Product Carbon Footprint of Cryogenic Turboexpanders Equipped with Active Magnetic Bearings in Hydrocarbon Gas Processing

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Abstract

This paper examines the lifecycle greenhouse gas (hereafter "GHG" or "product carbon") footprint of turboexpanders used in an ethylene process, with a focus on comparing those fitted with magnetic bearings versus oil bearings. While the results favor the use of magnetic bearings, the analysis highlights the importance of considering appropriate boundary conditions and working hypotheses, which may introduce biases. For instance, the effectiveness of their sealing systems, as well as the type of gas or simply the simulation models used to evaluate losses, can significantly affect the results. However, this analysis helps quantify the amount of greenhouse gas (GHG) emissions from turboexpanders and indicates reducing emissions would not be the sole factor of bearing technology choice. The choice of magnetic bearings in turboexpanders is mainly driven by other advantages, including reliability, availability, and the elimination of oil contamination, all of which introduce indirect carbon emissions.

Keywords: *Turboexpander, active magnetic bearings, Carbon footprint, greenhouse gas emissions*

1. Introduction – Goal of the Study

Cryogenic turboexpanders are essential components in various oil and gas applications, such as natural gas treatment, gas liquefaction, and petrochemical applications such as ethylene production. Turboexpanders can produce high volume refrigeration by extracting energy from high-pressure fluids and converting it into mechanical shaft power. Detailed descriptions of turboexpanders and their performance can be found in various publications [1]-[3].

The bearings used in turboexpanders play a crucial role in the reliability and safety of the machine. There are two main types of bearings used in turboexpanders: active magnetic bearings (AMB), shown in figure 1, and oil bearings with high-speed journal bearings, tilting pad bearings and sleeve bearings. Turboexpanders with both bearing technologies have proven to have high availability and reliability, with some studies showing AMB having the highest availability of 99.95% [3].

AMBs offer advantages over conventional oil bearings in turbomachinery, such as reduced friction and wear, improved stability and vibration control, the elimination of oil contamination, maintenance cost reduction and finally the reduction of operational cost [4]-[6]. Several studies have investigated the application of AMBs in turboexpanders and their potential benefits in terms of efficiency and reliability [7][8]. Due to the low temperature, high power and zero contamination requirement of many hydrocarbon and ethylene processes, turboexpanders equipped with AMBs are often specified. As a result, the application list for users of turboexpanders with magnetic bearings is quite extensive.

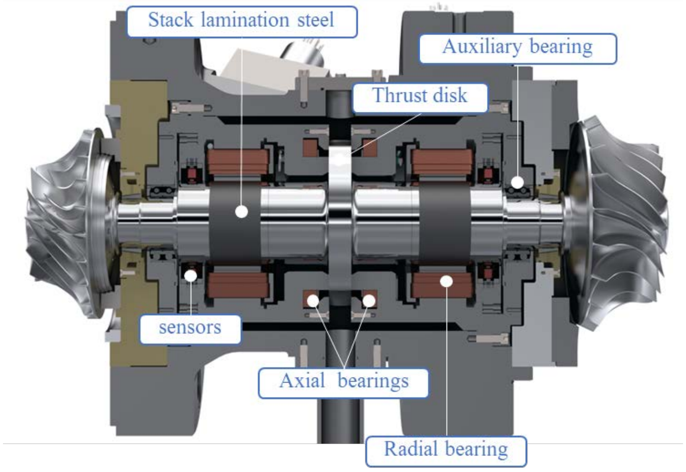

Figure 1 Cross view of a turboexpander with AMBs

The technology of magnetic bearings has become widely prevalent in several fields, making it unnecessary to introduce its principle of operation and control mechanisms [9][10].

Despite the many advantages of turboexpanders and their bearings, several challenges must be overcome to ensure their sustainable and environmentally friendly operation. One of the most critical challenges is the emission of greenhouse gases, primarily methane, during the processing and transportation of natural gas. The energy industry has come under significant pressure to reduce its carbon footprint and adopt cleaner technologies. Therefore, it is crucial to assess the environmental impact of turboexpanders and develop strategies to mitigate their emissions.

