Experimental Analysis of Hot Startup and Cold Startup of Bog Compressor at LNG Terminal

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Abstract - Liquified Natural Gas (LNG) terminals are crucial for receiving, storing, and transferring natural gas in liquid form. A key component of these terminals is the Boil off Gas (BOG) compressor, which is used to manage the vaporized LNG during storage and transfer processes. The compressor's ability to start up efficiently is critical for maintaining smooth terminal operations, especially in managing boil-off gas (BOG), which occurs when LNG naturally vaporizes due to heat ingress into storage tanks. This study presents a detailed comparison between Hot and Cold Startup procedures for Boil-Off Gas (BOG) compressors at an LNG terminal. BOG compressors are crucial for managing vaporized LNG during storage and transfer, and their startup processes significantly impact system performance and efficiency. Hot Startup refers to initiating the compressor without achieving the cryogenic temperature when the system components are at operational temperatures and pressures while Cold Startup occurs after an idle period, by gradually cooling the line and compressor for operating system at lower pressures and temperatures.

The experimental analysis was carried out for hot startup and Cold startup which primarily focused on key parameters such as pressure, temperature, energy consumption, Flow rate, cost and system stability during both startup conditions. The results indicated that Hot Startup requires lower energy consumption and results in quicker stabilization but leads to system stress thereby damaging the internal machinery parts whereas the cold startup requires more time, higher energy input leading to concerns about gas loss and environmental impact.

The findings highlight the operational challenges and efficiency trade-offs associated with each startup type, the design modifications made in cold start type to cater to the needs of optimizing LNG terminal operations and enhancing overall system performance without compromising with economic losses.

Keywords: *BOG compressor, Hot startup, Cold startup, LNG industry*

2.INTRODUCTION

Natural gas (NG) is considered one of the most promising clean energy sources and is becoming increasingly important in our daily energy consumption. NG is commonly stored and transported either as compressed natural gas (CNG) or liquefied natural gas (LNG). When liquefied, LNG occupies only 1/600th of the volume of that natural gas occupies at atmospheric pressure. Due to these physical properties of NG, transporting it in LNG form is the most economical option for long-distance shipment.

LNG is typically stored in containers at extremely low temperatures, around -162°C. However, some heat inevitably transfers from the surroundings to the cryogenic LNG, causing continuous vaporization known as boil-off gas (BOG), which occurs at approximately 0.05% per day by mass. At LNG terminals, BOG generation increases significantly during the unloading of LNG from ships. The accumulation of excess BOG raises the pressure inside the storage containers. Thus, effective management of BOG is essential.

The two main methods to recycle BOG are direct compression into distribution pipelines or re-liquefaction. The latter method is more commonly used because it offers 30-60% higher energy utilization efficiency. A typical BOG recycling system at an LNG terminal is illustrated in Fig. 2.1, where BOG is first compressed by a BOG compressor and then re-liquefied in a BOG recondenser. The BOG compressor is a crucial component for managing the boil-off gas generated from the system.

Currently, BOG compressors employed in LNG terminals are primarily classified into vertical labyrinth compressors and horizontal piston ring compressors. The compressors operate under cryogenic suction conditions, with inlet temperatures ranging from approximately - 155°C to -110°C and differential pressures between 40 mbarg and 2.6 barg. These compressors are designed in multi-stages, consisting of two or three stages of compression. Due to the low suction temperature and pressure conditions, the pressure ratio distribution across the stages differs from compressors operating at ambient conditions, with the first compression stage exhibiting a significantly higher-pressure ratio than subsequent stages to accommodate the vapor compression requirements of boil-off gas.

The startup procedure for these compressors plays a key role in determining system performance, energy consumption, operational stability. Two primary types of startup procedures are commonly encountered: Hot Startup and Cold Startup. Two stage non lubricated Reciprocating compressors are suitable for both hot startup & Cold startup are

3. Materials

BOG FUNDAMENTALS & COMPONENTS
BOG COMPRESSOR FUNDAMENTALS:

BOG compressor captures the vapor that evaporates from LNG during storage or transport due to ambient heat input and

compresses it for reuse either for Re-liquefying it, Re-injecting it into pipelines or burning it as fuel.
The major components of BOG compressor are:

- CRANKSHAFT

The crankshaft is a one-piece alloy steel forging to carry lubricating oil from the main bearings to the crankpin bearings. An oil seal arrangement is installed at the drive end to prevent oil leakage.

