overall efficiency and reliability of axial piston pumps. Replacing worn parts recovers the efficiency to "like-new" condition but acts like drag on the efficiency advantage. Water quality can play a major role in the maintenance intervals between parts replacement, because small particulates in the RO feed water (lubricating fluid) can accelerate the wear on sliding surfaces. This is particularly true in the case of the plastic-stainless bearings used by some manufacturers. On the other hand, one manufacture offers ceramic replacement parts and claims extended service intervals over the plastic-stainless steel parts. Therefore a sensitivity analysis was performed varying the replacement cost/interval for a typical AP system. Similar to the capital cost analysis a multiplier of 0.5-3 was used to adjust the Total AP 20 Year AP Spares/Consumables Costs shown in Table 5.

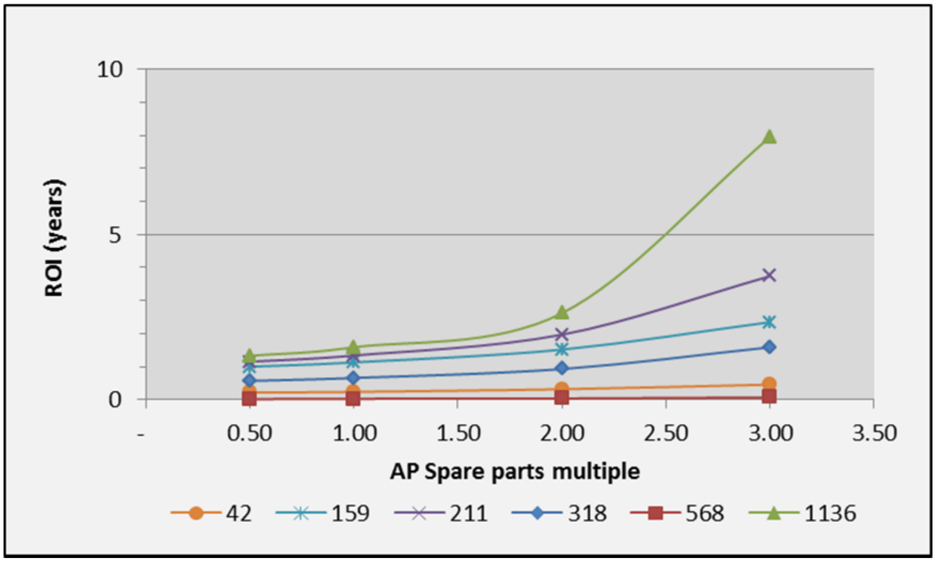
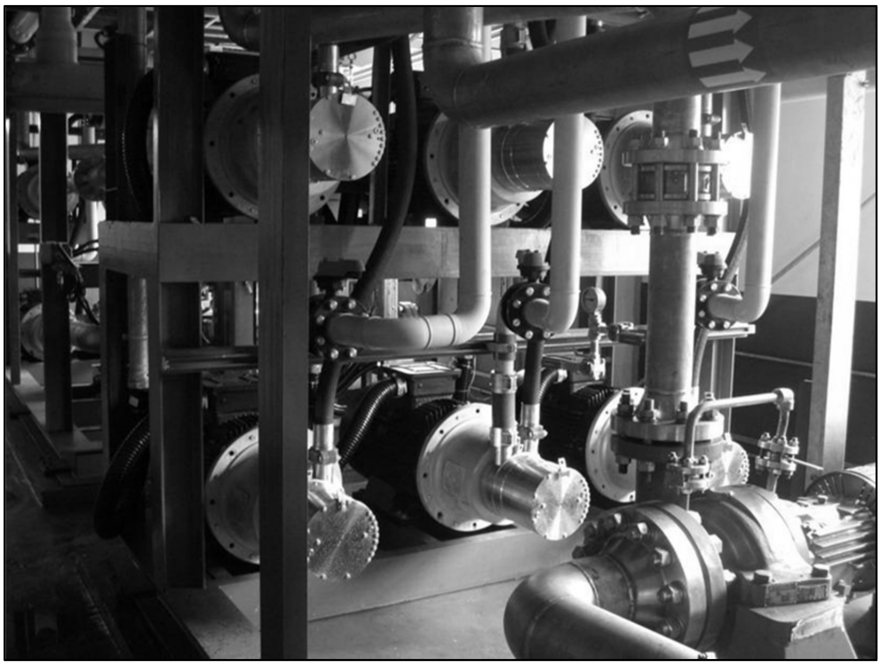


Figure 9. Payback Period Versus AP Annual Spares Costs

Applying a multiplier of 0.5 reduces Total 20 Year Spares/Consumables Costs by a factor of 2 or equivalently extends the assumed replacement intervals in table 5 by 2X, while a multiplier of three increases the Total 20 Year Spares/Consumables Costs by a factor of 3X or equivalently shortens the assumed replacement intervals by 1/3. A multiplier of one corresponds to the same spares and consumables costs and replacement interval (/pump/year) in table 5.