The use of magnetic bearings in certain applications such as chillers [11]-[14] and turbo blowers[15][16], has been shown to result in significant energy savings and a reduction in carbon footprint by nearly 30% compared to "oiled compressors". Additionally, the hermetic design of magnetic bearings used in oil and gas applications has been found to reduce gas leakage and thus further minimize the carbon footprint [17]-[18].

This paper aims to compare the greenhouse gas emissions of turboexpanders equipped with magnetic bearings and oil bearings used in ethylene plants. The study will focus on differences in emissions resulting from the use of materials and the operation of turboexpanders during their life cycle considering both replacement portion of new parts and end life stage.

A dedicated section will discuss the results of the study, including the limitations of the analysis. It is important to note that extending the conclusions to other applications beyond ethylene may have limitations, which will be addressed in the discussion section.

2. System Boundaries - Scope

The study evaluates two turboexpander configurations in a representative ethylene process, operating under the same conditions (Table 1). The turboexpander operates in a hermetically sealed environment with all components exposed to a hydrogen-rich process gas. The functional unit is power in kilowatts (kW) of turboexpander refrigeration, evaluated over its 25-year lifespan, including GHG emissions related to material inventory, lifetime maintenance including spares and consumables, in-use utility consumption, energy recovery losses, and end of life disposal. A 25-year lifespan was chosen based on typical machinery service life, which is 25% greater than the minimum service life specified in industry standard API 617.

Only the GHG emission that are different between the two configurations are considered. The two configurations have comparable duty, stage geometry and performance. Both machines are a Frame 3 by the manufacturer's convention, which is determined by the expander wheel diameter. To support this duty, a 110mm bearing is required for the AMB system versus a 51mm tilt pad bearing required for the oil machine. Other assumptions are detailed in the corresponding sections.

Table 1 Representative Process Conditions for Turboexpander in Ethylene Process

	Expander	***Compressor***
Inlet Pressure (bara)	15.0	5.9
Inlet Temperature (C)	-150	30
Outlet Pressure (bara)	6.8	7.0
Outlet Temperature (C)	-163	49
Molecular Weight	4.5	4.5
Gas Power (kW)	710	
Shaft Speed	29000	

3. Turboexpander Description

Turboexpanders are radial inflow turbines used in refrigeration applications to extract energy from a fluid. They commonly consist of an expander stage, a compressor stage, and a bearing center section (Figure 1). When a turboexpander is directly coupled to a compressor, they operate as simple variable-speed machines, requiring no external shaft seal or drives. The aerodynamics of the turboexpander and compressor depend on the bearings' ability to support the required speed, power, and thrust loading. Critical speeds are typically avoided in their design, from zero to trip speed.

3.1. Common Configuration for Both Bearing Systems

Turboexpanders require shaft sealing to prevent cold, unfiltered process gas from entering the bearing carrier. Buffered labyrinth seals are commonly used in both magnetic bearing and lube oil-based systems due to their simple, non-contacting design, which enhances the system's robustness. The hermetic design of turboexpanders allows the seal gas to be contained within the process, eliminating any loss of gas to the atmosphere or a flare system. Turboexpander packages are often equipped with a seal gas conditioning system, which filters and regulates seal gas flow to the turboexpander. While these features are similar, their implementation differs based on the bearing technology.

3.2. Difference in Configuration

To operate the oil bearings, lubrication oil at specific pressure and temperature ranges must be delivered to the machinery. The lube oil support system achieves these pressures and temperatures through a system of valves, piping and vessels, including motor driven pumps and cooler fans. The oil delivery system adds significant material inventory to the turboexpander package. Skid layout differences are shown in Figure 2. For a typical frame 3 turboexpander package, a lube oil skid is 6.5x3 meters (LxW) versus 4x3 meters for a magnetic bearing skid. Rotating assemblies for bearings also vary in size, with AMB having less capacity per unit area and requiring greater shaft and thrust disc surface area for equivalent duty. Figure 3 offers a visual comparison.

