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Submerged Pumps and Expanders with Magnetic Coupling for Hazardous Applications

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ABSTRACT

Presentation and discussion of a unique magnetic coupling design that has been developed for cryogenic service in liquefied gases that allows the submerged motor or generator to be isolated from the process fluid in a safe, proven and compact design.

INTRODUCTION

In many applications, it is necessary to provide a pump or expander to either increase or decrease pressure in a flow stream. This is particularly challenging when the fluid is a chemical such as ammonia, which is potentially conductive and corrosive.

To meet the challenges of providing a submerged motor driven pump or submerged expander driven generator in a hazardous or toxic liquid a unique design has been developed using a magnetic coupling.

This paper will discuss designs and applications of submerged magnetic coupling rotating machinery for use in liquids that pose a safety risk due to leakage or flammability and where it is not desirable to submerge the motor or generator directly in the fluid.

SUBMERSIBLE MOTOR DESIGN VERSUS CONVENTIONAL EXTERNAL MOTOR

A pump or expander can be designed with a shaft extending out of the fluid with the motor or generator outside of the tank, but that presents some important issues. With an external motor or generator, a shaft sealing system must be used to contain the fluid at the exit point of the shaft and the motor or generator must be supplied with a proper housing and possibly a purge system to allow installation in a hazardous location.

An external motor or generator design is not only more complicated, but it also increases safety risks as the shaft seals can leak the product into the atmosphere and the motor or generator is also exposed. In some cases, for example in a large storage tank, this design is not practical as the shaft would need to extend for quite some distance to the top of the tank.

The advantages of using a submersible design with magnetic coupling are as follows:

Elimination of Shaft Seals: The submersible design does not have a shaft penetrating the tank or vessel so no shaft seals are required, which are prone to leakage. This is the main aspect for this design as it is inherently much safer for rotating machines pumping a hazardous fluid. By eliminating shaft seals, there is also no external gas seal equipment required such as buffer fluid pumps, etc.

No Alignment Problems: Conventional, external motor pumps normally have a mechanical coupling located between the motor and the pump for driving the pump. This requires precise alignment during installation which is critical for reliability. The submerged design with a magnetic coupling is mounted together as an assembly and alignment is accomplished at the factory when the machine is manufactured and assembled. Plus, the magnetic coupling is not a direct mechanical connection, so there is additional tolerance allowed between the drive shaft and the driven end.

Compact Size: A motor or generator submerged in the liquid is smaller than a conventional design and with no seal chamber or coupling in between, the overall size is much more compact and lighter.

Explosion Proof Motor Not Required: In a conventional design, the motor is outside of the containment area and must be provided with an explosion proof housing to meet hazardous area requirements depending on the fluid being handled. With the motor or generator located inside the tank or vessel, which is classified as a non-hazardous area due to the lack of oxygen during operation, the motor or generator is not required to be explosion proof.

No Bearing Lubrication System Required: Conventional pumps with external motors may require an external lubrication system for the motor bearings. This adds complexity to the system and requires maintenance.

The bearings in the submerged motor design with magnetic coupling are lubricated by the product in the wet or hydraulic end, and sealed grease bearings are used in the dry end where the motor or generator is located. The sealed grease type bearings require no external equipment or maintenance except periodic replacement which is common with any bearing. The bearing life is very good since the bearings are located in a very clean, contained environment.

Reduced Noise: The submerged motor design is much quieter as the motor and all other components are submerged and isolated in the tank or vessel. This eliminates the need for any external noise attenuation.

No Delays for Startup: In a conventional design, prior to startup, the lubrication system and seal systems must be started and prepared. In the submerged magnetic coupling design, since there are no external lubrication or seal systems, the pump or expander is always ready for immediate startup.

MAGNETIC COUPLINGS

Magnetic couplings have been used for many years in a wide range of applications including chemical processes and the medical industry. A magnetic coupling with a can type sealing element can provide separation of hazardous chemicals from the system side or vessel to prevent leakage of those chemicals to the outside environment.

