Trends in tribological behaviour of materials for compressors

Shrey Shaileshbhai Patel¹, M Surjith Shiva¹, Tarun Kataray¹, Divyansh Srivastava¹, Sambuddha Maji¹, Chinmay Kapruan¹, Piyush Pankaj Kumar¹, Bharath Yarram¹, Utkarsh Chadha¹, Senthil Kumaran Selvaraj¹*

¹ Department of manufacturing engineering, school of mechanical engineering (SMEC), Vellore Institute Of Technology(VIT), Vellore, Tamilnadu, India-632014

Senthilkumaranselvaraj82@gmail.com

Abstract. This review accumulates information from various research works about the preferable manufacturing process, process parameters, parts of the compressor, working principle, material, and critical issues with some of the solutions that might be possible in the era of future industry. In addition, some work is also done on the tribological trends in the compressor. In this paper, detailed information has been gathered about the compressor parts and their working principle. A detailed analysis has been done on the material used to manufacture the compressor. Some details have been shared about preventing the loss to the compressor when it is in the application mode. As per this paper, PTFE/MoS2, FC, PEEK/Ceramic materials, mica-filled tetrafluoroethylene are advanced materials used for the compressor. Protective layers can be made on the parts to prevent some functional loss. Numerous studies have brought about great advancements in compressor performance, but many remain to be discovered. With n-TiO2 and n-MnO2, ZDDP (zinc disulfide) should be increased for antifriction properties. Some research has proven that CO₂ can improve the tribological performance of two interacting surfaces by forming a lubricating carbonate layer that reduces friction and wears. New lubricating oils are showing promising results, but with the gradual depletion of natural oil resources, efforts have to be made to make various oils obtained from sources other than oil reserves or petroleum. A completely oil-free compressor with no lubrication in the crankcase and no lubrication in the other components dry oil-free air supply may be accomplished by employing various oil-less compressor technologies such as scroll water-injected screw, two-stage dry screw, and so on. In the 21st century, it aims to maximize energy savings from air compressors. It is critical to operating at a compression level that matches the amount of air consumption (optimal volume) and to avoid operating at a compression level that is greater than necessary. The conclusion can be obtained that understanding for the compressor will be established, and some tribological issues will be solved with new technology and material.
1. Introduction

Compressors are widely used today in numerous refrigeration, air-conditioning systems, automobile and aircraft engines, etc. Since their inception, the demand for compressors for use in numerous industrial and domestic applications has grown rapidly. This rapid growth came with more efficient and advanced compressor designs ranging from a simple household air conditioner to a large jet aircraft. In this paper, some topics are dealt with by studying and analyzing various advanced materials to design more efficient compressors. The study of various materials' effects on the tribological characteristics of different compressors working under various refrigerants. Authors have also analyzed the effect on tribological characteristics when the refrigerant itself is changed. Comparisons have been made between materials like various polymer blends, lubricants, coatings, and commercially available refrigerants to determine the most suitable materials that can help produce an efficient working compressor design. Some papers have underlined the change in materials that can be made to existing compressors and have simulated the working parameters of those compressors under commonly used refrigerants like R134a. Polymer blends like ATSP with PTFE or various coatings of varying layer thicknesses were tested in many papers. The manufacturing of bio-lubricants to replace existing lubricants was also proposed. Papers also performed tribological tests on various new and existing refrigerants to determine the effects of the refrigerant on a compressor’s efficiency and tribology. HFCs, HCFCs, CO₂, etc., were compared against each other to figure out which refrigerant gave the best tribological characteristics while causing very little or no harm at all. In this paper, every suitable material’s tribological effect on the compressor’s working and have analyzed all the data to propose the most suitable materials for an efficient compressor design.

2. Understanding Compressors

A compressor is a machine that compresses the air supplied to it, increasing the temperature and pressure of air. As a result, a rise in temperature and pressure can occasionally cause issues if proper material is not used. So, the selection of material to manufacture the compressor is very important. Different types of materials used in the compressors are listed in Table 1. Figure 1 shows the Hermetically sealed compressor (a) and its Section View (b). The material should be hardened since the strength of the material is essential for the compressor’s operation. According to the literature survey, nanotechnology may be utilized since nanomaterials have extraordinary strength. The electro erosion alloying process, in which the hardness of the material is enhanced by electrical current, can be used to harden the material. This multifunctional technology delivers numerous benefits such as surface hardening, a protective layer, and machine component repair [1]. However, this does not imply that this procedure can be used for all of the compressor’s parts because some are heat-treated, and this method fails on heat-treated parts.