- CONNECTING RODS

The connecting rods are made of forged steel and are drilled the length of the rod to carry lubricating oil from the crankpin to the crosshead pin, bushings and shoes. Two- piece shell-type crankpin bearings are used to allow assembly on the crankpin. The crankpin bearings are precision-type (shimless) that are sized to the correct running clearance and do not require fitting.

- CROSSHEADS

The crossheads are fitted with shim-adjustable shoes. The shoes can be adjusted to ensure the correct running clearance between the crosshead and crosshead guide, as well as to correct rod runout.

- FRAME LUBRICATION SYSTEM

The frame lubrication system utilizes positive pressure to supply lube oil to the bearings and running gear components. The compressor is equipped with a shaft- driven main oil pump and an auxiliary motor driven oil pump. The auxiliary oil pump is designed to automatically activate and pressurize the lubrication system before startup, and it will also engage if the main oil pump fails.

- COMPRESSOR CYLINDERS

The non-lubricated (NL) cylinder is designed for operation without oil lubrication of the cylinder bore and piston rod packing. Cylinder surfaces and parts have an increased tendency to rust due to the lack of protection normally provided by the lubricating oil used in lubricated cylinders.
Cylinder gas passages, faces of cylinder heads and the inside of valve covers are normally coated with an aluminium paint to prevent corrosion. These passages should be periodically inspected and any bare spots cleaned and re-coated.

- PISTONS

The piston is mounted on the piston rod with a minimum clearance fit and is held tightly against a shoulder (or collar) on the rod by a piston nut. Each piston contains a number of piston ring and rider ring grooves, depending on cylinder operating pressures. The BOG compressor used in experiment contains single piece pistons. Single-piece pistons with rider bands located outboard of the piston rings use solid stretch-on rider bands for maximum rider band width and thickness.

PISTON RINGS
Piston rings are pressure-actuated seals; there must sufficiently side and bottom clearance in the ring groove so that gas pressure can force the rings outward against the cylinder bore. One-piece rings have a single end gap and are machined somewhat larger than the cylinder bore so that they contact the bore with some force prior to being pressure actuated.

RIDER BANDS
The function of the rider bands is to prevent metal-to-metal contact between the piston and cylinder bore. Rider bands commonly overtravel the cylinder counterbore by 1/3 of their width. Overtravel is the distance the rider band travels past the cylinder counterbore or valve hole at the end of the stroke; this prevents a wear step at the ends of the cylinder. The standard piston ring material is carbon-filled PTFE (Teflon®) which is suitable for most gases and pressures, and prevents bore scoring if lubrication is temporarily interrupted.

PISTON RODS
Piston rods have rolled threads and are induction hardened for high fatigue strength and long wear life. Piston rod coatings may be used for maximum surface hardness. For high pressure, small bore cylinders, the piston may be an integral part of the rod.

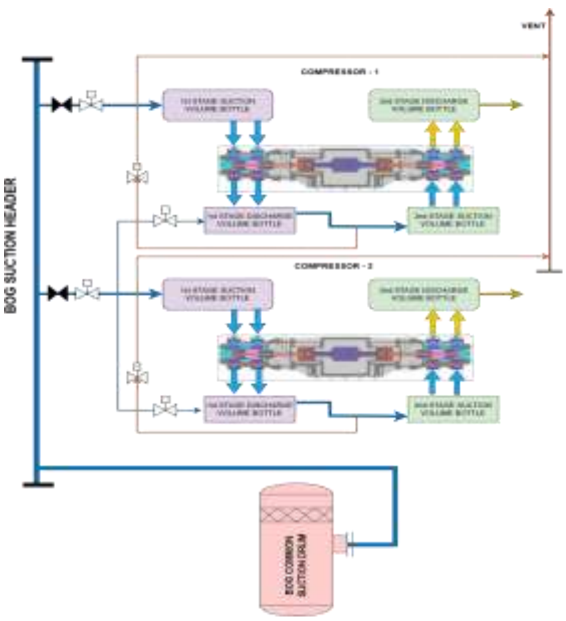

Fig 1 : Schematic of working of BOG compressor

4. RESULTS AND DISCUSSION

OBJECTIVE APPROACHES TO THE STUDY
This study employs an experimental approach to compare the hot startup and cold startup of a two- stage, non-lubricated reciprocating BOG (Boil-Off Gas) compressor used in the LNG plant. The various objectives of the study are:
Analysis and compare key performance indicators (KPIs) such as compressor efficiency, energy consumption, pressure stability, and time to achieve operational conditions during hot and cold startup procedures.
Quantify the energy consumption required for both hot and cold startup processes, assessing the efficiency of each method and the potential for energy savings.
Identification and evaluation of operational challenges encountered during hot and cold startups, including potential