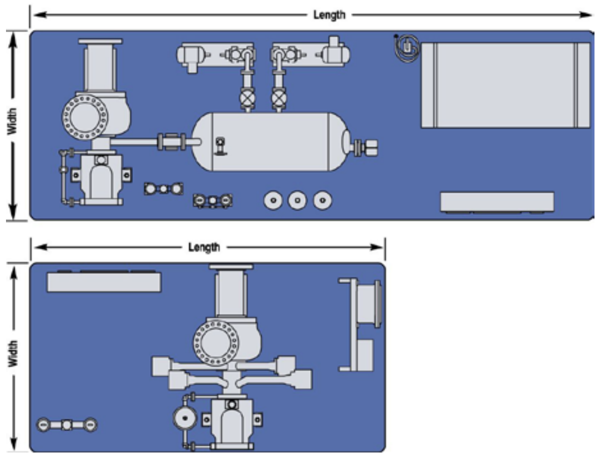

Figure 2 Turboexpander Package Comparison between Oil (Top) and Active Magnetic Bearings (Bottom)

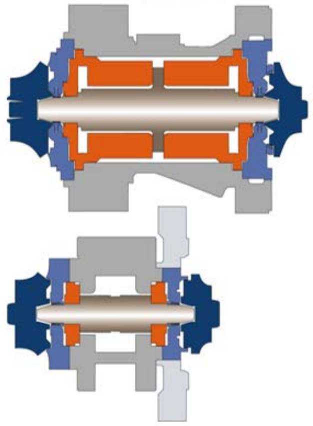

Figure 3 Turboexpander Rotating Assembly Comparison between Active Magnetic (Top) and Oil Bearing (Bottom) Systems

4. Material Inventory and Corresponding GHG Emissions (Supply and End of Life Phases)

Embodied GHG emissions due to material inventory were calculated using emission factors (EF) from ICE database v3 and ecoinvent 3.7.1 databases. The emission factor for raw material has been uplifted by 32% to account for supply chain waste and processing. The emission due to transport and facility operation are comparable for either configuration, therefore are excluded from this study. End of life emissions based on emission factors from Ademe are added to embodied emissions to complete the material life cycle. Maintenance includes capital spares and Oil Bearing maintenance included 3 replacement fills of the oil reservoir. Table 2 shows the results for each respective configuration.

Table 2 Materials Carbon Footprint

Material	Materials Emissions (kg CO2e)	
	AMB Configuration	**Oil Bearing Configuration**
Steel*	20952	30099
Aluminum*	4906	4636
Switchboard**	2040	
Epoxy*	2083	1941
Battery**	1012	
Electronics: (chips, boards, etc.)***	853	560
Copper*	732	511
Electrical: Power Supply/Control**	511	1394
Nylon***	243	958
Brass*	188	256
Polypropylene***	24	24
Rubber*	9	9
Electric Motors***	4	6352
Oil****		1680
PVC*		72
Material Total	33556	48493
Maintenance	2182	14167
Grand Total	35738	62660

* ICE Database V3.0 (Inventory of Carbon & Energy), Nov 10, 2019

** Ademe (French Environmental Governmental Agency), 2012, https://base-empreinte.ademe.fr/donnees/jeu-donnees, emission factor “Tableau électrique” and “Pile”, retrieved on April 28, 2023

*** ecoinvent v3.7.1 Database, Dec, 2020

****U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020

Upon analyzing the emissions of each element, several interesting findings have emerged. The lubricated bearings system, for example, requires a larger quantity of steel and motors (pumps, cooling), but fewer electronic and electrical components when compared to the AMB system. When looking at the overall balance, it's worth noting that the AMB system produces 43% fewer GHG emissions due to the materials used.