The magnetic coupling is made up of three basic parts; the inner rotor, the can and the outer rotor. With the outer rotor driven by the motor, a magnetic field is produced which penetrates the can and creates a magnetic connection with the magnets of the inner rotor, causing it to rotate with the outer rotor. The inner rotor is connected to the pump or turbine shaft which is immersed in the product.

The type of magnetic coupling normally used for this application is a laminated can design and a slotted outer can which reduces eddy currents to improve performance. All of the main components are stainless steel with PTFE seals in the can segments. The magnets are contained in stainless steel membranes in the outer and inner rotor portions of the coupling.

One of the biggest advantages of this type coupling is that there are no rotating seals on either shaft and the can provides complete separation between the product and the motor environment.

Other advantages of the magnetic coupling are:

Reduced Vibration: Since there is no direct mechanical connection, any vibration in either shaft is not transmitted directly to the other which helps to reduce overall vibration.

Protection from Overload: If the maximum torque of the coupling is exceeded, the magnetic field collapses and the motor side is protected from overload damage. Therefore if mechanical damage occurs in either section, it is not transmitted to the other section, limiting overall damage.

No Maintenance Required: Since there is no contact between parts of the coupling and therefore no wear, maintenance is not required. The magnets retain their strength indefinitely and do not require periodic replacement.

Very Low Heat Transfer: With the slotted can design, eddy currents are reduced to a minimum and there is very little heat transfer to the pumped fluid or to the motor housing section.

Simplified Alignment: Since the coupling separates the two shafts with no direct mechanical connection, the alignment does not have to be very precise and some misalignment can be taken up in the coupling.

MAGNETIC COUPLING PUMPS

While the design discussed here can be used in a variety of fluids, it was initially developed for use in liquid ammonia. Ammonia is a particularly difficult liquid to handle, as it is very hazardous to personnel and can cause asphyxiation, even at very low concentrations. In addition, ammonia is flammable, highly corrosive to copper and copper alloys, and has a huge affinity for water which can make it highly conductive unless it is in its purest form.

To meet the challenge of pumping liquid NH_3, a submersible, magnetic coupling design was developed which is in use today in several locations (Figure 1). This design uses a sealed stainless steel casing to house the motor, which has inert nitrogen gas fed into the casing from the outside of the pump vessel or tank to keep the motor section dry and free of ammonia (Figure 2). The nitrogen pressure can be maintained to prevent ammonia from entering the casing and also to provide the proper differential pressure across the magnetic coupling membrane.

The key feature of the design is safety. The pump has no penetrations through the vessel or outer casing with a shaft seal, so there is no possibility of leakage into the surrounding atmosphere. In addition, since the motor is

Figure 1: Installation of a Removable Type Ammonia Pump with Magnetic Coupling

located within the tank or vessel along with the pump hydraulic section, there is no need for an explosion-proof housing around the motor since the interior of the tanks, under operating conditions, have no oxygen present.

These pumps can be installed in a suction vessel to act as an in-line design that can be used in almost any location where it is necessary to transfer liquid or boost pressures, including tanks where a few specifications still require bottom or side connections. The liquefied gas industry almost universally recognizes the enhanced safety of having no storage tank penetrations below the liquid level, where pumps are installed in storage tanks in a pump column, similar to a submersible deep well design, to transfer liquid from the storage tank to another location such as a ship or other process area.

For larger storage tanks, the retractable, or in-tank, type of magnetic coupling pump is an excellent choice for the application as it is installed through a column from the top of the tank. In many ammonia tank applications, where the liquid is stored at near atmospheric conditions, an external shaft seal type pump is used, which requires a side or bottom penetration from the storage tank. The penetrations, with valves in the piping, are potential leakage areas, and the pump type used would have the same issues as noted above with the external motor and shaft seals.

For the electrical portion of the design, the power cables from the motor are enclosed in a flexible conduit/hose arrangement that is seal welded on both ends. This conduit, which is connected from the head plate at the top of the tank to the motor casing at the bottom, allows nitrogen gas to be applied into the hose and casing to keep those spaces inert and free from moisture. This space can also be monitored to determine if any leakage is present, and if such an event happens, the pump electrical system can be shut down immediately for safety purposes.