Consequently, carburizing and nitriding can be performed following the electro erosion process. There are several materials available that can tolerate these specific qualities. Furthermore, at greater temperatures, some materials corrode. To preserve the material, a film (thin protective layer) must be formed around the material utilized in the compressor. Certain effective coatings are commonly utilized. The coating material here is also determined by the refrigerant used in the compressor.
Figure 1(a). Hermetic sealed compressor

Figure 1(b). Hermetically sealed compressor-Section view

Table 1. Parts of the compressor and its significance

| Name of the part of the compressor | Description                                                                 |
|-----------------------------------|-----------------------------------------------------------------------------|
| Piston                            | It will move in the straight line (up-down)                                 |
| Crankshaft                        | It will help to transfer the power to the compressor from the source.       |
| Rotor                             | It will rotate on its axis at a very high speed.                            |
| Bearing                           | It will help to support the rotor.                                         |
| Lubrication Oil                   | It will reduce the friction between moving parts                           |
| Accumulator                       | It will make the gases clean so that they cannot affect the parts of the compressor. |
| Valve                             | It will let the gas in and let it out of the compressor under certain condition |
2.1. Working principle of compressor

There are three types of compressors, each of which performs the same function but with different components [2]. These include 1) Reciprocating type compressors, 2) Scotch-York type compressors, and 3) Connecting rod type compressors. The compressor is the machine that compresses the supplied fluid. Filling the cylinder with air and compressing it with the piston is known as air compression. Because of the air's compression, the air's pressure will rise, and according to gas laws, the rise in pressure will raise the temperature of the air. As a result, after passing through the compressor, the air will be highly pressurized and hot [3]. For the gas, pressure is exactly proportional to temperature. As a result, increasing the pressure raises the temperature. Several types of compressors are available, each of which is specifically intended to achieve a certain goal. The piston-cylinder mechanism can be used to power a compressor. As air is delivered into the cylinder through the inlet, the inlet is closed, the piston compresses the air, increasing the pressure, and the discharge valve is opened to allow the compressed air to exit. As a result, the compressed air will be continuously discharged from the compressor, as several pistons can be fitted.

2.2. Types of compressors

2.2.1 Rotary screw compressor (RSC) It is a revolving device that compresses gas by alternating one or more screw compressors, where the threads of one compressor contact the slits of another through which it travels [4]. A rotary-screw compressor is a type of gas compressor that uses a spinning positive-displacement action. Gas enters an RSC by a high-pressure port and spirals down along a tight helical channel produced by protrusions on the shaft of a screw. Before departing, it spirals back up to acquire more gas from a low-pressure side branch. This method allows for good heat transmission between the pressure and vacuum sides and high compression ratios [5]. These compressors are commonly employed in industrial applications that require more compressed gas power, such as massive refrigeration cycles such as cooling systems or compressor systems to power air-driven equipment such as jackhammers and impact wrenches [6].

2.2.2 Reciprocating air compressor Reciprocating air compressors work on the idea of reciprocation, which means they move stuff back and forth. These devices, sometimes known as piston compressors, appear to be positive displacement compressors, which implies that they raise air pressure to compress it. The operating concept of a Reciprocating Compressor is described in Table 2. The Pathway of a Reciprocating Compressor is depicted [7]. A reciprocating compressor is a positive-displacement compressor that compresses air with the help of a piston and cylinder propelled by a crankshaft. A tiny piston compresses the air to a pressure of up to 175 PSI in the second stage of the two-stage compressor [8].

2.2.3 Axial compressor It is a rotating compressor with an airfoil, the working fluid or gas flows axially, or parallel to the rotational axis. Centrifugal, mixed-flow, and axi-centrifugal compressors include a "radial component" that runs throughout the moving fluid. The fluid's energy level rises as it travels through the compressor due to the torque exerted by the rotor blades. The fluid is slowed by stationary blades, turning circumferential motion into pressure [9]. Dynamic compressors include axial compressors. Dynamic compressors, unlike displacement compressors, operate at constant pressure and are impacted by changes in external factors such as inlet temperature. In these compressors, axial flow is employed, which means that the air or gas travels between rows of spinning and stationary blades as it goes down the compressor shaft. A balancing drum compensates for the axial force produced by the blades when they convert kinetic energy to pressure.

2.2.4 Centrifugal compressors This mechanical device compresses fluid by applying the impeller's radial acceleration, which is contained within the compressor housing. Air or gas enters the impeller
axially and exits radially in a centrifugal compressor. The impeller of a centrifugal compressor converts the kinetic energy of the working fluid (gas or air) into speed, increasing the working fluid's speed (gas or air). The speed of the air or gas is subsequently converted into pressure energy via the diffuser. Radial centrifugal compressors have a higher high-pressure ratio than axial compressors at low flow rates [10,11].

![Diagram of Types of Compressors]

**Figure 2.** Classification of compressors

### 3 Tribological Challenges in Compressor & Material Characterization

#### 3.1 Solutions for the better efficiency of the compressor

Besides using any particular material for the compressor, it is necessary to provide a certain amount of lubricating oil. 2 main internal fluids should be specific as they can create problems from the inner side of the compressor [1]. (1) Lubricating oil (2) Refrigerant gas. The oil is the fluid that is in direct contact with the compressor, so it should have certain properties for the long life of the compressor. It should have a very high oxidation resistance. The compressor should not attend its boiling temperature and the freezing temperature. As if the freezing temperature of the oil is achieved, then it will be converted into the solid form, which is not useful for lubrication, and if the boiling temperature is attained, then the oil will form a gaseous form which may interact with the refrigerant gases and form undesired product inside the compressor. The oil should not be a carbon collector as it can increase the tendency of the carbon deposition inside. Also, the fluid used inside should be an inert gas [1]. according to the characteristics, POE can provide one of the best lubrications in acidic form. It is an acid catcher as well as an anti-oxidant [3].

