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# Economics of water injected air screw compressor systems

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**Abstract.** There is a growing need for compressed air free of entrained oil to be used in industry. In many cases it can be supplied by oil flooded screw compressors with multi stage filtration systems, or by oil free screw compressors. However, if water injected screw compressors can be made to operate reliably, they could be more efficient and therefore cheaper to operate. Unfortunately, to date, such machines have proved to be insufficiently reliable and not cost effective. This paper describes an investigation carried out to determine the current limitations of water injected screw compressor systems and how these could be overcome in the 15-315 kW power range and delivery pressures of 6-10 bar. Modern rotor profiles and approach to sealing and cooling allow reasonably inexpensive air end design. The prototype of the water injected screw compressor air system was built and tested for performance and reliability. The water injected compressor system was compared with the oil injected and oil free compressor systems of the equivalent size including the economic analysis based on the lifecycle costs. Based on the obtained results, it was concluded that water injected screw compressor systems could be designed to deliver clean air free of oil contamination with a better user value proposition than the oil injected or oil free screw compressor systems over the considered range of operations.

**Key words:** Water injected screw compressor, lifecycle costs, value proposition.

## 1. Introduction

ISO 8573-1 classifies the quality of air based on oil content in classes 0 to 4 [1]. Class 0 is completely free of oil while Class 1 will contain less than 0.01 mg oil per m<sup>3</sup> of air. Higher classes will allow one order of magnitude higher content of oil from each other. The pharmaceutical and food industries for products in direct contact with compressed air will require class 0 while industries dealing with food and beverage with non-direct contact with air, power product transport or film processing will allow use of air in class 1. It is expected that in future the legislative limits of oil contamination in air will lower. Typically, industrial air systems operate at pressures of 6-10 bar in power range of 15-300kW using packaged air compressors. The most widely used are rotary twin screw compressor systems due to their reliability, low maintenance and efficiency.

Oil injected screw compressor systems with multi filtration stages are associated with the high risk of oil contamination and at best can only meet air quality of Class 1 of ISO 8573-1. The presence of multiple filters decreases their efficiency and hence increases their power consumption, installation costs and associated maintenance costs.

A conventional oil free compressor system usually can offer a better quality air but it requires a 2-stage oil free compressor, inter cooler, special bearings to handle high temperatures and speeds, and an



expensive sealing system to prevent mixing of oil and gas. This makes an oil free screw compressor system expensive, both in terms of initial and operating cost. It is usually more expensive than oil injected compressor in a package with multi filtration system.

Delivering compressed air to a manufacturing facility is an expensive operation as it requires expensive equipment that consumes significant amount of electricity and needs frequent maintenance. In spite of this, many users do not know how much their compressed air systems cost on an annual basis, or how much they could save by appropriate selection of the compressor type and system. In a situation, where various compressor types and sizes overlap, one may prove more energy efficient and controllable than the other for a particular duty. Equally, maintenance costs between the different types can vary considerably.

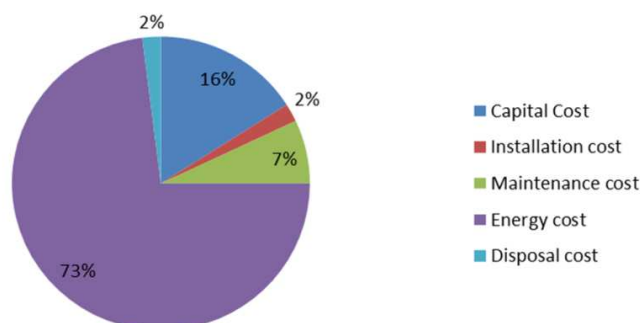


Figure 1 Lifecycle costs of a typical oil free air screw compressor system

A typical break-down of costs associated with a compressor utility over its assumed life cycle of 10 years is shown in Figure 1, as reported in [2].

This paper aims to compare the lifecycle costs of the newly designed water injected screw compressor system with traditional oil free compressor package and oil injected screw compressor in the multi-filtration system. As information for water injected compressors were not available for analysis, a family of water injected compressors was designed. A prototype water injected compressor system of 55-75 kW was built and used to check commercial viability of water injected screw compressor systems in the required range of operating conditions.

