CONTINUOUSLY TRANSIENT OPERATION OF TWO-PHASE LNG EXPANDERS

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ABSTRACT
Variable speed LNG expanders are able to control the mass flow of LNG plants by changing the rotational speed. Some LNG plants, particularly small Nitrogen rejection plants have continuously changing mass flows, which the expanders control with continuously changing rotational speed. The expanders operate therefore in a continuously transient mode. The paper presents long-term field experience of two-phase LNG expanders operating with continuously changing rotational speed.

INTRODUCTION
A significant quantity of natural gas is not produced economically because its quality is too low to enter the pipeline transportation system without some type of processing to remove the undesired gas fraction. Such low-quality natural gas contains significant concentrations or quantities of gas other than methane. These non-hydrocarbons are predominantly nitrogen, carbon dioxide, and hydrogen sulfide, but may also include other gaseous components. The most reliable and widely used process for nitrogen rejection from natural gas consists of liquefying the feed stream using temperatures in the order of -300°F and separating the nitrogen via fractionation. In order to reduce the gas temperature to this level, the gas is compressed, cooled by heat exchangers, and expanded to a low pressure over a Joule-Thompson valve.

The turbulent friction losses in a pressure drop across a Joule-Thomson valve are very high as is the energy wasted in frictional heating of the fluid. To keep frictional heating in the process to a minimum, two-phase liquid expanders replace Joule-Thompson valves. This is due to the near isentropic expansion process achieved while generating shaft power from previously wasted two-phase energy.

Some nitrogen rejection plants, especially smaller ones, experience a continually changing mass flow rate. To control this, two-phase expanders utilize variable speed drives to adjust the mass flow rate through the expander by continually adjusting its rotational speed. Two of these type of expanders were built and installed at the existing nitrogen rejection plant and have been in continuous operation for over one year. Regular inspections of these expanders show no failures in bearings or materials and the vibration levels are less than 20% of the API 610 allowable levels [10].
VARIABLE SPEED EXPANDER DESIGN

The design of the two-phase expander used to replace the Joule-Thompson valve in nitrogen rejection plants is based on existing turbine and expander technology. A hydraulic nozzle transforms the hydraulic energy of high-pressure fluid into kinetic energy. A runner and exducer attached to the shaft transforms the kinetic energy into mechanical shaft power. Finally, an electric power generator converts shaft power to electrical energy [5].

There are two basic methods used for power generation in cryogenic technology. One method utilizes an externally cooled generator coupled to the expander and mounted outside the cryogenic liquid. The second method uses an induction generator mounted integrally with the expander shaft. Cryogenic liquid completely submerges and cools this configuration [6].

Figure 1 shows the cross section of the two-phase expander installed in the nitrogen rejection plant. This particular design utilizes a completely submerged hydraulic expander and induction generator mounted to the same shaft. The hydraulic expander consists of a radial inflow nozzle ring that generates rotational fluid flow, a reaction turbine runner and two-phase jet exducer that transform the kinetic energy of the fluid to shaft power.

![Cross Section of Two-Phase Expander](image)

**Figure 1:** Cross Section of Two-Phase Expander
Figure 2 shows an enlarged view of the two-phase runner assembly. The flow direction of this two-phase expander is upward to take advantage of the buoyant forces of the vapor bubbles and to minimize flow induced vibrations. The hydraulic assembly is designed for continuously decreasing pressure to avoid any cavitation along the two-phase flow passage [1].

Figure 2: Close-up of Expander Hydraulics

To effectively replace the Joule-Thompson valve in a nitrogen rejection plant, two-phase expanders must be able to adjust to accommodate continually changing mass flow rates. To accomplish this, a variable speed constant frequency drive (VSCF) is used. A VSCF drive allows the generator to operate at any speed desirable and still supply constant frequency power to the power grid [6].
TEM DESCRIPTION

One problem observed in non-thrust balanced cryogenic turbine expanders is heavy axial loads on the rotating assembly and bearings causing a decrease in efficiency due to friction losses. To alleviate this problem, some cryogenic turbine expanders are equipped with an axial thrust-balancing device to create a no axial load condition. Common thrust balancing devices use the hydraulic pressure of the fluid to equalize the axial thrust. Originally developed for centrifugal pumps, the design of the Thrust Equalizing Mechanism (TEM) has permitted them to operate maintenance free in the field for several decades. The mechanism is entirely and unconditionally applicable to two-phase expanders. The benefits of installing this Thrust Equalizing Mechanism in hydraulic expanders are; extended life, increased reliability, higher efficiency and reduced operational costs [2].

This two-phase expander uses the self-adjusting mechanism design because it performs equally well over a wide range of differential heads, flow rates and variations in turbine speed. It operates independently of the direction of the rotational axis, which can be either vertical or horizontal. It will also operate if the turbine outlet is located above or below the inlet.

Situated on the backside of the first stage turbine runner, the runner implements the thrust equalizing mechanism into its design. It consists of a two-orifice system, one fixed orifice and one variable orifice. The design of the turbine shaft allows for slight movement in the axial direction thus opening or closing the variable orifice. On the left side of Figure 3, the turbine shaft is in its maximum upward position closing the variable orifice. This creates a high-pressure condition in the inner ring chamber below the runner effectively creating down thrust. On the right side of Figure 3, the shaft is in its’ lowest axial position opening the variable orifice to its maximum position. This causes a lower pressure condition in the inner ring chamber creating an up thrust condition. Between these two limiting axial shaft positions, there is one position at which the sum of all the axial forces due to upstream and downstream thrust is equal to zero. In this position, the equilibrium of axial forces on the shaft causes it to run in a balanced position [3].
Figure 3: Thrust Equalizing Mechanism
OPERATION OF TWO-PHASE EXPANDER

During the operation of the two-phase expander, the mass flow rate required to flow through the expander is continuously changing. To cope with this, the rotational speed of the expander shaft must continually adjust to match the required flow rate. Figure 4 shows the typical relationship between expander speed, differential pressure and flow rate. At a constant pressure drop across the expander, represented by the dotted line, the mass flow rate through the expander increases as the rotational speed decreases and decreases as the rotational speed increases.

