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 approaches 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.

Keywords: Water injected screw compressor, lifecycle costs, value proposition.

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 m3 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 the use of air in class 1. It is expected that in the future the legislative limits of oil contamination in the air will lower. Typically, industrial air systems operate at pressures of 6-10 bar in the 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 better quality air but it requires a 2-stage oil-free compressor, intercooler, 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 costs. It is usually more expensive than an oil-injected compressor in a package with a multi-filtration system.

Delivering compressed air to a manufacturing facility is an expensive operation as it requires expensive equipment that consumes a significant amount of electricity and needs frequent maintenance. Despite 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.

A typical breakdown 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 the traditional oil-free compressor package and oil-injected screw compressor in the multi-filtration system. As information for water-injected compressors was not available for analysis, a family of water-injected compressors was designed. 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.

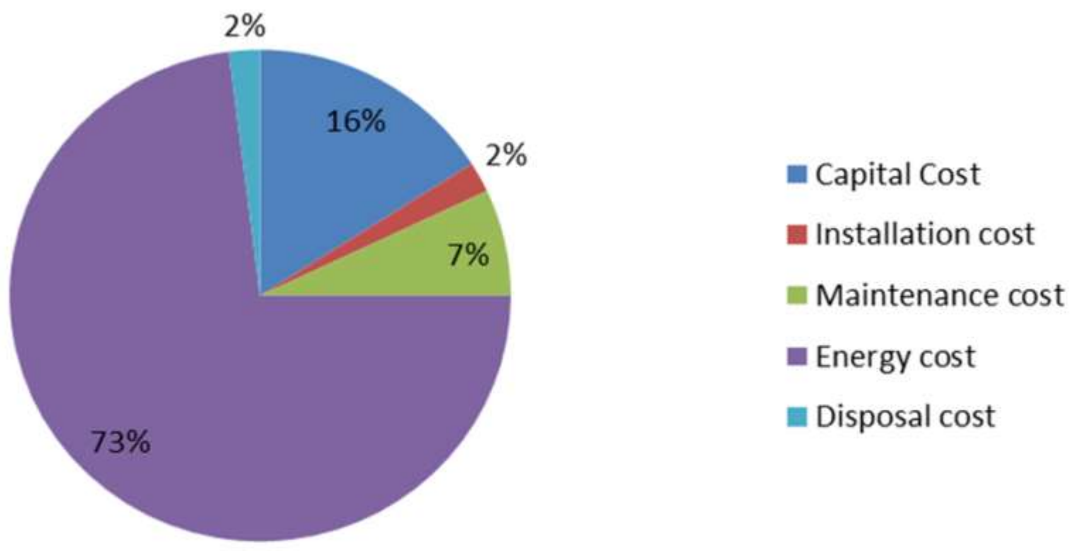

Figure 1. Lifecycle costs of a typical oil-free air screw compressor system

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 a 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.

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 ratios1.55 and 1.88, built-in volume ratio 4.5, and tip speed range between 10 and 32 m/sec. Some of the previous designs using similar configurations are given in [5].

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

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.