To enable the power cables to exit the tank, a dual seal penetration is used, which is the same design used for pumps and liquid expanders used in LPG, LNG, ethylene and other liquefied gas applications. The design meets all of the more common codes such as NFPA 59 and 59A, and meets the requirements of NFPA 70, National Electrical Code, for equipment used in Class 1, Division 2, Group C/D atmospheres. The equipment also meets applicable IEC codes for Class I, Zone 1 or 2 hazardous areas. This system has been in regular use in thousands of applications and has proven to be extremely safe and reliable.

For the pump design itself, many features from standard submerged motor pumps are used. The hydraulic end of the pump carries the impeller(s) and inducer as well as the wet end coupling, and the bearings are product lubricated. This is a stiff shaft design which uses low mass rotating components made from aluminum to ensure minimal radial loads and low vibration, thereby extending bearing life. The motor section, or dry end, uses typical shielded grease filled bearings with the magnetic coupling attached at the lower end. (Figure 2)

The pump design also uses an inducer, or axial flow impeller, in the inlet to provide very good NPSHR characteristics (Figure 2). The inducer is designed to enable operation of the pumps in very low liquid level situations and is perfectly suited for storage tanks on land and in marine applications.

Another key feature in the design is the use of a thrust balancing system to minimize axial thrust loads on the bearings (Figure 2). When using the pumped product, which in this case is a liquefied gas, for lubrication, it is imperative that the axial thrust loads are balanced to prevent vaporization of the fluid in the bearings to ensure reliability. This type of system has been used in many thousands of liquefied gas pumps all over the world with very high reliability.

The current magnetic coupling design was developed in the mid 1990’s and eleven units are now installed and operating in Taiwan and mainland China with the most recent units just installed in a plant near Shanghai.

