ANAX POWER

Anax-Star Turboexpander: Generating Electricity from Natural Gas Pressure Reduction

ANAX HOLDINGS, LLC
401 Wilshire Boulevard
12th Floor Penthouse
Santa Monica, CA 90401

Generating Electricity from Gas-Pressure Let Down

1. Introduction

Several large companies, such as Honeywell and GE, as well as smaller startups, list gas let down generators as available products on their websites. Despite these options existing for over 10 years, there has yet to be widespread adoption, as a majority of organizations do not harness the energy wasted in natural gas let down. This paper assesses the feasibility of existing let down systems for and offers suggestions as to why the technology has yet to take off. It goes on to describe how the Anax-Star Turboexpander navigate the obstacles to adoption in the gas let down generator market. Finally, this paper projects what this market will look like in the future.

2. Technology

There are two main types of expanders used in gas let down applications: turbines and screws. While other possibilities to use compressor technologies as expanders exist, but they are significantly more complex and expensive that turbines and screws. Additionally, they are less-efficient and have yet to be used in any successful trials.

2.1. Turbines

The turbine was developed as a cheap alternative to piston devices in the 1930s and is used as compressor, pump and expander. A car turbocharger is an example of a turbine-based device containing both a compressor (which pushes a higher quantity of air into the cylinders of the engine) and an expander (which uses energy recovery from the engine's exhaust to directly drive the compressor wheel). Car turbochargers are mass produced for about $100, demonstrating the how inexpensive and simple these machines can be. At the other end of the spectrum, expander turbines are also used in large, expensive engineering packages to process hydrocarbons and liquefy air. In this application, similar to the car turbocharger, an expander wheel drives a compressor wheel, with the primary objective being to reduce the substance's temperature. Since the expander extracts energy from the gas stream, its temperature drops, enabling the gas to be processed. These liquefaction applications typically drop the temperature to -100°F or lower, depending on the type of process. Furthermore, these process machines are typically very large, with the turbine wheel measuring several feet in diameter, and the package weighing up to 60 tons. Thus, these machines are very expensive, and are typically used exclusively in the cryogenics market. They are typically "open-drive" machines (the turbine drives a shaft which passes through the pressure casing of the machine and connects to an electrical machine which acts as the alternator, generating electricity from the rotational motion) that use hydrodynamic journal bearings, which are lubricated by oil. Problems arise when these oil-lubricated bearings are mixed with the gas stream, prompting a separation process. Larger machines also require more precise turbine speeds in order to synchronize the output frequency with the electrical mains. This requirement has made the turbine systems difficult to control with variable and fluctuating operating conditions, earning them a reputation for being difficult to manage.

Recent developments in power electronics have enabled the use of permanent magnet generators operating at variable high frequency, typically up to 750Hz. The generated electrical current is converted to DC and then reconverted in a second inverter to AC at the required frequency. This process requires the use of IGBT electronics, but the combination of permanent magnet motors and thyristor drives has become common in recent years, such as in drive motors for electric vehicles.

The turbine used as a compressor draws a flow of gas along the axis of rotation into the "eye" of the turbine (the center of the turbine wheel). Channels in the turbine wheel direct the gas perpendicular to the turbine so that it flows away from the axis and is forced to accelerate. The acceleration creates the compression, as the velocity increases. This process is known as "kinematic" (as opposed to "positive displacement", such as piston or screw machines). When used as an expander the gas flow is in the opposite direction. It is introduced through a fixed ring of nozzles at the circumference of the wheel, and it flows towards the center of the wheel. Channels in the wheel turn the gas flow through 90°, directing it along the axis of the shaft and away from the wheel. The gas moves from the high velocity periphery to the low velocity center of the wheel, thus decelerating and reducing the pressure and temperature. The energy extracted from the gas stream through this deceleration rotates the shaft (through the shape of the turbine wheel), which either drives another device (for example the compressor end of a turbocharger) or is converted to electricity in an alternator (like an electric motor but turning movement into a moving magnetic field which generates electric current, rather than the other way around).