## 2. Design of the water injected screw compressor system

The water injected compressor systems consist of the specially designed water injected screw compressor driven by the constant speed electric motor. Other elements of the system include separator tank and filter, fan assisted air water cooler, air dryer and the control system. The layout of this new system is shown in Figure 2.

Table 1 Size of screw compressor blocks for water injected compressor systems

Power Range [kW]	Male rotor Diameter [mm]	Female rotor Diameter [mm]	L/D ratio
15-22	102	80	1.55
30-45	159	125	1.55
45-75	159	125	1.88
75-110	225	175	1.55
132-200	284	220	1.55
250-315	310	275	1.55

Six sizes of the water injected compressor systems were designed in the power range of 15 to 315 kW. The critical components of the system, the air compressors, are designed with “N” rotor profile [4], lobe combinations 4/5, length to diameter ratios 1.55 and 1.88, built in volume ratio 4.5 and tip speed range between 10 and 32 m/sec. Some of previous designs using similar configurations are given in [5]. At a constant prime mover speed sets of gears with different gear ratios are used to vary the male rotor speed. The selected screw compressor sizes are shown in Table 1.

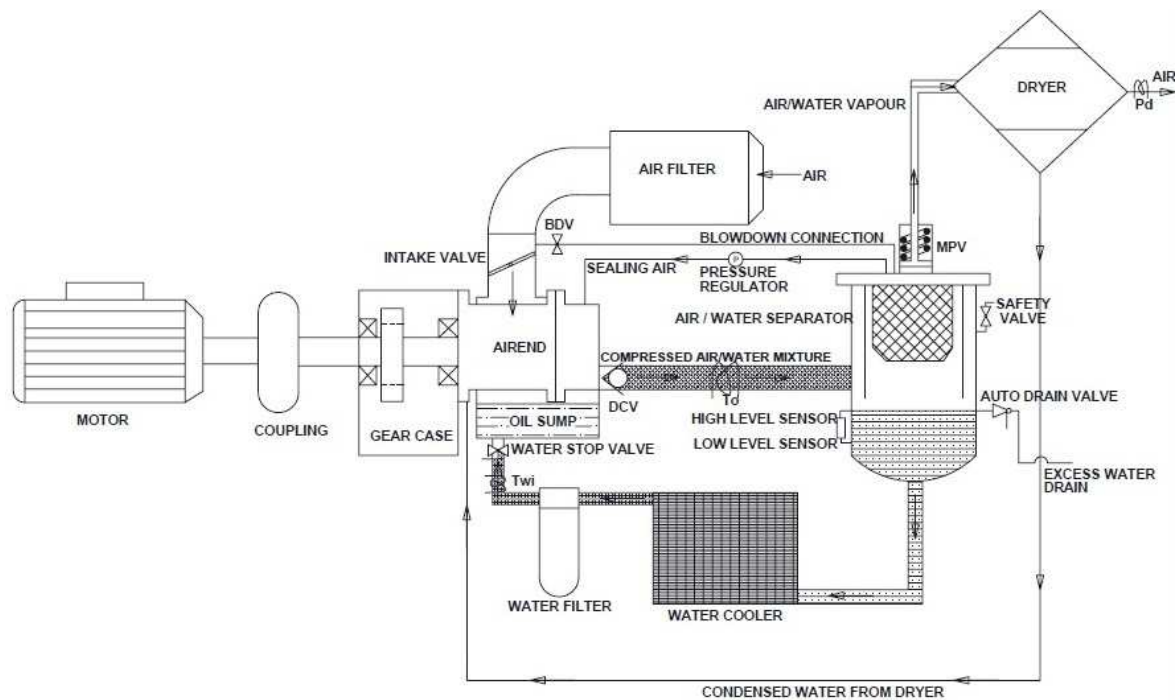


Figure 2 Water Injected compressor system lay-out

Other compressor system components were selected or designed considering the flow, power and performance requirements. The presence of water is associated with scaling & corrosion of materials and causes their deterioration. Hence, due consideration was given for their selection to prevent corrosion at the same time to avoid excessive costs. The special attention is given to water treatment. Water quality was maintained by the use of treated water in the loop. Corrosion was avoided by providing a special corrosion free coating on the parts that are exposed to water e.g rotors, housings tank, pipes etc. A stainless steel water filter was also provided in the water circuit for ensuring the purity of water entering the compression chamber.