Refrigerant gas should be chemically and physically inert in properties. The situation should be produced in which no rapid evaporation of refrigerant should occur. Appropriate installation of the compressor and its parts are necessary for the better efficiency of refrigerant gases [1]. Electro-erosion alloying is one of the most admirable multipurpose solutions. It will provide the 3 most recommended benefits under its use [12]. (1) Protective layer (2) Surface hardening (3) Restoration of the parts
for the heat-treated parts, electro-erosion alloying will not show the desired outputs. As per the record, it should be less hardened, but because of this alloy, it will be more hardened, which results in a high amount of wear, so it is compulsory to use iron-nitriding for these parts. For providing high smoothness to the parts, electro-erosion with carburizing will make the layer of carbon on the part. Sulphuring is also a good option for making a protective layer against scratches [12]. According to the wear property, stainless steel and Ni-Cr steel have less wear property, but the combination of these two metals will result in alloy with maximum wear property. Only in the acidic medium of Al-Si alloy with FC [3]. Clogging inside the capillary tube is a problem that should be addressed. It happens due to some chemicals released from molded parts, lubrication oil, parts wearing, etc [3]. One of the most commonly used materials in the compressor is mica-filled tetrafluoroethylene. There are 2 types of seals. (1) Abradable seals (2) Non-abradable seals.

There will be some problems at working temperature as temperature differences will occur, resulting in the expansion and contraction of the material of the parts, which will change the dimensions of the parts and can result in leakage. This will change the flow rate of gas inside the compressor. So, more work is to be done which will reduce the efficiency of the compressor [2]. Abradable seals reduce clearances and limit the risk of damage to the rotating or stationary member. Labyrinth seals have been replaced by honeycomb seals when some rotor instability problems have occurred in high-pressure compressors [13]. The new concept of non-abradable seals was come up, which are made up of soft material and the stainless steel manufactures the teeth so at one instinct the deformation in the teeth will occur. For overcoming the problems that occurred in the seals, the given material in table 2, can be used.

Table 2. Materials used in compressor

| Material name   | Specification                        |
|-----------------|--------------------------------------|
| 1. PTFE         | protective from corrosive gases      |
| 2. Ni-graphite  | good thermal coefficient             |
| 3. Ni-Cr        | high erosion resistance and hardness with non-corrosive |
| 4. Al-Si graphite | corrosion resistance              |
| 5. Silicon rubber | Cant be used for the sprayed coatings, non-corrosive |
| 6. Al-Si polyester | high erosion resistance         |

Nanotechnology can be used to overcome difficulties. It is beneficial to use n-TiO₂ and n-MnO₂ then ZDDP (zinc disulfide, common anti-wear lubricants, and anti-oxidants) for antifriction properties. Abrasion resistance property is high of nano-nickel hydroxide oil. Also, the layer of Lanthanum Borate can be made to reduce frictional behavior. After applying the nanomaterial, it observes a decrease in power consumption, high COP, and high value of cooling capacity [19]. Erosion in the jet engine will negatively affect the compressor blades. It will mostly affect the high-pressure compressor blades as there will be more particle velocity and concentration. Erosion depends on the size and shape of the particle and material used to manufacture the compressor [20].
A polymeric material with a low friction coefficient and high wear resistance is needed for a compressor. PTFE is one of them. It exists in the form of several layers so that its coefficient of friction is very low, and also it has a very low shear strength. For a lower friction coefficient, it is advisable to use PTFE-MoS2 material as the layer on the parts. But its only for the temperature up to its glass transition temperature, which is 179 degrees Celsius as temperature increases from this level, wear resistance starts to decrease, which is not desired. The deposition of the PTFE/MoS2, FC, and PEEK/Ceramic materials can be done for a better experience [21]. The main part of the compressor is the impeller, and the material for it is selected based on the environment in which it is going to be implemented. Generally, it is manufactured by low alloy steel or stainless steel. When the impeller is put inside the environment of Cl2 gas, then Ti or Ti-based alloy is used for the impeller. Carbon steel is used in Compressor casing. The grey cast iron manufactures diaphragms. PEEK with additives and PAI where PAI is in crystalline material, which is a good moisture absorber can be used.

4 Characterization & Analysis

4.1 Advanced Materials Viable for Compressor Design and Manufacturing

Advances in technology and research and the materials used in compressors, both industrial and commercial, have gone a long way. There are several articles available today that discuss a variety of materials that may be utilized in the manufacture of compressors to boost performance and considerably improve their tribological features.