Turbines typically run at high speeds and require a gearbox or electronic inverter to reduce the electrical frequency and match the grid requirement. They cannot cope with moisture on the wheel of the impellor for long periods of time. At such high operating speeds, even small liquid droplets in the form of a fine mist would cause severe damage through erosion. However, provided the bearings can carry the load, the turbine will handle a short-term flow of liquid without damage.

2.2. Screws

Helical screw devices have been used since the time of Archimedes and were even used by the Ancient Egyptians to pump water. The screw compressor was developed in the 1930s and is now widely used in industry due to its relative simplicity (compared with the reciprocating, or "piston" compressor) and compact size. There are two variants of the screw machine in widespread use, although many other designs are possible. Both variants can be used as expanders, with pressurized gas driving the rotors, but screws are more frequently used as compressors. Screws are typically direct driven at a speed which matches the mains frequency of the electrical supply. For the most common-sized screws this gives a good match to the optimum speed of the tip of the rotors required to ensure most efficient operation. Very small machines are inverter driven at higher speeds and very large machines run at half or one-third speed to keep the rotor tip speed in the optimal range.

2.2.1. *Twin screws –* the twin screw compressor has a single compression path which lies between two cylindrical shafts with a helical screw profile machined into them. As the shafts rotate, the gas pocket between them is reduced, causing gas trapped between the two rotors to be compressed by positive displacement. When used as an expander, the high-pressure gas drives the rotors as it expands, allowing the shaft rotation to drive an alternator or other machine. Most twin screws are oil-injected because the oil provides a useful function in sealing between the rotors and lubricating the rubbing faces. However, oil-free variants are also available, but generally have lower efficiencies. This reduced efficiency is a function of the rotor gap being less well sealed and because a gearbox drive is required between the two shafts since they are not lubricated and cannot drive directly. Although these machines are described as "oil-free" there is still a need for oil in the gear box and the bearings. The name means that the process fluid does not contain any oil, unless a shaft seal leaks.

2.2.2. *Single screws* – the single screw compressor has only one cylindrical shaft with a helical screw machined into it, but it interfaces with one or two flat rotors which engage with the main cylindrical shaft from the side. These side wheels have blades which mesh with the screw profile, enabling a volume of gas to be trapped between the cylinder, the blade and the casing of the machine. The side wheel shaft is perpendicular to the main shaft, so it is difficult to use a gearbox to drive them synchronously. Therefore, there needs to be at least a small amount of oil in the gas stream to lubricate the contact between the main shaft and the blades of the side wheel. Paradoxically, although the twin screw machine has a single gas path (between the two rotors), the single screw machine is usually configured with two gas paths since is beneficial to use a bladed side wheel on both sides of the machine. Single screw expanders were considered for the ASTE but the concept was not pursued because of the need for lubricating oil in the gas stream.

2.3. Other devices

Several other types of compressors could be considered as expanders, and many new compressor variants are under development, so this sector needs to be regularly monitored for possibilities. However, the turbine and twin screw are the best large-scale options for many years to come.

2.3.1. *Piston expanders* – the piston compressor is like a car engine. Linear motion of the piston is converted through connecting rods and a crankshaft to rotary motion. This requires a robust and complicated lubrication system for all the bearings. In a compressor the inlet and outlet valves on each cylinder operate by gas pressure which makes them simple. However, in an expander (as in an automobile engine) the inlet and outlet valves need to be actuated, such as by the camshaft in an automobile engine. Bearing complexity and valves makes the piston expander unlikely to be used in gas let down applications.

2.3.2. *Other rotary devices –* several concepts exist for rotary engines which could be adapted as expanders. At present these devices have not been widely commercialized, and are likely to be more suited to very small-scale applications, which will not threaten the position of the turbine or twin screw expander.

3. Gas let down basics

The energy contained in a gas at a certain pressure and temperature is called the enthalpy (h), and comprises the internal energy (u) plus the product of pressure (p) and volume (V). Thus

$$h = u + pV$$

Pressure, volume and temperature (T) are related by the ideal gas laws that state, for example that:

$$pV = mRT$$

Where 'm' is the mass of gas in the system and 'R' is the universal gas constant, and the definition of an expansion or compression process is:

$$pV^{\gamma} = k$$

Where γ (gamma) is the index of compression (or expansion) and k is a constant value. These useful equations mean that if any two of the three conditions (pressure, volume and temperature) are known then the third can be calculated at that condition and that if one of them changes in accordance with the third equation, as is the case (approximately) in an expander, then the other two can be recalculated for that new condition.