The challenge of poor lubricity of water compared to oil for driving rotors in compression chamber is handled by using a time gear set that synchronizes the rotation of male and female rotors. An integrated oil sump was provided within the air end for lubricating the bearings and timing gears. The method of splash lubrication is used to lubricate the gears and bearings; this eliminates the need of a dedicated oil circuit. The cold water returning from the water cooler is used to remove the heat generated in the oil. A sealing system comprising of a combination of viscos-seals and floating carbon seals is used to prevent the mixing of water from the compression chamber with the oil from the gear and bearing chambers.

### 3. Analysis of lifecycle costs for different compressor systems

The lifecycle costs of the compressor system include initial capital expenditure, operating cost of energy used to drive the system, maintenance costs and disposal costs. The disposal costs are assumed equal for all evaluated compressors systems and therefore not elaborated further. The costs are based on modelling of the performance and independent audit reports on global manufacturing competitive index [6], [7], [8].

#### 3.1. Initial costs

The initial cost of a compressor system is related to the required flow or power rating but is highly influenced by the type of compressor system. The logistics of the manufacturing location, transportation, installation etc. also influence the compressor initial cost.

The Initial costs (purchase prices) of oil free and oil injected compressors of various manufacturers were collected from the respective users of these compressors. The data was collected from users in seven countries including India, China, Indonesia, Germany, Italy, Brazil and the USA. The Initial costs (purchase price) of water injected compressors were estimated considering manufacturing costs of the designed compressor components made by the author and corrected to global manufacturing costs considering manufacturing index. Overheads, profits averaged by several compressor system manufacturers were considered for initial cost estimation..

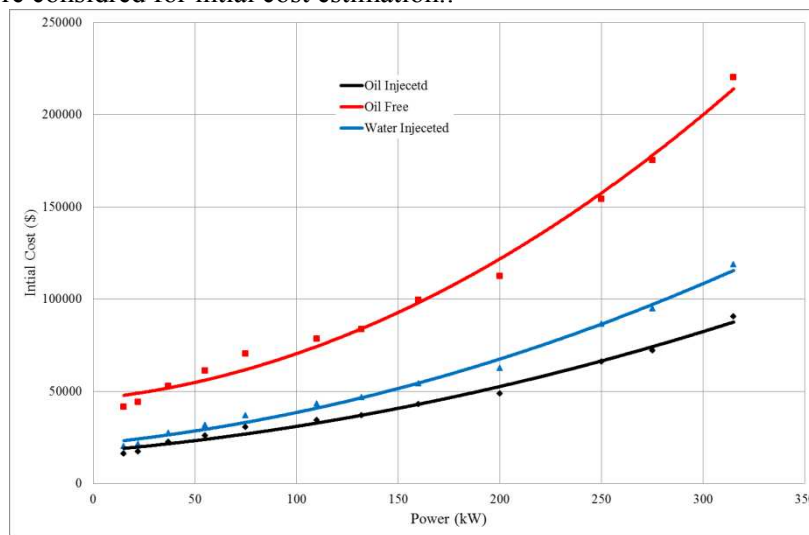


Figure 3 Comparison of average initial costs of three compressor system types

The average initial costs (purchase prices) of conventional oil free, oil injected compressors of various manufacturers at different parts of the World along with the estimated selling prices of water injected compressors in the power range of 15 to 315 kW were represented in graphical format in Figure 3. In order to show the relative comparison of costs for different compressor systems, costs for future analysis will be normalised to the relevant costs of the oil injected compressor system. The normalised initial costs for the range of considered compressor systems are shown in Figure 4.