VI. Full Scale Examples

Thus far, this paper has stressed the importance of efficiency going so far as to say it is of utmost importance. However, one major factor more important than efficiency is reliability. Can the AP pump array operate reliably over time? One indication, is that manufacturers of water lubricated equipment such as pressure exchangers and axial piston pumps tend to offer standard 2-5 year warranties. In the case of axial piston pumps, one leading manufacturer provides an 8000 hour maintenance free guarantee. However, the best evidence will be provided by actual working systems and to that end several select installations are provided as examples below.



Installation date: 2010

Size: 2 x 2800 m3/day SWRO

Region: China

Notes: First large/full scale application of axial piston pump array. System is an open intake. An eye witness review of the operating logs revealed the system had initially operated more than 3 years maintenance free.

Installation date: October-2014

Size: 1,450 m3/day SWRO

Region: Caribbean

SEC: 2.1 kWh/m3 (7.8 kWh/gkal) at 58 bar (840 psi)

Installation date: No data

Size: 1,800 m3/day SWRO

Region: Taiwan

VII. Conclusions

In addition to the obvious energy efficiency advantage that positive displacement pumps maintain over centrifugal units, the technology also improves the operation and control of the system there by yielding additional gains in the net system efficiency. There are also potentially significant cost efficiency gains related to manufacturing and building modular systems around a standardized unit.

Some of the advantages and disadvantages associated with the Modular High Pressure Pump System using Axial Piston Pump Technology include the following:

Advantages

- Significant energy savings due to the 90% efficiency of positive displacement pumps compared to centrifugal pump designs.
- Applying one standardized high efficiency pump as a building block in multi-unit modules allows smaller trains to be as efficient as the largest systems.
- A standardized modular design reduces inventory requirements for spare parts. Relatively small and inexpensive service kits and spare parts can support modular arrays whereas large centrifugal pumps require massive spare motor(s) and/or rotor kits, mechanical seals, etc.
- Lead times for large centrifugal pumps are significant and substantially lengthen project deliveries whereas axial piston pumps can be kept on the shelf and used as building blocks for any size system to significantly reduce project delivery times.
- Smaller standardized pumps can be maintained in-house with minimum staff training compared to large centrifugal pumps, which require specialized factory trained technicians and/or shipping equipment back to factory for maintenance and repairs. This will significantly decrease down-time in facilities using Axial Piston Pump technology.
- No huge VFD or RVS are required. Axial Piston Pumps can be started across the line (depending on country and electrical supply requirements) due to the smaller individual motors.
- No regulating valve or VFD is required to control AP pumps, which further improves the overall system efficiency compared to centrifugal pump process designs.
- Low voltage power can be used to drive smaller motors arranged in a modular array.
- Virtually eliminates in rush current associated with starting large electric motors.
- Smaller individual pumps arranged in a modular array allow for additional system flow control by turning pumps on or off within the array while maintaining peak efficiency and optimal power usage.
- Multiple-small diameter discharge check valves are less expensive and have less lead time than large, exotic alloy valves due to the specialized nature of the large valve industry.
- No complex shaft alignment required with close coupled axial piston pumps

Disadvantages

- More plant space may be required for the axial piston pump modular array, though less electrical space will be required.

- Longer installation and commissioning period may be required due to multiple pumps and components
- Multi-start system opposed to one larger centrifugal pump may lead to a longer start-up time.
- More instrumentation (flow meters on each pump on the array) may be required, but will provide additional data for troubleshooting and system efficiency monitoring.
- The efficiency of centrifugal pumps increases with flow rate reducing the efficiency advantage of the modular axial piston pump concept at the higher end.
- Additional spare parts, maintenance and down time are needed although the service intervals are predictable.