Lototskyy, M. et al. (2019) [1] investigated a few metal hydrides producing compounds that may be utilized to construct a 1-stage and a 3-stage compressor capable of compressing hydrogen effectively. The pressure-composition isotherms for hydrogen absorption and desorption of LaNiSn0.1, La0.08Ce0.02Ni5, and C14-Ti0.65Zr0.35(Mn, Cr, Fe, Ni)2+x were studied. It was discovered that in a metal hydride container made of LaNiSn0.1, hydrogen absorption begins when the metal hydride's temperature drops below 90 °C and accelerates beyond 4 m3/h. At a pressure of around 15 bar and a temperature of 100 °C, hydrogen desorption begins. In 90 minutes, about 2.0 Nm3 of H2 was absorbed, and nearly 1.9 Nm3 of the gas was desorbed in an hour. LaNiSn0.1, La0.08Ce0.02Ni5, and C14-Ti0.65Zr0.35(Mn, Cr, Fe, Ni)2+x may be effectively employed to create a three-stage compressor with pressures of 3-20 bar (1st stage), 20-50 bar (2nd stage), and 50-200 bar (3rd stage). The first stage of
the compressor was made of LaNiSn$_{0.1}$, the second stage was made of La$_{0.8}$Ce$_{0.2}$Ni$_5$, and the final stage of the compressor was made of C14- Ti$_{0.65}$Zr$_{0.35}$(Mn, Cr, Fe, Ni)$_{2+x}$, which could efficiently compress hydrogen at a pressure of 200 bar.

Vithya, P. et al. (2019) [12] investigated the tribological properties of a biodegradable rapeseed oil-based trimethylolpropane tri ester, which may be utilized to replace existing crude or Polyalkylene Glycol (PAG) oils as a cylinder liner/piston ring material for hermetically sealed compressors. They discovered that the rapeseed oil bio lubricant showed thermo-oxidative stability and successfully decreased the coefficient of friction by 20% compared to the presently utilized PAG and crude oils. The use of oxide-based nanoparticles in refrigerant compressor oils, on the other hand, can assist enhance the tribological performance of current Polyalkylene Glycol (PAG) lubricants. According to Sanukrishna, S.S. et al. (2018) [3], SiO$_2$, TiO$_2$, and Al$_2$O$_3$, SiO$_2$ nanoparticles dispersed in PAG oil obtain the best wear scar and friction reduction. Because SiO$_2$ based nano lubricants have better thermal and rheological properties than standard PAG oils, they may also replace conventional lubricants in HVAC systems and compressors.

The refrigerant used is another essential factor that significantly impacts the tribological performance of compressor components. M. U. Bhutta et al. (2018) [2] investigated the tribological performance of numerous commonly used refrigerants, including HFCs, CFCs, HCFCs, and HFEs. CFCs and HCFCs both have superior tribological qualities than HFCs, but hydro-fluoro olefins proved to be the best for usage in-car air conditioning compressors. HFO-1234yf appears to be the best refrigerant for this application. HFEs, on the other hand, have the finest tribological qualities because they create a protective tribo-film, but their high boiling temperatures prevent them from being used in commercial refrigeration systems.

CO$_2$ can replace common refrigerants (HFCs, CFCs, and HCFCs). CO$_2$ can enhance the tribological performance of two interacting surfaces by forming a lubricating carbonate layer that decreases friction and wears, according to Demas, N. G. et al. (2006) [19]. Under varied working pressures, CO$_2$ outperformed the typical HFC refrigerant R 134a, particularly without lubricants. Instead of replacing the refrigerant, self-lubricating polymer blends can be employed as bearing materials on interacting surfaces. Polycarpou, A. A. et al. (2008) [22] evaluated the tribological properties of different blends of aromatic thermosetting polyester (ATSP) and polytetrafluoroethylene (PTFE) and examined their applicability as coating materials to minimize friction and wear in compressor contact surfaces. ATSP/PTFE 50-50 mix (by composition percent) was deemed the best alternative to replace currently commercially used polymer coatings, as it demonstrated almost
identical but significantly more stable friction co-efficient values throughout the test. In an air conditioning compressor setting, the 50-50 mix also demonstrated a much-reduced wear rate (0.5 x 10-5 mm3/ Nm) even without applying any additional lubricant. However, like Yao, M. S. et al. (2010) [20] discovered, combining ATSP with fluoro-additives resulted in a similar (often even lower) frictional coefficient and a significantly lower wear rate (7.36 x 10-7 mm3/Nm) than normal PTFE or ATSP/PTFE 50-50 blends.

On the other hand, oil-less swashplate compressors can utilize coatings on contacting surfaces to improve compressor performance by allowing tighter tolerances and higher speeds, both of which are not achievable in typical refrigerants (HFC, CFC, HFCFs, etc.) working settings. To prevent scuffing failure in compressors, the use of HFCs and CO2 as refrigerants needs suitable solutions. Coatings come in helpful here because of their excellent friction and wear reduction qualities. A. T. Solzak et al. (2008) [21] simulated the use of CrN + WC/C and TiAlN + WC/C coatings in oil-free swashplate compressors. With a capacity of around 2000N and a friction coefficient of around 0.05, a CrN layer with a WC/C underlayer proved to be the best load carrier. As a result, CrN + WC/C (underlayer) appears to be the ideal coating for improving the performance of oil-free compressors utilizing normal refrigerants.