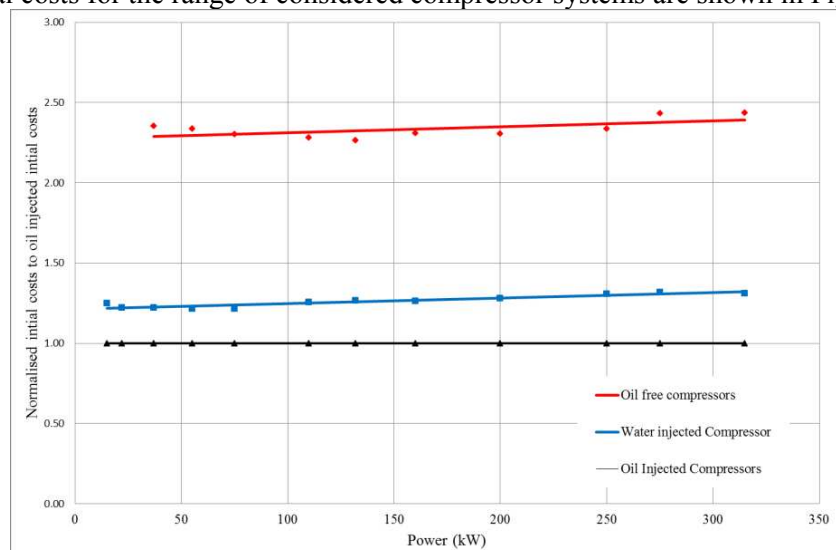


Figure 4 Normalised initial costs of the screw compressor systems.

The initial costs of water injected screw compressor system is 20-30% higher than the oil injected compressor system due to the additional costs associated with materials and surface coatings

employed to prevent corrosion resistance. Oil free compressor systems have the highest initial costs due to the two stage configuration required for this pressure range, internal timing gears, gearbox, inter cooler and after cooler.

### 3.2. Maintenance costs

The cost of maintenance accounts for cost of parts which need to be changed at specified intervals and the cost of labour. It depends on the number of consumables, their service life and their cost. For oil injected and oil free compressors, consumable costs were based on the recommendations of several manufacturers for maintenance of their systems. For water injected compressors, the consumable cost is based on the expected life and the type of consumables. The cost of consumables is estimated by averaging quotes received from manufacturers of those parts.

Figure 5 shows the comparison of the maintenance costs in the power range between 15 to 315 kW for of all three types of compressor systems. The maintenance of oil injected compressor system will cost almost twice the maintenance of other two systems with water injected system being marginally more expensive than the oil free system.

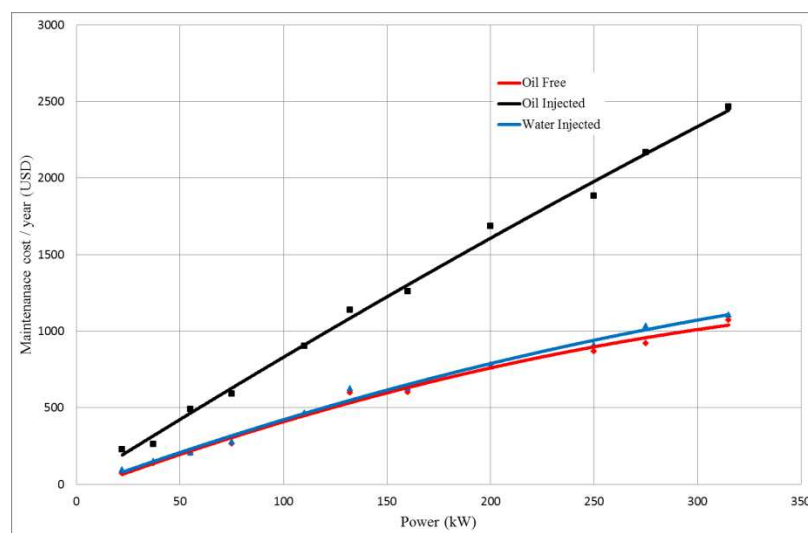


Figure 5 Estimated annual maintenance cost for different types of compressor systems

### 3.3. Operating costs

The operating cost of a screw compressor system is measured through the cost of electricity for operating the compressor in order to meet the user requirements. This includes the power required for the compressor and auxiliary devices inside a compressor system like the oil pump, air cooler fan, water cooler pump etc. The operating costs were calculated in the load and unload mode of operation and considering various cycles of load and unload which depend on the capacity of installed compressor system and the plant requirement for the compressed air.