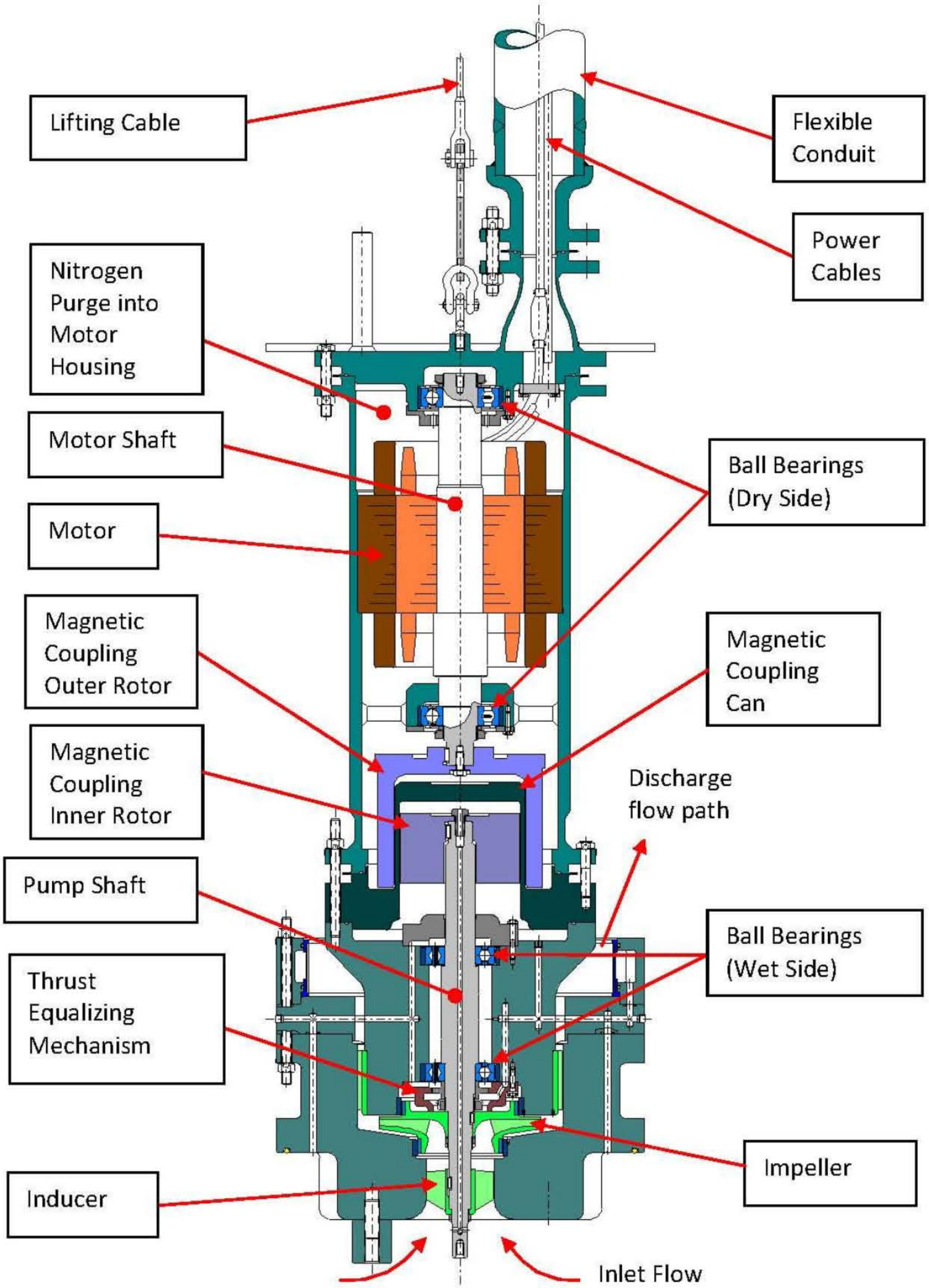

Figure 2: Pump Design with Magnetic Coupling

MAGNETIC COUPLING LIQUID EXPANDERS

As the magnetic coupling pump for ammonia service has now been in operation for a number of years, it has become obvious that the design can be adapted for other rotating machine applications. The design can be used in the process for manufacturing liquid NH3 and many other liquefied gases, or in any liquid stream where a pressure reduction is required and the fluid is incompatible with a standard submerged design. A patent for the expander as shown in Figure 3 for the ammonia process is pending.

In the cryogenic liquefaction process, the process gas must be cooled, compressed, and expanded in order to liquefy the gas for efficient and compact transportation and storage. As part of the process, the liquid pressure must be dropped to allow the liquid to go into another stage of compression, or for transfer into low pressure storage. Typically, the pressure drop is accomplished by expanding the compressed fluid in an isenthalpic process across a Joule-Thomson (JT) valve. In the JT pressure reduction, the enthalpy of the liquid does not change, and depending on the inlet and outlet pressures, the temperature of the fluid may increase or decrease. Pressure drop across a JT valve also creates high turbulent friction losses, wasting energy through frictional heating of the fluid and reducing the amount of the liquefied gas. Substitution of liquid expanders in place of liquid JT valves will increase the amount of liquefied gas produced and improve the overall process efficiency while recovering electric power.

In order to provide a much more efficient drop in pressure, as in an isentropic expansion, a rotating machine such as an expander can be used in place of a JT valve (Figure 3). In LNG liquefaction plants, expansion turbines have been regularly installed for several years, and that type of expander is now used in many liquefaction systems today. These machines are now well proven and are known to increase the overall process efficiency by as much as 4% to 7%. Figure 4 is a simplified schematic comparing the benefits of installing a liquid expander in the place of a JT valve in an existing liquefaction plant. The key difference between a JT valve (Fig. 4a) and an expander (Fig. 4b) is that the expander reduces the vapor resulting from the liquid expansion. This reduction in vapor output decreases the required re-compression which in turn increases the percentage of both the feed gas input and the process output, all while recovering energy. As an additional benefit, replacing a JT valve with an expander does not require other plant size or capacity changes.