Micro-textured surfaces on piston rings and other contact surfaces can increase load bearing strength by serving as micro-load bearing structures. Ramesh, A. et al. (2013) [23] investigated this in-depth and discovered that micro-textured surfaces exhibit around 80% reduced friction in a lubricating environment. It also helps maintain a suitable lubricant layer thickness, reducing friction between interacting component surfaces. As a result, the micro-texturing of contact surface rings can reduce friction while boosting the load-bearing capacities of compressor components.

According to several articles that investigate the uses of different novel materials to improve the efficiency of compressors, the use of coating and polymer-bearing materials appears to be the most suited choice for designing compressors with improved performance. ATSP blends significantly increase the tribological performance of air conditioning compressors, whereas CrN + WC/C coatings favor oil-less swashplate compressors. Dispersing SiO2 nanoparticles in regular PAG lubricant also reduces friction and wear significantly. A rapeseed oil tri ester can replace PAG oils and help conserve petroleum resources while enhancing compressor tribological properties. Manufacturers can also use CO2 to replace HFC or HFCF-based refrigerants, adding a helpful carbonate coating that decreases friction on interacting surfaces. Micro-texturing will be very useful when the objective is to enhance load-bearing while decreasing friction because the micro-machined textures work as small load-bearing structures and tend to increase lubricant layer thickness.

4.2 Process Parameters: A Path to Efficient Treatment

Advanced composite materials and coatings have shown promising results in enhancing compressor efficiency. Coatings and polymer layers are the most effective ways to reduce friction and wear at contact surfaces in both oil-based and oil-less compressors [21,22]. When HFC and CO2 are used as refrigerants, these aid in preventing scuffing failure and enhance oil-free compressor operation [8]. In oil-free compressors, CrN + WC/C (underlayer) has previously been shown to be an excellent composite coating material. Chromium nitride (CrN) is a highly hard, corrosion-resistant material with a melting point of 1770 C that is stable enough to keep structure even at high temperatures in a running compressor. WC/C, like CrN, is exceptionally resistant to wear and corrosion. It comprises alternating lamellae of tungsten carbide (WC) and carbon (C). As a result, CrN + WC/C (underlayer) is an ideal choice for improving the performance of oil-less compressors when working at both low and high temperatures and pressures.
Polymer blends, unlike solid coatings, are suitable for all types of compressors and, due to their lubricating properties, reduce friction significantly. ATSP + PTFE (50-50) is a highly effective polymer combination used as bearing and coating materials in compressors [22]. Aside from testing and applying new composite coatings and layers, changing current lubricants can improve performance. When SiO$_2$ nanoparticles are distributed in PAG oil (a current commercially used lubricant), they can lower the friction coefficient by approximately 24% [3]. SiO$_2$ is a mineral abundant all over the world and is stable at high temperatures. As a result, the solution would be inexpensive and economically feasible.

In a lubricated environment, micro-textures on piston or valve surfaces have resulted in considerable friction reductions and improved load-supporting capacities of compressor components because the textures operate as micro-load bearing structures [23]. Machined patterns such as circles and squares can be used on component surfaces, with circles with diameters of 100-120 m producing the lowest coefficients of friction.

Because refrigerant has a big influence on how compressor functions, rather than making structural and material changes, the simplest solution is to alter the present refrigerants utilized. Demas, N. G. et al. (2006) [19] investigated CO$_2$ and found it quite effective. CO$_2$ is easily caught and stored, and it possesses self-lubricating properties by producing a carbonate layer on surfaces with which it comes into contact. This can assist reduce friction and wear to far lower levels than are now produced by HFC and HCFC-based refrigerants. However, due to the high working pressure of a CO$_2$-based compressor, the gas is unsuitable for most commercial applications. Despite being somewhat flammable, HFO-1234yf is the apparent option for car air conditioning, and it may also be used in residential refrigeration and air conditioning applications. HFO-1234yf generates a protective coating that improves tribological performance and interacts more favorably with metals and lubricants [2].

5. Results and Discussions

Compressors are one of the most important mechanical components in the modern world. From carrying out important functions in household air conditioners to powering jet plane engines, compressors have become a part of everyday life. This has led numerous scientists and engineers to study more and more on improving compressor performance. Advanced materials, manufacturing methods, lubricants, and coatings have been studied in great detail, and a lot has been achieved in compressor efficiency and innovation.