Enthalpy is a useful concept because the form of the energy is not specified. Therefore, heat energy, potential energy and work energy are all subject to the same rules and can be treated the same way. For a consistent set of calculations, the enthalpy is given relative to a datum point, so one must be careful when comparing different calculations, done at different times, by different people, to ensure that they used the same datum. It is usual to consider the enthalpy per mass of the gas, sometimes called the specific enthalpy, which is measured in BTU per pound (in metric kJ per kg).

When gas pressure is reduced, its volume per pound and temperature are altered, and its specific enthalpy most-likely changes (it is possible to do pressure reduction without changing the enthalpy; the gas volume increases and the temperature drops. This is a special case known as adiabatic expansion, but it is not relevant to gas let down generation because no enthalpy change means no work output from the expander).

The drop-in temperature during pressure reduction in a regulating valve is an example of adiabatic expansion and is called the Joule-Thompson effect (named after two pioneers of thermodynamics, James Joule and Lord Kelvin Thompson).

In a standard gas let down station the Joule-Thompson effect causes the outlet gas to cool, typically by about 5°F per 100 psi pressure drop. So in the Corus example cited by Lehman and Worrell, where the pressure is reduced from 930 psig to 120 psig the gas might drop from an inlet temperature of 60°F to about 9.4°F. This is too cold for onward transmission, so gas let down stations must incorporate some form of heating, often just taking a small portion of the gas and burning it to heat a water bath which is used to warm up the gas flow either before or after expansion.

If the Joule-Thompson expansion produces no useful work and makes the gas cold, it will get even colder when more energy is extracted by an expander.Fortunately, it is easy to split the expansion process into steps, so that heat can be added in stages to regulate inlet and outlet temperature. Multi-step expansion is necessary because the limiting pressure ratio for a turbine is less than for positive displacement machines, so several stages are required to achieve full expansion. This gives insight into why turbines have not achieved significant market penetration yet – if they are applied to a large pressure ratio they will be inefficient and maybe even less reliable.

In contrast to turbines, screw expanders are more difficult to separate into multiple stages (except by using two machines, which is expensive). Although the screw expander is theoretically capable of handling a much higher pressure ratio, it is limited by the practical arrangements required to maintain moderate temperatures. Low-grade waste heat limits the inlet gas temperature, but this heat is still preferable because it is much more likely to be available in a typical industrial environment. Low grade, in this context, means less than 150 °F.

While it is easy to view this gas let down process as converting pressure into electricity, it is more complex than that. Extracted energy is available because of the pressure reduction, but the gas should be considered as a "carrier fluid" for the energy, which might be considered to be supplied entirely from the waste heat added to the carrier.

4. Literature review

In their paper, "Electricity Production from Natural Gas Pressure Recovery (2002)," Lehman and Worrell, of Lawrence Berkeley National Laboratory, provide an overview gas let down as an electricity generation technology. Lehman and Worrell discussed three case studies (two in The Netherlands and one in Japan) with what seemed to be mature technology. Despite these factors, it seems that the market has not progressed since their paper.

Lehman and Worrell assess the potential generating capacity of the North American gas distribution network to be 21,000 GWh per year, or 11% of the total energy contained in pressurized gas pipelines. However, they assume that the 3.4% of gas extracted from the pipeline to power the compressor stations is converted into energy in the gas stream (200,000 GWh per year) which would theoretically be available for recovery. This is unrealistic as it ignores compressor efficiency losses, pressure drop in the pipe and leakage of gas along the way (which presumably is also in the 3.4% figure). Nevertheless, their 11% conversion number is a reasonable figure (the conversion from the amount of energy actually available will be higher than this but the net result is the same). They also note that increased use of gas fired power stations improves the prospects for gas let down by reducing supply variability, and that gas supply figures were expected to rise from 16 million mmscf (million standard cubic feet) in 1986 to 32 million mmscf feet by 2020. Much of the increase is achieved by improving the system load factor, in other words running at higher pressures for longer periods. As the pressure must be dropped to the same levels as before (ultimately to just above atmospheric pressure) the prospects for gas let down generation look strong.