The operating costs were calculated for three application cycles; 1) Full load, 2) Part load of 70% operation and 30% unload which is most commonly used in sizing of the system and 3) Part load of 30% operation and 70% unload which reflects emergency situations. These three modes are commonly accepted compressor application cycles in manufacturing industries [4]. The average number of hours in operation annually is assumed to be 5000. The assumed cost of electricity is 0.1 \$/kW

The power consumption depends on the performance of the installed screw compressor system. The performance of the designed family of water injected compressor system in the power range of 15 to 315 kW was estimated using well established proprietary software suite for thermodynamic modelling of screw compressors, SCORPATH [4] developed at City University London. The performances aspects of the existing oil free and oil injected compressor systems in the same power

range are established by collecting published data from various manufactures of these compressor systems and averaging them. The performance of all three considered compressor systems is shown in diagrams in Figure 6 and Figure 7.

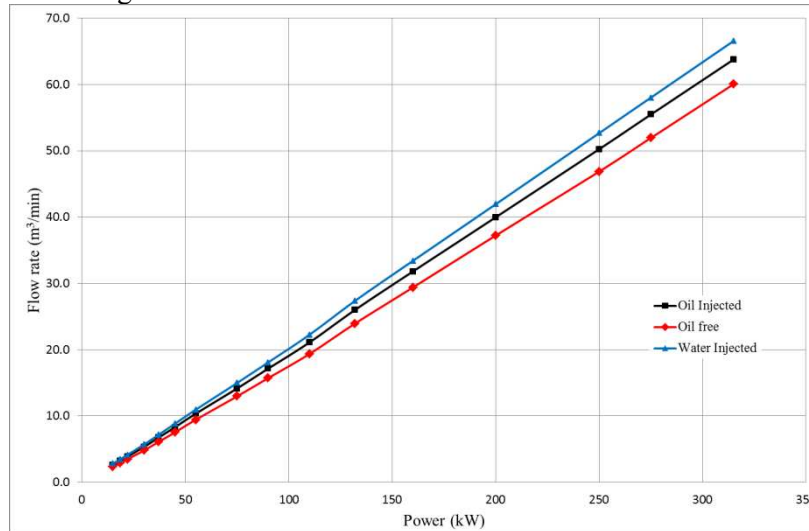


Figure 6 Average specific power of considered compressor systems at 7 barg discharge

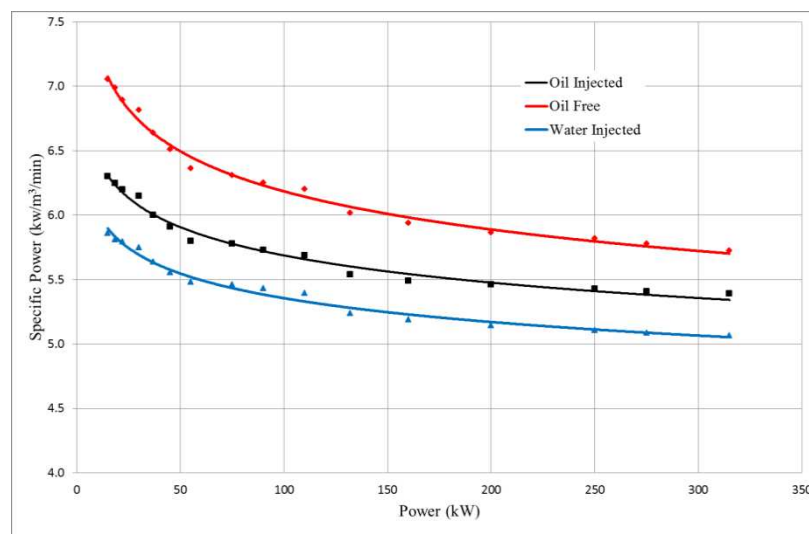


Figure 7 Averaged specific power of considered compressor systems at 7 barg discharge

The comparison of operating costs for the considered compressor systems at full load is shown in Figure 8. The operating power costs of water injected compressor systems are 5% and 15% lower than oil injected and oil free systems respectively in full load operation. The data indicates that the operating power cost trend follows the efficiency of the compressor type. As shown in the normalised operation cost diagram, Figure 9, this trend remains the same during the compressor operation in 70-30 mode. In the 30-70 application cycle, the operating costs of water injected compressor system are 10% lower than both, the oil injected and oil free compressor systems. This reduction is mainly due to the lower unloading power of the water injected compressor systems than that of the other two types.