Compressors run using a refrigerant. The refrigerant environment directly affects the tribological performance of the compressor, which in turn impacts the overall performance of the compressor itself. Hence, numerous research works have been focused directly on bringing out alternatives to currently used refrigerants. Earlier, CFCs were being used heavily, but since discovering their harmful effects on the environment, the common refrigerant for household applications became HFC-134a. However, there was one serious problem with HFC-134a, it could not effectively mitigate the problem of global warming. As Bhutta, M. U. et al. (2018) [2] investigated, HFCs were replaced with CFCs, and HCFCs were replaced with HFCs, but HFCs did not yield good friction and wear resistance properties under moderate temperature and pressure conditions in a compressor. Hence, the HFCs were phased out, and HC (hydrocarbon) refrigerants with better friction properties were brought into the market. HCs were inflammable, and thus, studies were made to find their replacement. Recently, HFOs (hydro fluoro olefins) have been formulated. HFO-1234yf has shown excellent enhancement of a compressor’s tribological performance as it can form a protective film on interacting surfaces even in the absence of a proper lubricant. Hydrofluoroethers (HFE) has also been studied extensively, and they have proved to be even less flammable than HFO-1234yf.
While their tribological performance is much better than HFCs, the high boiling point of HFEs has rendered them unsuitable for household refrigeration application. A study from Demas, N. G. et al. (2006) [19] analyzed the results possible from using CO2 as a refrigerant rather than the conventional HFCs or HFOs. CO2 showed signs of better friction and wore resistance than HFCs and HFOs even in the absence of lubricants, as it produced a self-lubricating carbonate film on the interacting surfaces. CO2 can also maintain stability under numerous operating pressures and is much more eco-friendly. However, the major problem with CO2 lies in the fact that CO2 has high operating pressure, making it unsuitable for most commercial compressor applications.

Apart from studying the effects of a refrigerant, scientists have made numerous advancements in making composite coatings or polymer blends that can be used with the available refrigerants but still make an effective impact on enhancing the performance of the compressors. Coatings like WC/C or an underlayer of WC/C and a final layer of CrN have been studied extensively. Solzak, A. T. et al. (2008) [21] studied these layers and found their effect on the tribological behaviors of interacting surfaces in a compressor. The coatings reduced friction and improved the load support abilities of the compressors that were tested, hence allowing oil-less operation. These coatings are an important advancement, as the use of HFCs and CO2 as refrigerants require proper protection against scuffing failure [21]. CrN + WC/C reduced the coefficient of friction to as low as 0.05 but still helped the compressor maintain a 2000N load-bearing ability. These coatings generally come in handy when used in oil-less swash plate compressors. The coatings tend to maintain their tribological performance even in the absence of lubricating oil, and thus, they can be effectively used in oil-less compressors and an HFC or CO2 environment.

Polycarpou, A. A. et al. (2008) [22] made a great advancement in the field of polymers that can be used to make compressor components. Their study found out that ATSP + PTFE (50-50 by composition) acts as an excellent bearing material and a great coating material. This blend showed a wear rate of 0.5 x 10^-5 mm3/N·m without any lubricant in an air conditioning compressor. Yao, M. S. et al. (2010) added in on the topic and studied the addition of fluoro additives ATSP. ATSP blended with fluoro additives yielded even better results than ATSP-PTFE blends. The fluoro additive ATSP blend had a very low wear rate of 7.36 x 10^-7 mm3/N·m, and it maintained almost similar frictional properties [20].

Some researchers have also studied micro-machining to put micro-textures on compressor component surfaces. Ramesh, A. et al. (2013) [23] investigated the micro-texturing effect on a compressor’s tribological performance. They successfully showed how the machining of micro-textures on components reduced their friction by up to 80% when operating under fluid lubrication conditions. The textures acted as micro-load bearing structures and even improved the total load-bearing capability of the compressor components. Though this method is still not in use properly, this can prove to be a great innovation as far as the performance of compressors is concerned.

5.1 Current Critical Issues

With the rapid advancement of science and technology, numerous studies have brought about great advancements in compressor performance, but a lot remains to be discovered. Refrigerants have progressed a lot, but even the current HFOs still risk being mildly flammable. Even though HFOs provide great results and are much cleaner than HFCs or CFCs, they still are not quite as non-flammable as HFCs. Also, for small-scale industries that use compressors, the use of HFO as a refrigerant proves too costly. CO2 has great tribological characteristics and is easy to manufacture and eco-friendly, but its high operating pressure makes it almost unusable in standard commercial refrigeration and air conditioning purposes. Scientists are still discovering one such refrigerant with tribological properties similar to CO2 but operate at more suitable pressures for much commercial
refrigeration and air-conditioning currently in use. The refrigerant also has to be eco-friendly enough not to cause a significant contribution to global warming. Scientists have developed composite coatings, but their application is not that easy and requires good reliable manufacturing practices to implement properly. New lubricating oils are showing promising results, but with the gradual depletion of natural oil resources, efforts have to be made to make various oils obtained from sources other than oil reserves or petroleum. Few advancements have been made to extract rapeseed oil and make a triester, but more studies are required to make it commercially viable. As for micro-texturing, few compressor manufacturing industries have the required micro-machining tools required to precisely machine the textures onto components. This method will bring about additional costs that small industries that mass produce compressors will avoid. Hence, more studies are required to improve the manufacturing processes of compressors and, in turn, improve their tribological performance.