Lehman and Worrell's case studies confirm that the two key areas for generation are gas fired power stations and citygate letdown stations. Additionally, it is important to note that the cases discussed (Amsterdam, Ijmuiden and Osaka) used machines larger than the ASTE, which is 250kW output power. The Amsterdam, Ijmuiden, and Osaka machines were 3.6 MW, 1.5 MW and 1.2 MW respectively (back calculated from data in the paper). The variations in mass flow and pressure result in a usage factor substantially less than 100% for these installations, at 34%, 65% and 30% respectively. These usage factors make it difficult to maximize a machine's full potential in a practical application, due to flow and pressure variations, downtime and other real-world factors. Nevertheless, at the prevailing electricity rates, all three projects showed acceptable payback times with the longest (Amsterdam) being 7.6 years and the other two being less than 5 years. Lehman and Worrell note that the payback depends on the cost of electricity and that the Amsterdam case was due to the use of CHP as a source of reheat, with relatively high Dutch gas prices adding considerably to the operating cost.

Lehman and Worrell's observation that, "Without a site-by-site review it is impossible to accurately assess the potential for energy generation and cost savings using expansion turbines" is a major reason for this technology's slow development. Until the ASTE, and owing to their lack of operating flexibility, these machines have needed to be specifically tailored for each site. This customization increases cost and significantly delays the payback period. It even inhibits potential users by adding complexity to the solution. Even a system only slightly off the optimal design condition would be highly inefficient. However, Lehman and Worrell also observe that "concern lay with the economics of the approach, not the technology" which suggests that installations were too expensive, projected payback periods were too long or the selling price of electricity was too low or too uncertain. The electricity market has not changed dramatically in the last 15 years, but the introduction of higher tariffs for environmentally sourced electricity, if applied to gas let down, could help to improve the financial proposition. Lehman and Worrell concluded that "the next steps in more accurately evaluating expansion turbine potential and encouraging their use lie in identifying likely sites and installing pilot projects." These steps are hampered by regulatory constraints and the innate conservatism of utility companies. Therefore, the market requires a technology which is significantly easier to apply, more robust, less affected by off-design conditions and more efficient in operation than previous generations.

The paper gives the impression that the authors were not familiar with the practical details of gas let down. For example, it states that the use of an expander and generator in a gas let down system is no more hazardous than the default arrangement of using a pressure regulating valve. This is true on the gas side of the system, but the electrical connection, whether it is to the national grid or to an "off-grid" network, is significantly more complicated and requires a high level of detailed design and product approvals. This over-simplification leads to the speculation that issues surrounding grid connection were not addressed by Lehman and Worrell, with the conclusion that the capital and installation cost figures do not include the grid connection, which could easily be an additional 25% - 50% of the cost of the package. The safety issue becomes apparent in the event of a power cut, or sudden grid disconnection, as the load would be taken off the generator and the turbine would immediately accelerate. Without some form of protection, it would be possible to reach dangerously high speeds within a fraction of a second. Measures must be taken to ensure that this speed increase cannot cause damage. Typically, units would contain a fast-acting brake, and an extra electrical load can switched on if the mains connection drops out.

Care must also be taken to design the turbine so that it can withstand a sudden acceleration. All of these measures incur additional cost, and the last (which might seem to be the easiest) would likely be prohibitive in cost due to the manner in which out of balance forces increase with rotational speed.

There is also an apparent flaw in Lehman and Worrell's logic when they state that "it makes sense to put as much waste heat into the gas flow before expansion as possible, especially if the heat is cost-free". This seems to ignore the fact that for a given pressure and mass-flow the amount of electricity that can be recovered is virtually fixed. The main effect of increasing the temperature is to make the gas less dense. Reducing the density slightly increases the power generated but it is necessary to add approximately 13kW of heat for every 1kW of extra power produced, so this is not a good value proposition. This is shown in Table 1.