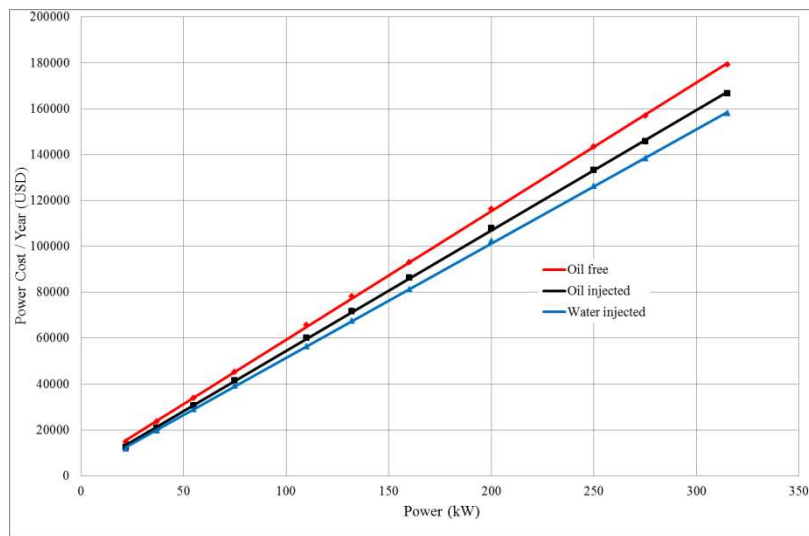


Figure 8 Operating annual power costs at full load and 7 barg discharge

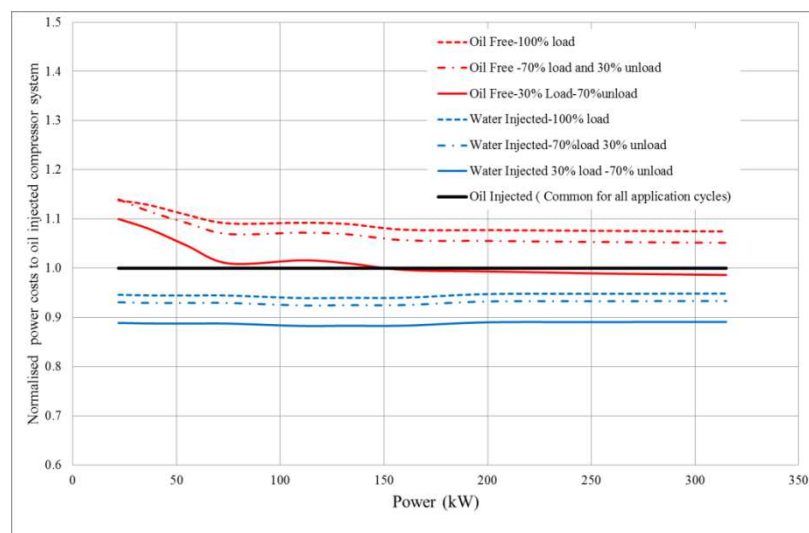


Figure 9 Operating costs of the considered compressor systems normalised to the oil injected system

### 3.4. Lifecycle costs

The lifecycle costs analysis takes into account the total fixed and variable costs of installing, maintaining and operating a compressed air system over its useful life. In this study, the lifecycle costs are calculated for 5 years operation and normalised to the cost of the oil injected screw compressor system. Full details on the analysis of the lifecycle costs are presented in [3].

The initial and lifecycle costs of water injected compressor system are significantly lower than the oil free compressor systems, Figure 10. For applications where oil injected compressor systems are not an option due to the high quality air requirements, water injected compressor systems would be better choice than oil free systems. The users get immediate benefit on cost during the purchase of water injected compressor system compared to oil free compressor system and even higher benefit on the long term use.

The initial cost of water injected compressor systems is higher than the oil injected compressor systems with multistage filtration; however, the life cycle cost of water injected compressors is lower up to 7%. The highest benefit is achieved for the 30-70 cycle. An average payback period for water

injected compressor systems will be less than 3 years in the power range of 55 to 315 kW, and between 4 to 5 years in the power range of 22 to 37 kW.