![Figure 4: Typical Two-Phase Expander Performance](image)

Adjustment of the rotational speed is accomplished by adjusting the VSCF controller using a PID control system. Figure 5 shows a simple schematic of the two-expander system. In this system, plant throughput is measured by the change in the liquid level in the column. When the liquid level in the column begins to increase, the mass flow rate into the system is increasing. This causes the PID controller to decrease the rotational speed of the turbine allowing a higher mass flow rate through the expander. When the liquid in the column begins to decrease, the PID controller increases the rotational speed of the expander effectively restricting the mass flow rate through the expander.
OPERATIONAL TESTS
An on-site operational test schedule was implemented to verify the performance and long-term reliability of this novel two-phase expander. Two turbines were installed on site and subjected to normal operating conditions for a period exceeding 9000 hours. During this period of operation, the expanders operated at a wide variety of constantly changing mass flow rates, differential pressures and rotational speeds. Several different hydraulic component designs were mounted to the two-phase expander during the long-term operation and testing to verify that two-phase expanders designed for a wide range of duties would operate reliably. These different hydraulic components included several different nozzle rings of varying exit angles, two different runners with different blade heights and exuders with varying blade lengths.

A data acquisition method was developed to accurately measure and record all parameters of expander operation. This was accomplished by accessing data automatically stored in the nitrogen rejection facility’s DCS. This enabled measurements of differential pressure, mass flow, temperature drop, vibration and power to be continually monitored and recorded without disrupting the facility’s day-to-day operation. An Eddy probe system was mounted to the end of the expander shaft to
monitor the expander shaft’s axial position and rotational speed. The voltage signal from the Eddy probe driver was then routed to a high-speed data acquisition system that monitored and recorded axial position and rotational speed. These measurements of all relevant operational data were recorded and analyzed throughout the test to observe the long-term effects of continually transient operation.

RESULTS

Before long-term operational tests of the expanders could begin, it was necessary to confirm that the expanders would operate within their design specifications. This was done by measuring a wide range of expander hydraulic performance. Figure 6 shows the hydraulic performance during this initial test phase. The graph shows a wide variety of mass flow rates, corresponding differential pressures and expander efficiency for the expander operating at three different speeds. The data presented in this figure verifies that the expanders were operating at their design specifications.

Figure 6: Tested Hydraulic Performance Of Two-Phase Expander
The next step in the operational test process was to show that the thrust-balancing device was working properly. To do this, axial shaft position was measured and recorded for expander start-up, shutdown and automatic operation. Figure 7 shows the axial shaft position during expander start-up. As the expander control valve was opened, the expander shaft raised from its’ lower axial limit to its’ upper axial limit. Within 25 seconds, the axial thrust on the turbine shaft was completely balanced with the axial shaft position between its’ upper and lower limits.

![Axial Shaft Position at Start-Up](image)

**Figure 7:** Shaft axial position during start-up

With the expander running at normal capacity under automatic control, the shaft axial position was measured and recorded. The axial shaft position during automatic operation is important in determining that the thrust-balancing device will operate at a wide variety of flow rates. Figure 8 shows the expander shaft axial position during this automatic operation. The axial position of the shaft can be seen to remain between its’ upper and lower axial limits throughout the operation. Figure 9 shows the axial shaft position during expander shutdown. When the flow through the expander is reduced to zero by the control valve, the shaft returns to its’ lower position. This process ensures that the thrust-balancing device was not damaged during start-up or normal operation.
Figure 8: Shaft axial position during normal operation

Figure 9: Shaft axial position during shut-down
The next step in the operational test process was to verify the expander's ability to automatically adjust to the continually changing mass flow rate through the plant. Figure 10 shows the flow rate and expander speed over 30 minutes. The dashed line represents the volumetric flow rate measured at the inlet of the turbine. The solid line shows the expander speed measured by the expander VSCF’s monitoring system. These measurements show that as the flow rate through the expander decreases, the shaft speed increases and as the flow rate increases, the speed decreases.

![Expander Flow and Speed](image)

**Figure 10:** Expander flow and speed during normal operation

In figure 11, the expander flow is plotted against the expander shaft speed over the same period as figure 10. The linear relationship between flow and speed proves the accuracy of the measurements taken. The expander follows the rotating machinery affinity laws that are actually corollaries of the Buckingham Pi theorem with the dimensionless flow coefficient. The first affinity law gives a linear relationship between rotational speed and flow [7].

Due to the automatic balancing of the TEM system, continually transient flow conditions will result in continually transient shaft axial position. To further verify this type of operation of the expander, analysis of the shafts axial position over a relatively short period of time was conducted. Figure 12 shows the shaft axial position over a period of .2 seconds. This figure shows that the shaft is continuously moving in the axial direction to balance the changing thrust acting on the shaft.
Figure 11: Normalized Flow vs. Speed

Figure 12: Axial Shaft Position
CONCLUSION
Long-term operational tests conducted at a nitrogen rejection plant in have verified the use of two-phase variable speed expanders to control mass flow rate through the plant. These tests, conducted for over one year, have shown that these expanders can operate consistently and reliably for a wide range of flow conditions. Post test inspections of critical components on both expanders show no signs of damage or excessive wear. Due to the complex nature of two-phase systems, the development of new methods of predicting performance and monitoring the operation of two-phase variable speed expanders in nitrogen rejection plants will be necessary to ensure an optimized design.