The expander design uses many of the same features found in the submerged motor cryogenic pumps, but uses nozzle rings to direct the flow into the rotating expander runners, which are connected to a generator on a common shaft. The torque created by the generator is then used to extract energy from the fluid stream, thereby creating the thermodynamic efficiency that essentially produces more liquid versus vapor in the expansion process. The design uses fixed vane nozzle rings directing the flow into Francis type radial inflow runners which are designed to extract the maximum amount of torque from the fluid as possible (Figure 3). The machine is also often enhanced using variable speed technology where the generator speed is controlled using a Variable Speed Constant Frequency (VSCF) controller, thereby providing flexibility in the operating range to optimize the efficiency of the process system.

To take advantage of the natural flow of vapor in the upward direction, one of the noticeable differences in the expander design is the location of the generator in the lower portion (Figure 3). By placing the generator in the lower section, the lighter density fluid that has a slight rise in temperature after passing through the generator as well as the expanded liquid can rise naturally and helps improve efficiency.

For axial balancing, even though the flow in the expander is the reverse of the pump design, the flow and pressure distribution through the thrust balancing system is the same. This allows the same proven design to be used for axial balancing. The materials, bearings and other features and design techniques used in the pump are also basically the same as the expander including the installation inside a certified pressure vessel, which means there is reduced risk as proven design techniques and features are used extensively.

As previously described for the pump design, when the liquid is either conductive or not compatible with the motor materials, an expander that uses the same hydraulic and generator technology as the machines used for LNG liquefaction, combined with the magnetic coupling technology, can be used to produce a unique machine with proven technology. By marrying these technologies together, many plants can now benefit in a much more efficient process which will lead to an increase in production while reducing required power for compression. In fact, by replacing the traditional Joule-Thomson type expansion system in an existing plant with the expanders, the same volumetric flow can be achieved with a 5% reduction in compression and 5% reduction in overall liquefaction energy.