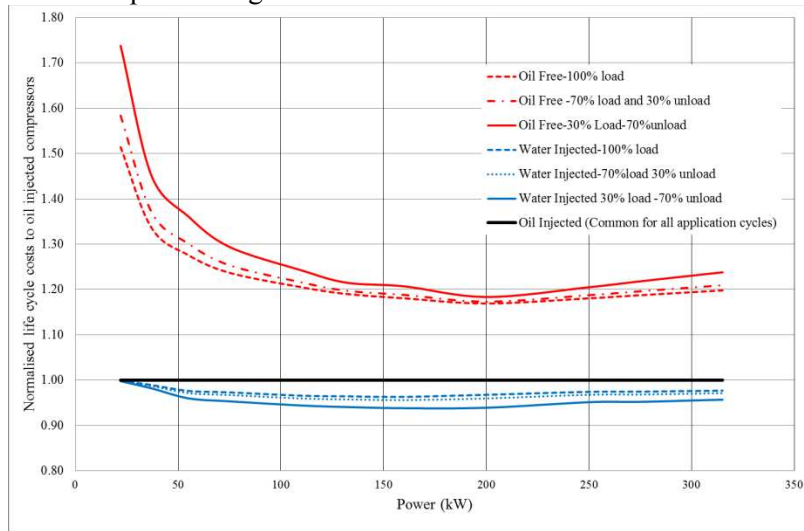


Figure 10 Normalized lifecycle costs of considered compressor systems to the oil injected system

**4. Validation**

*4.1. Performance measurement*

To validate the performance predictions, establish elements of the lifecycle costs and to examine reliability aspects of the material and components, a prototype of the water injected compressor in the power range of 55 to 75 kW was built. The prototype was tested over 1500 hours in order to obtain performance and to observe any potential performance deterioration and reliability issue over time, Figure 11.

The initial cost of the water injected prototype system was established and compared with the estimates made as part of the study.

The operating cost of a screw compressor is estimated through the cost of power which is related to performance. This also includes the power consumption of auxiliary devices inside a compressor plant like the oil pump, air cooler fan, water cooler pump etc.



Figure 11 Water injected compressor prototype under testing

Table 2 Measured performance and associated costs of operation at 7 barg discharge pressure

Compressor Power [kW]	Actual flow rate [m <sup>3</sup> /min]	Total Power Full load [KW]	Total power Unloaded [kW]	Operating costs [€]		
				full load	load/unload 70-30%	load/unload 30-70%
55	9.52	56.1	11.2	28050	21315	12335
75	12.86	77.5	15.4	38750	29435	17015

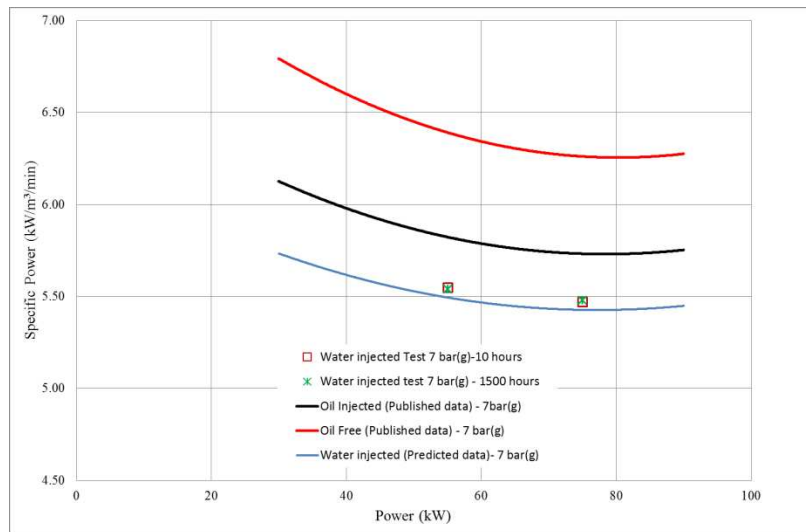


Figure 12 Comparison of measured and estimated specific power at 7 barg

The measurements showed that measured flow rates and powers for both compressors and both measured discharge pressures of 7 and 10 bar(g) did not change after 1500 hours of operation. Measured performance and associated costs are shown in Table 2 and Figure 12.

4.2. Initial and operating costs

The cost of building the prototype of water injected screw compressor system was compared with the estimates made earlier. The actual cost of the prototype was 9 % higher for the 55 kW and 11% higher than the estimated cost of the 75kW prototype. Since these two models were built on a common platform, the compressor components were specified such that all the components other than electric motor and drive gear sets are same for both 55kW and 75kW models. The production costs are recalculated based on the experience with building the prototype. The volume production will see the investment costs reduce 1-2% compared to the estimated value.