5. Use Phase GHG Emissions

The carbon footprint of machinery operation depends on power consumption and machine performance. A compressor loaded turboexpander has two functional outputs: refrigeration and gas compression. For simplification, this analysis considers the expander stage refrigeration as the single functional unit used to normalize carbon footprint. Impacts to the compressor output will be converted to a carbon equivalent based on the lost power that requires make-up compression from downstream machinery. For the sake of this analysis, the downstream compressor is assumed to have equivalent efficiency and driven by a gas turbine, which is typical in ethylene applications.

5.1. Machine Performance

5.1.1. Bearing Losses

There are losses due to windage and friction in the bearings that reduces the expander power recovered by the compressor. These are referred to generally as bearing losses. On a machine equipped with magnetic bearing, the only bearing loss incurred is windage as the rotor spins inside the bearing housing. The rotor windage is calculated separately for each surface of the rotor and depends on the geometry, air gap, speed, Reynold’s number, and density [19][20].

In addition to windage, machines with oil bearings have a loss associated with the viscous shearing of oil inside the bearing. For a given lube oil supply condition, this loss depends on the bearing geometry, thickness of oil film, the viscosity of the oil and speed.

5.1.2. Aerodynamic Performance

A turboexpander's aerodynamic efficiency has a major influence on its carbon footprint, but bearing selection has little effect on it. With open impellers, the shaft's position affects the clearance between the impeller and non-rotating follower [21]. Oil bearings only engage with the rotor when they are nearly in contact, meaning that oil-bearing rotors operate with minimal endplay. Magnetic axial bearings, on the other hand, keep the shaft centered and force it to straddle the designed endplay without any contact.

5.1.3. Seal Gas

Warm seal gas entering the process can have a detrimental effect on machinery refrigeration. This warming effect is represented in this report as a loss of refrigeration in kW.

Hermetic designs imply that the bearing carrier is submerged in the process fluid. In the case of an oil bearing, trace amounts of oil will become entrained in the seal gas before it is recompressed and sent back to the process. The amount of oil lost is limited by an oil separator. Some processes may not tolerate this trace oil being introduced to the system, and in such cases, the contaminated seal gas must be routed to a flare system. This configuration results in significant process gas loss and carbon footprint impact and is not considered in this study. For this study, the lost oil due to carry over from the seal gas system is considered in the maintenance footprint in Table 2.

In certain situations, it may be necessary to introduce extra cooling gas into the magnetic bearing housing to dissipate heat caused by windage and other losses. This cooling gas, when required, is typically obtained from the same source as the seal gas supply, and accounts for additional flow and system efficiency loss. Hydrogen-rich applications such as ethylene processing tend to have lower power density and higher cooling characteristic from the sealing gas, ultimately resulting in no need for additional cooling streams.

Due to the clearance required between the shaft and the auxiliary bearings, magnetic bearings naturally require a larger clearance at the labyrinth seal when compared to oil bearings. This excess gap can be improved with a floating seal design, where the stationary parts of the seal are allowed to move with the shaft and recenter upon levitation, however seal gas flows are still higher in this configuration when compared to oil bearings. (Figure 4 and Figure 5)