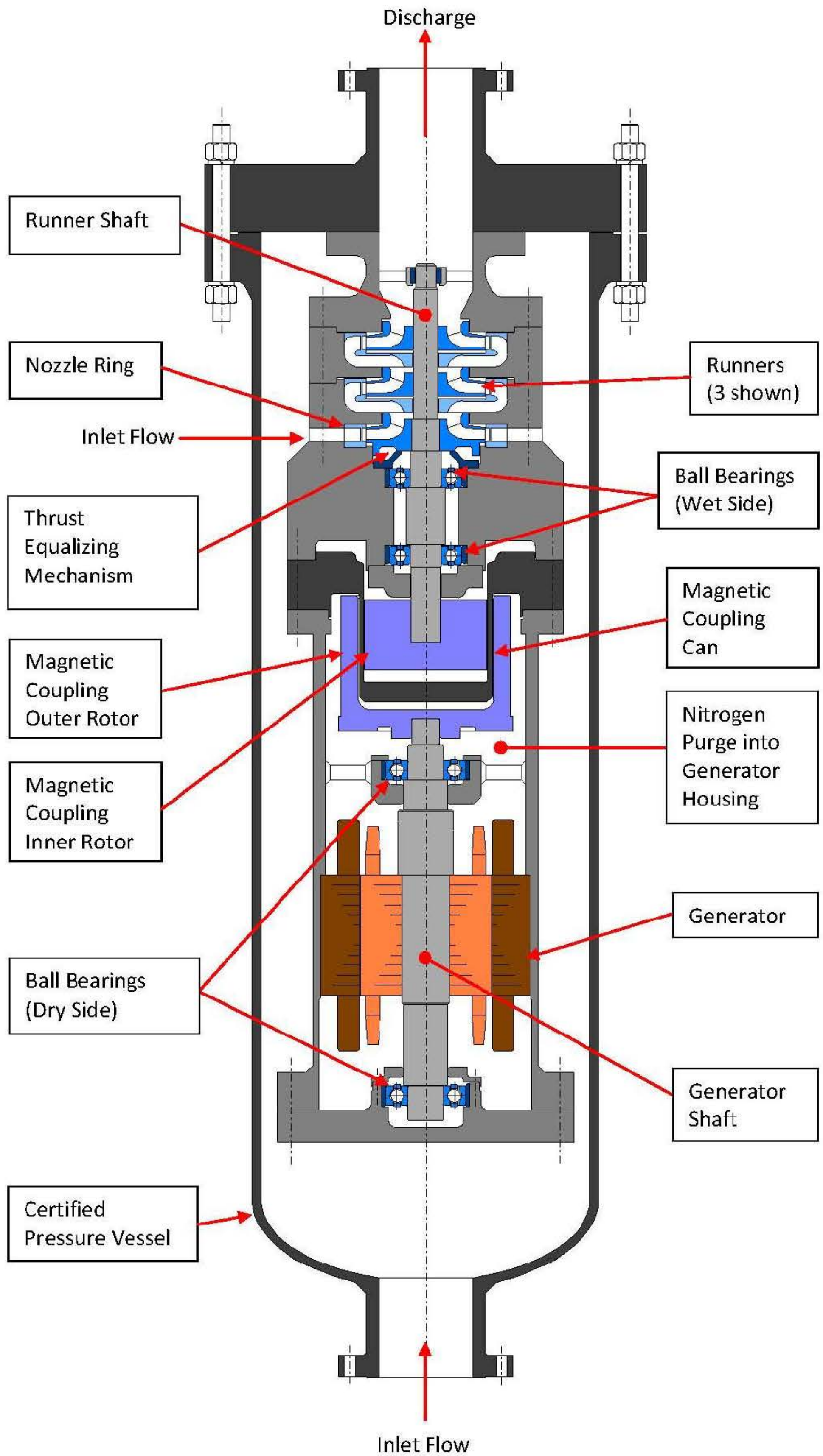

Figure 3: Expander Design with Magnetic Coupling

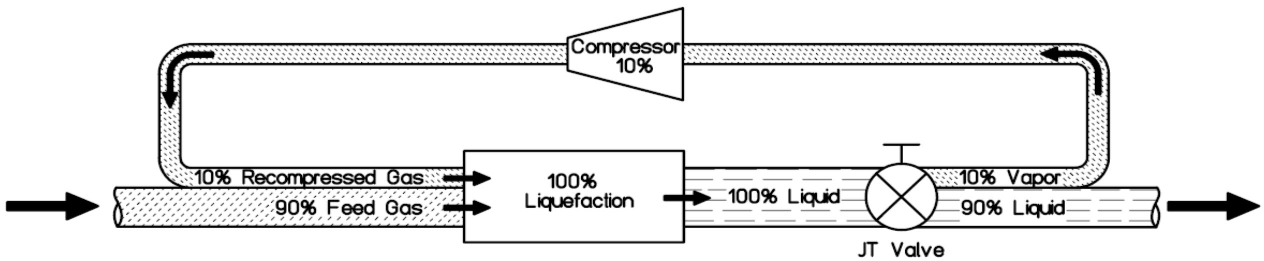

Figure 4a: Liquefaction Process using a Joule-Thomson Valve

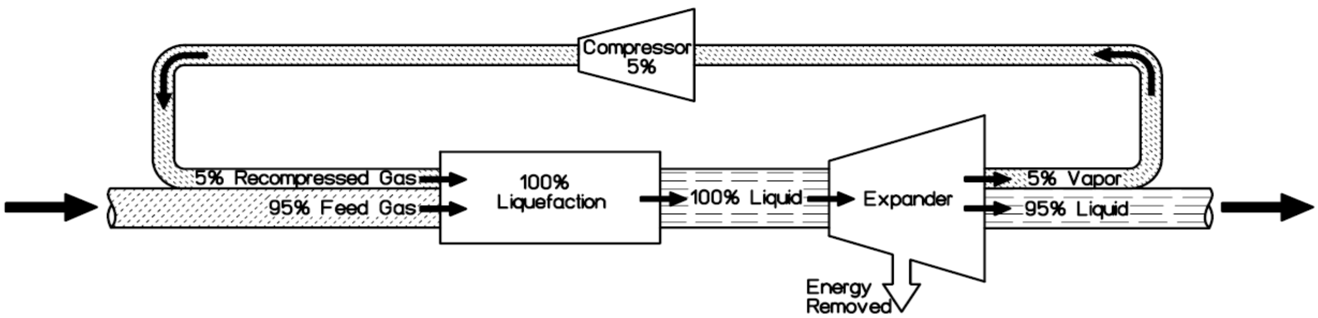

Figure 4b: Liquefaction Process using an Expander

IMPROVING THE LIQUEFACTION TRAIN USING TWO-PHASE EXPANDERS

The history of liquefaction starts with the first continuous process invented in 1895 to liquefy air which essentially compressed and cooled and then expanded the gas to a lower temperature until the gas condensed. Ever since then, major improvements have been made to the process beginning with the gas expander. Another leap in the technology came with the replacement of the JT valves in the liquid expansion step with liquid expanders. It follows that the improvement in the liquefaction process is with the integration of two-phase expanders to replace the JT valves used for two-phase expansion.

There are several two-phase LNG expanders in operation and the design is on the forefront of two-phase expansion technology. Figure 5 shows the current hydraulic design for LNG two-phase expanders which can easily be adapted to operate within the magnetic coupling design for other liquid applications. Again, by combining already known and proven technology in the LNG and ammonia industries, a two-phase expander can be designed to replace the two-phase JT valve in the liquefaction or pressure let-down process.

In Figure 5, the portion in red is stationary and is the fluid inlet with a series of converging guide nozzles. The nozzles speed up and direct the flow into the runner, which is rotating, and is shown in gold. The runner begins the process of reducing the fluid pressure through isentropic expansion by converting the fluid energy into shaft power.