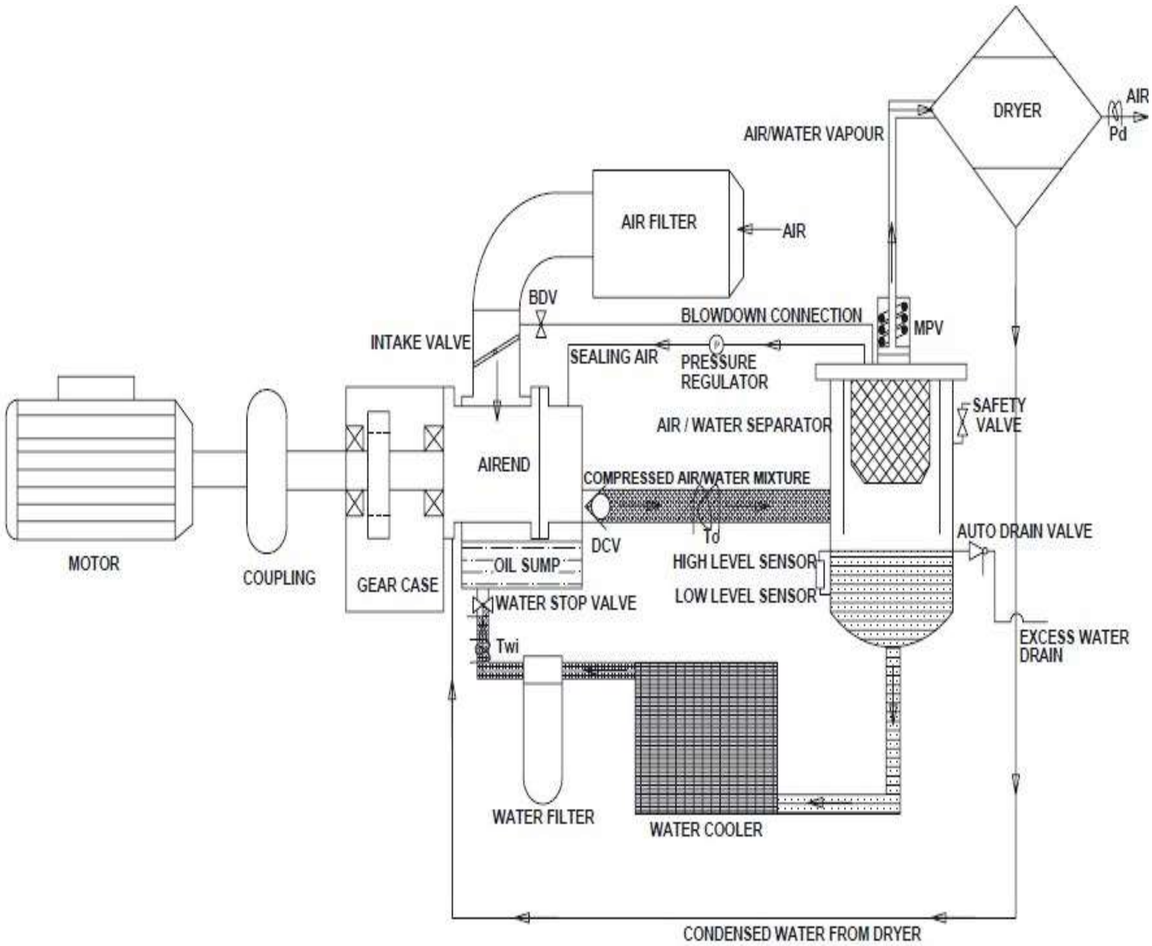

Figure 2. Water Injected compressor system lay-out

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. 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 a 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 for 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 viscous 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 modeling of the performance and independent audit reports on the 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's 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 the manufacturing index. Overheads, profits averaged by several compressor system manufacturers were considered for initial cost estimation.

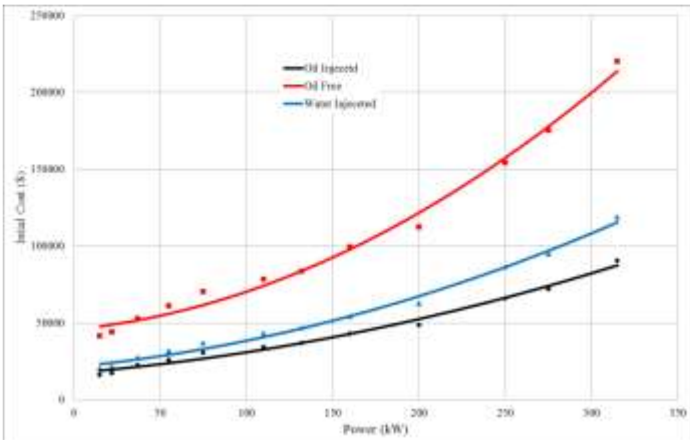

Figure 3. Comparison of average initial costs of three compressor system types

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. To show the relative comparison of costs for different compressor systems, costs for future analysis will be normalized to the relevant costs of the oil-injected compressor system. The normalized initial costs for the range of considered compressor systems are shown in Figure 4.

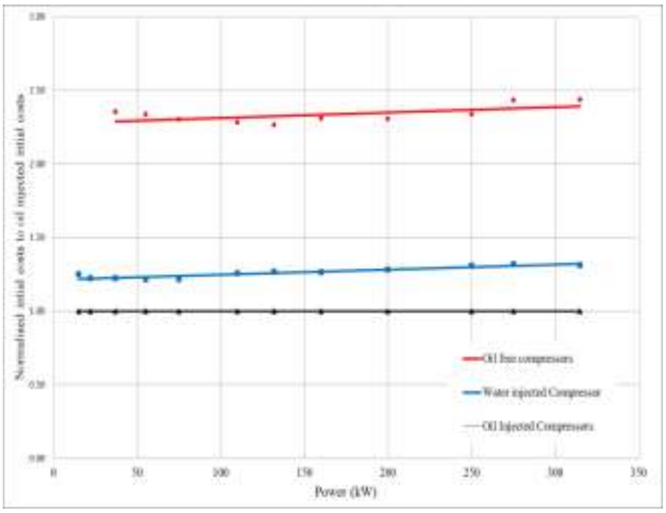

Figure 4. Normalized initial costs of the screw compressor systems.

The initial costs of a water-injected screw compressor system are 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, intercooler, and aftercooler.

3.2. Maintenance costs

The cost of maintenance accounts for the cost of parts that need to be changed at specified intervals and the cost of labor. 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 the 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 all three types of compressor systems. The maintenance of an oil-injected compressor system will cost almost twice the maintenance of the other two systems with water injected system being marginally more expensive than the oil-free system.