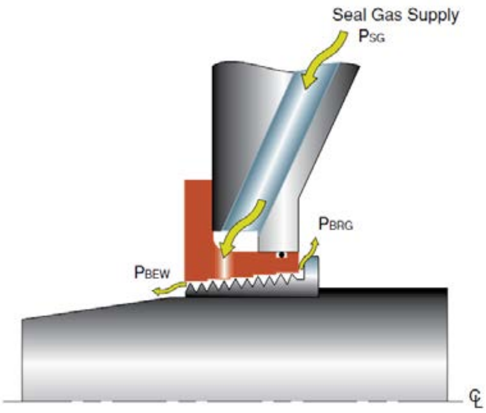

Figure 4: Labyrinth Seal for Oil Lubricated Bearings

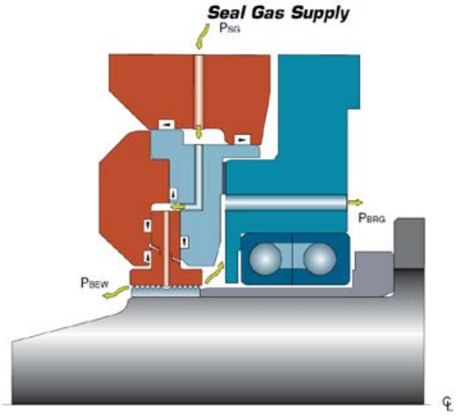

Figure 5: Floating Labyrinth Seal for Active Magnetic Bearings

5.2. Power Consumption

At an ethylene processing plant, the electrical power is typically generated on site from the combustion of hydrocarbon process gas. An emission factor of .44 kg CO2e per kW-h is used based on the average emission for US natural gas powerplants. [22]

5.2.1. Seal Gas Heater

For ethylene processes, seal gas is typically sourced from the process gas at expander inlet. When the seal gas source is too cold for safe operation of the bearing due to material considerations or oil sludging, it must be heated. The energy requirements of the seal gas heater are determined by the seal gas flow rate, temperature rise, and thermodynamic properties of the seal gas. For oil bearings, a temperature of at least 110°F is required to prevent sludging or freezing of the oil, while magnetic bearings components can tolerate lower temperatures, as low as 10°F. Most commonly this heating comes in the form electric heating element but may also come from steam or other heat source. An electric heater is considered for this study.

5.2.2. Auxiliary Utility Consumption

While the seal gas heater has the largest power consumption of all equipment that supports the turboexpander (further discussed in section 6), other equipment's power requirements must also be considered. The operating power consumption of the magnetic bearing controls and power supply cabinet (Figure 6) is considered as is the power used by the electric motors powering the lube oil system pumps and fans (Figure 7). The power required for instrumentation and controls of the support system is similar for turboexpanders with either bearing selection and therefore has been excluded from this analysis.

Figure 6: Standard AMB control cabinet

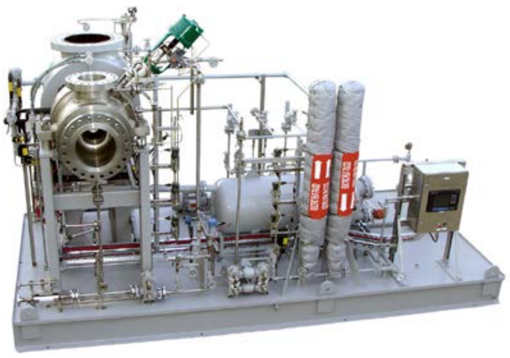

Figure 7: Turboexpander with lube oil system

5.2.2.1 AMB Control Cabinet

The AMB control cabinet is comprised of several essential items that work together to ensure the proper functioning of rotating mechanical parts. Firstly, a detection system is included to receive all inputs from the rotating parts. The data is then analyzed by a master controller, which adapts the control outputs for the amplifiers. These amplifiers send currents to the coils of the actuators (AMBs), which adjust the magnetic field and correct the position of the rotor. Additionally, in certain cases, there may be a power supply and associated battery pack included in the cabinet, which have been considered in this study.

6. Results and Comparative Analysis

Table 3. Machine Performance Impact

	AMB Configuration Power (kW)	**Oil Bearing Configuration Power (kW)**
Tip Clearance (Expander)	18.7	20.3
Seal Gas Heat (Expander)	4.9	3.5
Total	**23.6**	**23.8**
Adjusted Expander Power	**710.0**	**709.8**

Table 4. Machine Power Consumption

Power Consumption	**AMB Configuration Power (kW)**	**Oil Bearing Configuration Power (kW)**
Seal Gas Heater (Utilities)	22.2	12.9
AMB Cabinet (Utilities)	2.2	-
Pump (Utilities)	-	4.3
Cooler Fan (Utilities)	-	3.3
Windage Loss (Compressor)	5.6	0.3
Oil Bearing Loss (Compressor)	-	27.0
Total	**30.1**	**47.8**