Inlet T	Power Generated	Heat Input	Heat ratio
120°F	274.91kW	787.8 kW	12.9
130°F	280.78 kW	864.5 kW	13.1
140°F	286.6 kW	941.4 kW	13.2
150°F	292.42 kW	1018.6 kW	13.3
160°F	298.19 kW	1096 kW	13.4

Table 1 – Additional heat required to generate additional power

This error is compounded later in the paper when they state that "by assuming a constant enthalpy change across the turbine we were able to estimate energy output based on flow." The relationship between enthalpy and energy output is more complex than it is characterized here. This does not totally invalidate the findings of the paper, but introduces a margin of error in the calculated values which should be treated with caution.

5. Organic Rankine Cycle

Several of the companies offering gas let down technology link it to Organic Rankine Cycle (ORC) generation. This process also uses turbines to generate power, but is significantly different in several other respects. ORC has been applied to generate power from process waste heat and from high temperature geothermal sources. It is described as "organic" because it uses an organic chemical as the working fluid in a closed loop cycle, in contrast to the steam Rankine cycle used in most steam power plants. The organic fluid is usually a fluorocarbon, similar to those used as refrigerants but selected to operate at higher temperatures than those found in refrigeration systems.

ORC is a closed cycle system where the same fluid circulates many times through the turbine. Gas let down is an open loop, where the gas throughput may carry contaminants into the turbine and will be contaminated by any additional fluids, even with exceptionally high grade filtration on the expander outlet. The machine types that lend themselves to ORC are not necessarily suited to gas let down and vice versa.

Gas let down as a vehicle for recovery of energy from waste heat can deliver up to 100% of the waste heat as electricity, and under the right conditions can even exceed this apparent limit. In contrast ORC can at best convert about 15% of the heat to electricity. The remainder of the heat in the ORC system has to be rejected to atmosphere in a cooling tower or dry cooler. In gas let down, if some of the waste heat is not converted to electricity it is carried away by the gas stream so there is no external heat rejection. This is a major advantage in simplicity and ease of operation for gas let down.

6. Summary of gas let down systems on the market

Several older systems use open drive turbines with oil injected journal bearings, shaft seals and gearboxes driving synchronous generators at 3,000rpm or 3,600rpm to generate electricity at 50 Hz or 60 Hz respectively. These machines were typically developed for liquefaction plants in the cryogenics space, a price-inelastic market. Where expansion is to be done in two or more stages, they often use multiple turbines each with its own generator. The Atlas Copco expander illustrated on their website, for instance, shows a very traditional package with two open drive single stage turbines in series. It is said to have an integral gearbox; "the industry's most efficient and compact mechanical drive design". This misses the point that mechanical drives are bulky, noisy, inefficient and require maintenance. An electronic drive coupled with a permanent magnet machine is much cheaper and more efficient. The Atlas Copco packages are probably oil lubricated machines and will have a sophisticated shaft seal to minimize leakage. A similar package is shown on the GE website. The systems by Honeywell and Cryostar are believed to be similar, although fewer details are publicly available. It is possible that the latter uses magnetic bearings.

The Centripetal Flux machine, which works on the principle of directing jets of gas between parallel spinning disks, is suitable for gas let down applications (among many others), according to the website. This application, however, seems unlikely due to the low molecular weight and low viscosity of natural gas. It has not been proven in practice for gas let down. Furthermore, with a stated efficiency of 50%, it would not be attractive no matter how cheap it was.

The unique features of the new Anax-Star Turbo Expander (ASTE) are:

- Closed construction (no shaft seal)
- Active magnetic bearings (no oil contamination of the gas flow)
- Permanent Magnet (very compact design and high speed operation)
- Controls included on the skid for plug and play simplicity on site
- Lower grade waste heat (150°F) due to two stage expansion
- Adapts automatically to a wide range of pressure and flow rate conditions

The goal is to provide a package that is custom-designed for the gas let down application and capable of handling a wide range of operating conditions automatically, such as would be seen at a typical primary let down station on the gas distribution back bone. This flexibility was not designed into previous attempts at gas let down, and so they proved to be difficult to control in practical applications.