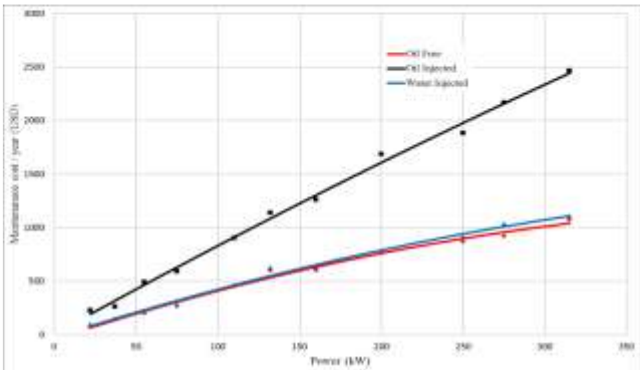

Figure 5. Estimated annual maintenance cost for different types of compressor systems

3.3. Operating costs

The operating cost of a screw compressor system is measured through the cost of electricity for operating the compressor 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 the 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 the sizing of the system and 3) Part load of 30% operation and 70% unload which reflects emergencies. 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 systems in the power range of 15 to 315 kW was estimated using well established proprietary software suite for thermodynamic modeling 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.

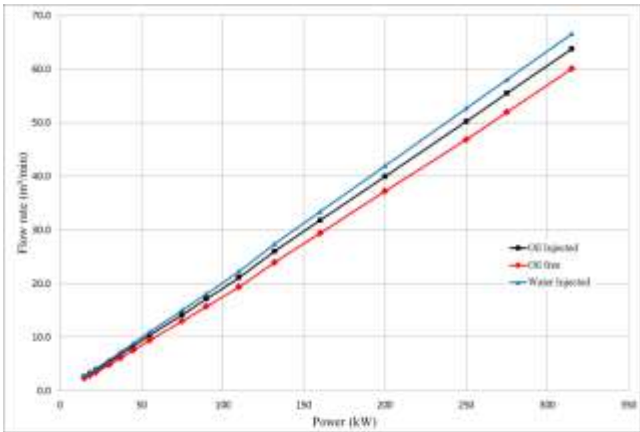

Figure 6. Average specific power of considered compressor systems at 7 barg discharge

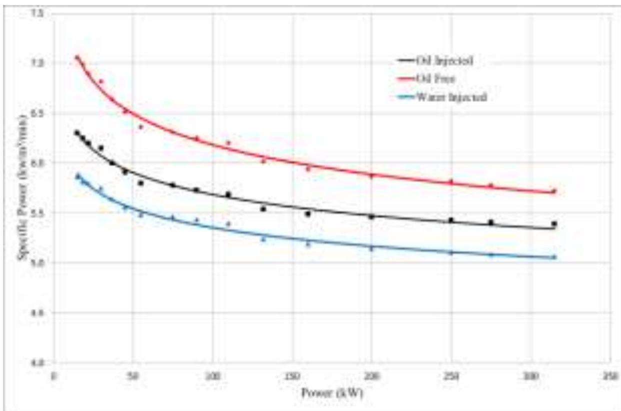

Figure 7. Averaged specific power of considered compressor systems at 7 barg discharge

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 normalized 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.

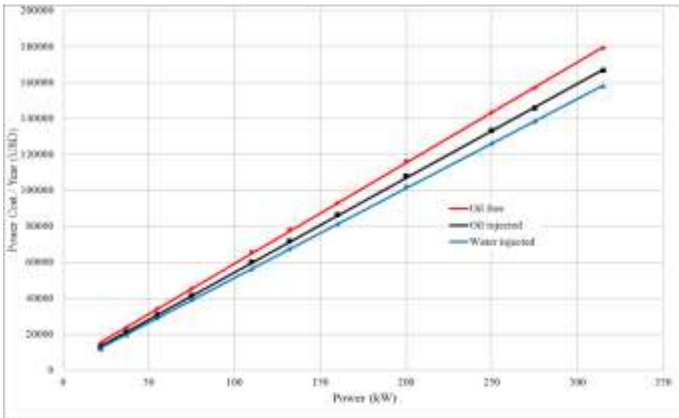

Figure 8. Operating annual power costs at full load and 7 barg discharge

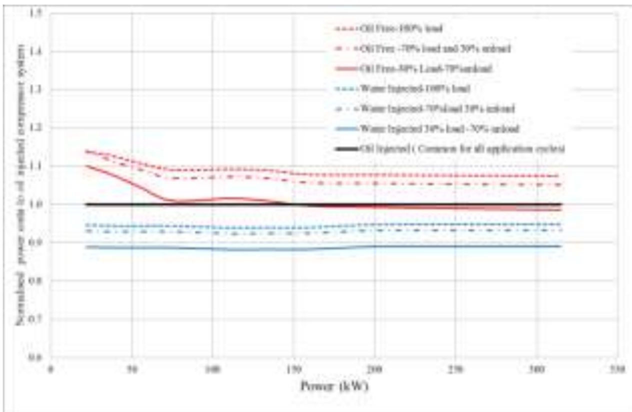

Figure 9. Operating costs of the considered compressor systems normalized to the oil-injected system

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