Table 5. Turboexpander Configuration GHG Emissions Comparison

	Materials GHG Emissions (tCO_2e)	***Use GHG Emissions (tCO_2e)***	***Total Life Cycle GHG Emissions* (tCO_2e)***	***Adjusted Expander Power (kW)***	***Normalized GHG Emissions (tCO_2e/kW)***
AMB Configuration	35.7	2844.8	2880.6	710.0	**4.06**
Oil Bearing Configuration	62.7	4517.9	4580.5	709.8	**6.45**

****For the scope considered, where there are significant differences between the two configurations***

Reviewing the breakdown of use power consumption in Table 4, note that the bearing losses including both windage and oil shearing are greater in the oil bearing, while the seal gas heater power is greater for the magnetic bearings. Although, the seal gas for magnetic bearings requires less specific heating due to the lower allowable temperature, the increased flow rate results in higher overall seal gas heating duty compared to oil bearings. These two factors, bearing loss for oil bearings and seal gas heating for magnetic bearings, account for the greatest individual carbon footprint for the respective configuration. The other utilities besides seal gas heating are significantly higher for the oil-bearing configuration, suggesting a more favorable performance for magnetic bearings when seal gas heating is not required.

Table 5 shows the materials and use GHG Emissions of machines equipped with magnetic and oil-bearings, with the operating carbon footprint being considerably higher for both bearing technologies. This is due to the turboexpander's extended operational life and high duty cycle, making even minor differences in power consumption or performance have a significant impact on the overall carbon footprint over its lifespan.

In summary, expander performance impact was minimal for either configuration, oil bearings experience greater bearing losses, while magnetic bearings require higher overall seal gas heating duty. This results in a total power consumption reduction of 37% in the AMB system when compared to oil bearing system. This improvement in performance results in the AMB avoiding 68 tCO_2e per year or 1700 tCO_2e over the 25-year life cycle.

7. Discussion and Limitation

In this example, the primary difference in carbon footprint between magnetic and oil-bearing equipment is due to bearing losses. The oil bearing requires a much smaller shaft, resulting in negligible windage loss. In contrast, magnetic bearing losses are exclusively due to windage and are highly dependent on fluid properties, shaft speed, and size.

Therefore, the variation in carbon footprint depends on the equipment's operating fluid. As demonstrated in this study, magnetic bearings have an obvious advantage in lighter gas applications such as ethylene and hydrogen liquefaction. However, as the fluid's density and viscosity increase, the difference in carbon footprint will decrease. For turboexpander applications with heavier process fluids, like natural gas processing, the decision to select magnetic bearings would not be dictated by the reduction in carbon footprint alone, but would depend primarily on other benefits, such as eliminating the need for oil lubrication systems, reducing the size and weight of equipment, improving its reliability, and reducing operating costs.

The second largest impact in this study is from the seal gas. While seal gas heating is common in ethylene processes, it’s typically not required in other turboexpander applications such as natural gas processing or liquefaction. In these applications, the increased seal gas consumption experienced by the AMB system has less of an impact on the overall carbon footprint. In this way, the carbon impact from increased windage losses in applications such as natural gas processing may be partially offset by the lack of seal gas heating.

8. Conclusion

The study shed light on several key aspects related to the carbon footprint of various systems. The lubricated bearing system was discovered to have more GHG emissions related to the amount of materials utilized, although this effect was minor compared to the impact during the usage phase. The study showed that the energy consumption of the magnetic bearing system was significantly lower, with a difference of more than 35% compared to the lubricated bearing system. This reduction in power consumption had the greatest impact on carbon footprint and is consistent with similar results reported in other applications cited in the article.

Moreover, it was recognized that the decreased energy usage exhibited by the magnetic bearing system relies heavily on boundary conditions, including the seal gas source and equipment operating fluid. Keeping this in mind, the machinery's carbon footprint should be assessed individually for each application, and a carbon footprint comparison across various applications would be necessary to confirm whether the findings of this study are universally applicable.

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