system instability, pressure fluctuations, and risks of equipment damage.
Assessing the time taken for the system to stabilize and reach optimal operational conditions after a hot or cold startup, and compare the duration required for both processes.
Examine how different startup methods impact emissions, including Boil-Off Gas (BOG) management, flaring, and adherence to environmental regulations.
Based on experimental data, provide recommendations for best practices for hot and cold startup procedures that enhance efficiency, reduce environmental impact, and extend the operational lifespan of BOG compressors.
Propose strategies to optimize startup operations, minimize risks, and enhance performance across different startup conditions (hot, warm, and cold).

- STAGES OF RESEARCH WORKS:

Exploration: Initial investigation into problems faced by BOG compressors across the LNG terminal.
Experimental Setup: This phase involved preparing the equipment, instruments, and environment for testing. It ensured that all variables are controlled, and the necessary tools for monitoring and measuring the performance of the compressor are in place.
Testing Procedure: In this phase, the actual testing took place. The compressor is started up under both hot and cold conditions, and various parameters are measured
.

EXPERIMENTAL SETUP:

The BOG compressor used for experiment is a two stage non lubricating type of reciprocating compressor with four cylinders running at 495 rpm.. The diameter of first stage cylinder is 32 inches with piston displacement of 13202.3 m3/hr. Similarly, the diameter of the second stage cylinder is 19.5 inch with piston displacement of 4852.6 m3/hr.
Table 4.1: Equipment Specification: Compressor used for experiment:

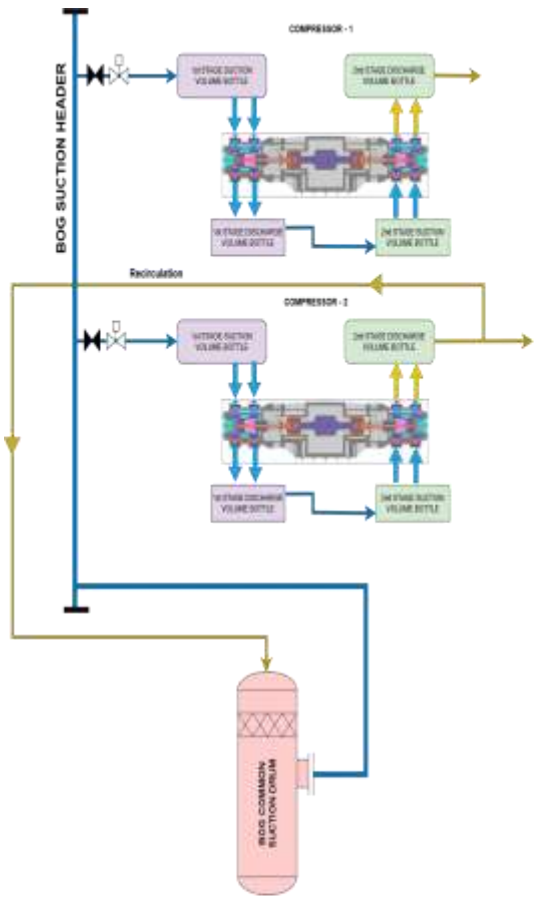

Fig 2 : Operation of BOG Compressor under Hot Startup

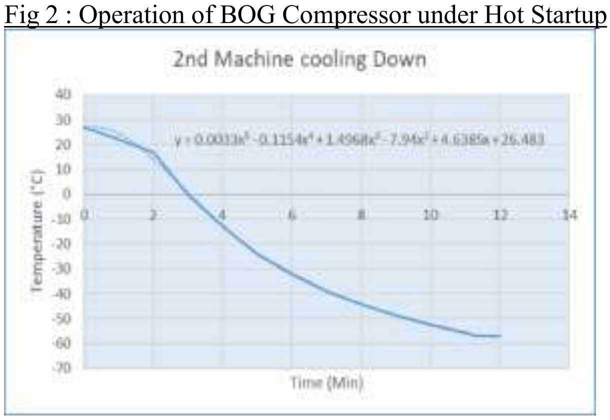

Fig 3 : Graph representing the cooldown curve of Standby compressor in 12 min

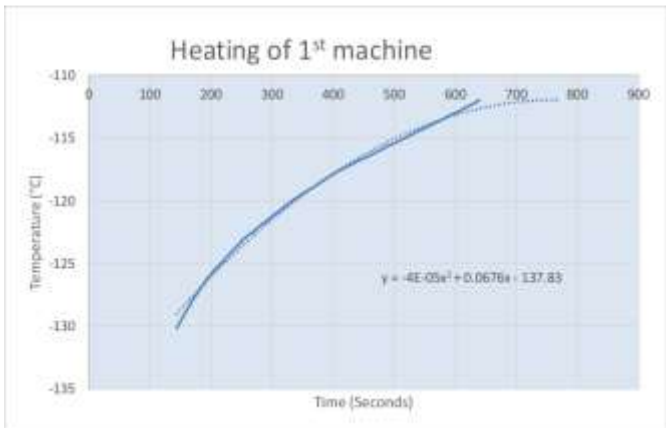

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Fig 4.7 : Graph representing the heating curve of running compressor due to mixture gas from standby compressor during recirculation

HOT STARTUP:

The discharge pressure reached till 1.81 barg. The 2^{nd} compressor was in 100 % circulation mode. The recycled gas went to common suction vessel and increased the temperature of the suction vessel due to thermal stress of piping. The 2^{nd} compressor was started, and the temperature went from $27^{0}C$ to $-57^{0}C$ in only 12 minutes whereas the temperature in 1^{st} compressor went from $-130^{0}C$ to $-110^{0}C$.

As the trip temperature is $-80^{0}C$, the experiment was continued, and it was observed that in 15 minutes the 1^{st} compressor reached $-100^{0}C$.

It was noticed that the second compressor took 17.54 minutes to come down to $-80^{0}C$. The 2^{nd} compressor was loaded with 25% and ready for send out. During this time the heating of 1^{st} compressor will be @ $1.5^{0}C$/min which equals to $26.31^{0}C$.

Therefore, 2^{nd} compressor started acquiring more pressure and increasing the temperature after put to 25% load. As a result, the piston and rider rings were damaged.

Alternatively, due to the non-functioning of 2^{nd} compressor, the suction temperature of 1^{st} compressor reached beyond $-80^{0}C$ and got tripped.

Due to this hot startup, the compressor faced mechanical failure. The piston and rider rings of the compressor got completely damaged and the compressors were stopped immediately affecting the plant availability.

Fig 4 Damaged piston rings of the compressor during hot startup process

5. CONCLUSIONS

This research demonstrates the feasibility, operational performances and environmental implications of operating the non-lubricating type reciprocating compressors used in cryogenic LNG handling. Through a sequence of experiments and case studies involving the starting of compressor at ambient temperature (Hot startup) and at cryogenic temperature (Cold Startup) the study demystifies how the parameters influence the performance of compressor, running time and its behaviour under different environmental conditions,

The experimental results indicate that in hot startup conditions the standby compressor underwent temperature changes from $27^{0}C$ to $-80^{0}C$ in 18 mins and was ready to start and operate. After startup the sudden increase of pressure and temperature resulted wear and tear of the piston and rider rings thereby forcing to stop. Due to the forced stop of the standby compressor, the recirculation gas which increased the temperature of common suction vessel and resulted in tripping of the running compressor. As a result the BOG compressors were completely shut down.

Alternatively, in cold start up conditions, the 1^{st} stage discharge of running compressor was diverted and connected to the 1^{st} stage discharge of standby compressor with continuous vent of the circulating gas. The gas entered the suction of running compressor and as the running compressor is already in cryogenic condition, the discharge gas gradually cooled the standby compressor, and the hot gas was vent to the atmosphere. The total process took about 79 hrs and the standby compressor was put to start after 79 hrs when it reached $-100^{0}C$. Approx. 2T of natural gas is vent to the atmosphere which has rich constituent of Methane, a major contributor to greenhouse gas.

In conclusion, from the environmental point of view, venting of natural gas to the atmosphere is not feasible and some alterations/modifications are required in the existing cold startup sequence to stop the venting and shorten the system readiness time of system readiness. Though in hot start up, it helps mitigate greenhouse gas emissions—particularly methane (CH_4) and carbon dioxide (CO_2)—by reducing the reliance on flaring and open venting, aligning operations with environmental regulations and sustainability goals. Financially, the energy savings translate into reduced fuel and utility costs, while lower emissions can decrease carbon tax exposure or generate benefits through emission trading credits. Still then the hot startup sequence is not recommended due to machine failure and plant shut down conditions along with safety override issues.

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