6. Future of compressors

True compressor improvements need complicated technical feats, and the challenges faced while developing compressors are due to the interdependence of elements that impact another. Increasing internal air leakage, rotor speed, exhaust gas temperature, and rotor and bearing wear, for example, can all be caused by changing the pressure ratio. Convex and concave rotor designs, on the other hand, may be changed in complex computational fluid dynamics (CFD) simulations to enhance airflow while maintaining consistency [24].

A completely oil-free compressor has no lubricant in the crankcase and no lubricant in the other components. The rotation of the bearings and the substance of the piston rings fundamentally assure rotation and friction between moving elements such as the connecting rod, crankshaft, piston, and cylinder. The advantage of such a compressor is that the compressed air contains no lubrication and is pure. On the other hand, the oil-free air compressor has a limitation in that it has a limited lifespan. As a result, how to extend the life of an all-oil-free air compressor has emerged as a critical research topic. Oil-free air compressor materials are relatively more expensive than oil-free air compressor materials. Another issue that must be addressed in utilization is how to reduce costs [25]. Oil-free air compressors are widely utilized in various sectors, including petrochemicals, fertilizers, medicines, automobiles, food and beverage processing, electronics, textiles, gas, oil, pharmaceuticals, chemical industries, power plants, papermaking, and other sectors [26].

Air compressor technology with enhanced performance and efficiency: To maximize energy savings from air compressors, it is critical to operate at a compression level that matches the amount of air consumption (optimal volume) and to avoid operating at a compression level that is greater than necessary (optimal pressure). This device offers both of the things mentioned above simultaneously by utilizing an inverter to regulate the rotating speed of the compressor. Installing a motor comparable to International Energy Efficiency Class 5 (IE5), established as the highest level of international efficiency requirements, has also increased energy-saving performance. Figure 5 describes the technology behind Air Compressors [27].
The volume of air required by the compressor varies depending on the severity of the manufacturing operation and the time slot. However, there are certain compressors in which the power consumption is not halved even when the air consumption is decreased in half (unloader-type compressors). In addition, if an inverter regulates the rotational speed, power consumption parameters that match the air consumption ratio can be achieved [28].

Electricity usage in air compressors rises as the discharge pressure rises. For example, if 0.1 MPa can decrease the ejection of a compressor, the power expense may be reduced by around 7% to 8%. Even if the user's air usage fluctuates, this device can maintain consistent pressure. This is done by regulating the rotational speed of the motor by installing an inverter, which led to significant energy savings by not operating the compressor at a greater compression level than necessary [29].

There are numerous concerns about today's compressed air technology, the most prominent of which is that such systems are inefficient and consume a lot of electricity [30]. However, variable-speed air compressors are a crucial trend driving the development of this technology. Most air compressors today operate at constant speeds. They disperse the same quantity of air regardless of the application. A variable speed air compressor, on the other hand, would allow users to modify the flow of air concerning the application. This might result in considerable energy savings while also increasing the efficiency and productivity of compressors. The worldwide air compressor market is anticipated to increase during the next few years, surpassing $37 billion by 2022.

7 References

[1] Lototskyy M, Klochko Y, Davids MW, Pickering L, Swanepoel D, Louw G, et al. Industrial-scale metal hydride hydrogen compressors developed at the South African Institute for Advanced Materials Chemistry. Materials Today: Proceedings 2018;5:10514–23. https://doi.org/10.1016/J.MATPR.2017.12.383.

[2] Bhutta MU, Khan ZA, Garland N, Ghafoor A, Usman Bhutta M. A historical review on the tribological performance of refrigerants used in compressors. EprintsBournemouthAcUk 2018;40:19–51. https://doi.org/10.24874/ti.2018.40.01.03.

[3] Sanukrishna SS, Vishnu S, Krishnakumar TS, Jose Prakash M. Effect of oxide nanoparticles on the thermal, rheological and tribological behaviours of refrigerant compressor oil: An experimental investigation. International Journal of Refrigeration 2018;90:32–45. https://doi.org/10.1016/J.IJREFRIG.2018.04.006.

[4] Mehltretter NA. Applying variable speed compressors in multiple compressor applications - Application success stories and improvement stories. Energy Engineering: Journal of the Association of Energy Engineering 2014;111:25–42. https://doi.org/10.1080/01998595.2014.10801404.
[5] Sesaiah N, Ghosh S, … RS-AT, 2007 undefined. Mathematical modeling of the working cycle of oil injected rotary twin screw compressor. Elsevier n.d.

[6] Krasheninnikov M, Kalashov A, Shapkin V, Koshurina A. The concept and methodology of creating the universal life-saver with rotary-screw mover. Lecture Notes in Electrical Engineering 2013;195 LNEE:477–90. https://doi.org/10.1007/978-3-642-33835-9_44.

[7] Wang F, Song L, Zhang L, International HL-2010 T, 2010 undefined. Fault diagnosis for reciprocating air compressor valve using pV indicator diagram and SVM. IeeexploreIeeeOrg n.d.