Since the performance of the prototype was within 2% of the estimated values and the operating costs of the measured compressor will be within the same deviation range to the estimated costs, the calculation model for operating costs is validated for the 55-75 kW water injected screw compressor system.

4.3. Reliability Aspects

The performance and reliability of the water injected compressor system was tested for 1500 hours of operation. The tests were performed in full load mode for 500 hours and 70% load and 30% unload mode for next 500 hours and then returned to full load mode and tested up to 1500 hours.

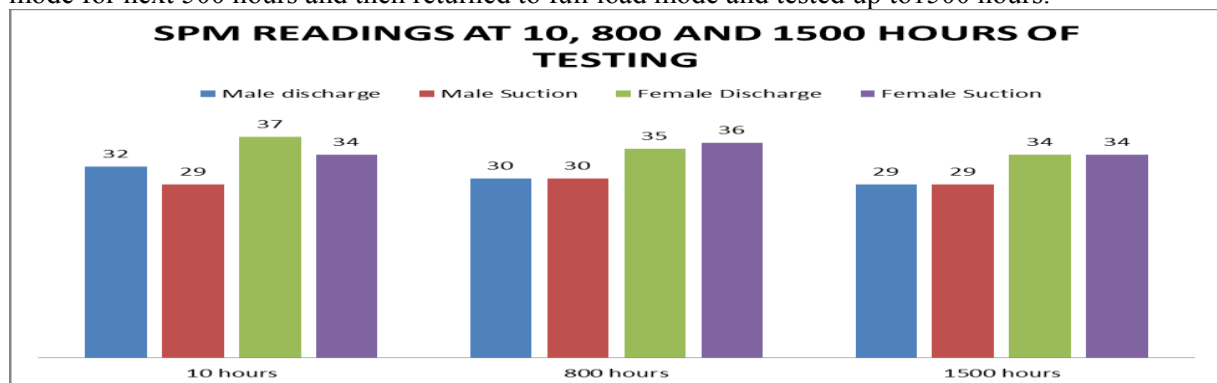


Figure 13 SPM (dBC) readings at 10, 800 and 1500 hours of operation

The compressor showed stable operation during this time. The measurements of bearing performance, seal performance and coating performance were taken at 10, 800 and 1500 hours of operations.

The bearing performance is normally determined by the shock pulse measurement (SPM). The increase in SPM by 15 units from the initial value is considered as the deterioration of bearings. The details of shock pulse meter (SPM) maximum readings (dBm) are shown in Figure 13. No visible increase in SPM was registered during the test.

The compressor housings, rotors, water separator tank and pipes, were coated with recommended coating and monitored during the endurance test of water injected system prototype. At the end of 1500 hours these were visually inspected. No visible signs of corrosion are noticed. The recommended coatings can provide reliable solution to prevent corrosion in the water injected compressor systems.

## 5. CONCLUSIONS

The study was carried out in order to identify the range of economically optimal water injected screw compressor systems considering performance, reliability and costs for industries requiring oil free air.

The performance and economic aspects including initial and lifecycle costs of oil free and oil injected screw compressors in the power range of 15 to 315 kW were established based on the data available from various manufacturers of these compressors. A family of water injected compressor system in the power range of 15 to 315 kW was designed. The performance and economic aspects of the newly designed water injected compressor system were estimated and compared with the established performance aspects of oil injected and oil free screw compressors.

Although the initial costs of the water injected screw compressors system are 20% higher than oil injected compressor, its operating costs over the period of 5 years are up to 11% lower depending upon the operation mode. Therefore lifecycle costs of the water injected compressor system are 5-7% lower than the oil injected compressor system and 25% lower than for the oil free system. The water injected system provides air completely free of oil.

Return on investment for water injected compressor systems in the power range of 55-315 kW is 2 to 3 years. Beyond this power, the break-even point is around 4 years.

The prototype of 55 to 75 kW power range was manufactured and tested over 1500 hours to validate the performance, reliability and economic aspects of water injected compressors. The testing confirmed estimated values.

Based on these findings it has been shown that water injected screw compressor systems are economically viable and reliable. These could become preferred option for delivering oil free air.

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