In the next step, as the fluid begins to vaporize, it goes into the exducer (shown in yellow). The exducer extracts energy from the fluid through its expansion into the vapor phase, imparting additional rotational energy (torque) to the shaft. The expansion is isentropic, and therefore the liquid temperature decreases as it passes through the exducer.

In the final step, the fluid enters the draft tube (shown in green), which completes the process by removing rotational energy and increasing pressure. This recovers some of the vapor and allows for a greater pressure drop across the hydraulic section resulting in increased energy extraction.

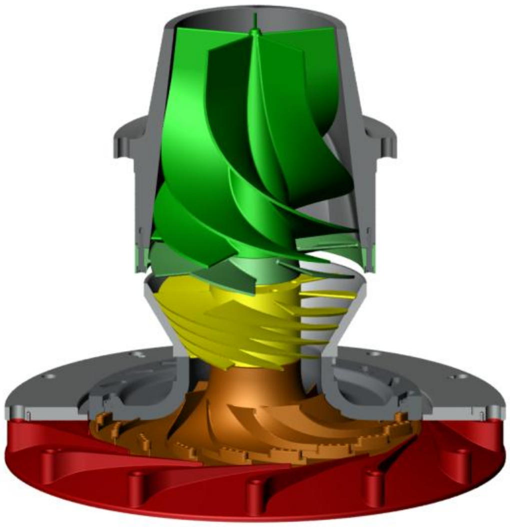

Figure 5: Two-Phase Hydraulics

The two-phase expander recovers most of the available energy from the liquid stream while further cooling the liquid and thus reducing boil off downstream and increasing liquid production. By replacing a two-phase JT valve with a two-phase ammonia expander, the enthalpy of the liquefied gas is significantly reduced and the frictional heating in the process is kept to a minimum. More importantly, the two-phase expander eliminates the need for JT valves in the liquefaction process.

SUMMARY

For pumps in difficult liquefied gas applications, a unique design using proven technology has been developed that enhances safety in a very difficult environment. The design not only improves safety but in doing so, also increases reliability by removing troublesome components that are prone to leakage.

Furthermore, by marrying proven liquefied gas pump technology with proven liquid and two-phase expander technology, a new expander with a magnetic coupling can be installed in any liquefaction or pressure let-down process to increase plant efficiency while keeping the same inherent safety philosophy intact. Additionally, the application of two-phase expander technology in liquefaction will increase liquid production while recovering electrical power and thus further improve overall plant efficiency.

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