[8] Sun S, Engenga A, Kim Y, Eng. RA-JF, 2003 undefined. The inlet flow structure of a centrifugal compressor stage and its influence on the compressor performance. AsmedigitalcollectionAsmeOrg n.d.

[9] Engenga A, Kim Y, Eng. RA-JF, 2003 undefined. The inlet flow structure of a centrifugal compressor stage and its influence on the compressor performance. AsmedigitalcollectionAsmeOrg n.d.

[10] Casey M, turbomachinery CR-J of, 2013 undefined. A method to estimate the performance map of a centrifugal compressor stage. AsmedigitalcollectionAsmeOrg n.d.

[11] Vithya P, Sriram G, Arumugam S. Effect of Biodegradable Refrigeration oil on the Tribological Behaviour of Liner/Ring Tribo pair material of Hermetically Sealed Compressors. Materials Today: Proceedings 2019;16:488–95. https://doi.org/10.1016/j.matpr.2019.05.120.

[12] Tarel’nik VB, Konoplyanchenko E v., Kosenko P v., Martsinkovskii VS. Problems and Solutions in Renovation of the Rotors of Screw Compressors by Combined Technologies. Chemical and Petroleum Engineering 2017;53:540–6. https://doi.org/10.1007/S10556-017-0378-7.

[13] Dowson P, Ross S, 20th CS-P of the, 1991 undefined. The Investigation Of Suitability Of Abradable Seal Materials For Application In Centrifugal Compressors And Steam Turbines. OaktrustLibraryTamuEdu n.d.

[14] Schmid R, Ghasripoor F, Dorfman M, 2000 XW-I, 2000 undefined. An Overview of Compressor Abradables. DlAsminternationalOrg n.d.

[15] Silveira E, Atxaga G, Analysis AI-EF, 2008 undefined. Failure analysis of a set of compressor blades. Elsevier n.d.

[16] Rajaram G, Kumaran S, A SS-MS and E, 2011 undefined. Effect of strain rate on tensile and compression behaviour of Al–Si/graphite composite. Elsevier n.d.

[17] Öksüz M, Yildirim H, Erturan S. Microstructure and wear properties of plasma-sprayed aluminum-silicon- polyester coatings. Journal of Applied Polymer Science 2006;100:3609–14. https://doi.org/10.1002/app.23115.

[18] Demas N, Joint AP-I, 2006 undefined. Tribological Investigation of Cast Iron Air-Conditioning Compressor Surfaces in CO2 Refrigerant. AsmedigitalcollectionAsmeOrg n.d.

[19] Yeo S, … EEN-A in S and, 2010 undefined. Tribological performances of polymer-based coating materials designed for compressor applications. Trans Tech Publ n.d.

[20] Solzak T, Engineering AP-, 2008 undefined. Tribology of Coatings for Use in Oil-Less Swashplate Compressors. AsmedigitalcollectionAsmeOrg n.d.

[21] Demas NG, Zhang J, Polycarpou AA, Economy J. Tribological characterization of aromatic thermosetting copolyester-PTFE blends in air conditioning compressor environment. Tribology Letters 2008;29:253–8. https://doi.org/10.1007/S11249-008-9303-8.

[22] Ramesh A, Akram W, Mishra SP, Cannon AH, Polycarpou AA, King WP. Friction characteristics of microtextured surfaces under mixed and hydrodynamic lubrication. Elsevier 2012. https://doi.org/10.1016/j.triboint.2012.07.020.

[23] Harris P, O’Donnell GE, Whelan T. Energy efficiency in pneumatic production systems: State of the art and future directions. Leveraging Technology for a Sustainable World - Proceedings of the 19th CIRP Conference on Life Cycle Engineering 2012:363–8. https://doi.org/10.1007/978-3-642-29069-5_62.

[24] Demierre J, Favrat D, Schiffermann J, of JW-I journal, 2014 undefined. Experimental investigation of a Thermally Driven Heat Pump based on a double Organic Rankine Cycle and an oil-free Compressor-Turbine Unit. Elsevier n.d.
[26] He Y, Xing L, Zhang Y, Zhang J, … FC-AT, 2018 undefined. Development and experimental investigation of an oil-free twin-screw air compressor for fuel cell systems. Elsevier n.d. https://doi.org/10.1016/j.applthermaleng.2018.09.064.

[27] Policy MY-E, 2009 undefined. Air compressor efficiency in a Vietnamese enterprise. Elsevier n.d.

[28] Patel M, Praveen B, Sahoo H, … BP-… and E in, 2017 undefined. An advance air-induced air-assisted electrostatic nozzle with enhanced performance. Elsevier n.d.

[29] Zhang B, Liu M, Li Y, Wu L. Optimization of an industrial air compressor system. Energy Engineering: Journal of the Association of Energy Engineering 2013;110:52–64. https://doi.org/10.1080/01998595.2013.10753695.

[30] Yao K, Li H, Shang W, Hassan AE. A study of the performance of general compressors on log files. Empirical Software Engineering 2020;25:3043–85. https://doi.org/10.1007/S10664-020-09822-X.