Instrumentation and control optimization of a standard pressurized LNG satellite terminal

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Master's thesis
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ABSTRACT

The use of natural gas (NG) is increasing worldwide due to its clean energy source and the fact that it offers a reduction of emissions related to global warming compared to other fossil fuels. It can be stored and transported as liquified natural gas (LNG) at a temperature of -162°C and pressure above 1 atm due to safety and economic reasons. The demand for LNG import has increased with the energy demand.

This has resulted in LNG receiving terminals being built onshore to import LNG. The LNG is stored in storage tanks, and it is vaporized through a regasification process before it is supplied to the end-user. After vaporization, it is delivered by pipelines to the end-users. However, not all end-users can be reached by a pipeline. This is where the use of an LNG satellite terminal comes into place. An LNG satellite terminal is a small-scale LNG receiving terminal, which includes all necessary processes and equipment to receive, store and vaporize LNG to end-users. The delivery of LNG arrives by mobile transport equipment.

The monitoring and the control of LNG processes in a safe manner are the most important parts of any LNG facility. Therefore, the control system needs to be reliable and designed accordingly, all the way from the control room to the measuring instrument of the process. Precise data needs to be delivered from the measuring instrument.

The objectives of this thesis are to a) review the instrumentation used for a standard pressurized LNG satellite terminal, b) analyze the need for the instrumentation c) find new methods and instruments that meet the requirements of the different measurement points in the systems, d) review control and instrument communication and connection from a reliability, safety and economical point of view, and lastly e) to finalize the instrumentation specifications according to the findings.

This thesis contains a technology overview of current and new monitoring methods for cryogenic conditions. These methods have been established and reviewed as suitable for the monitoring of LNG processes. Guidelines for design in the form of international standards have also been found and are included to help with selection, installation and recommendations for the design of the LNG processes. The result of this thesis is meant to help process design engineers to understand the background and the thought process for establishing the monitoring instrumentation in a pressurized and cryogenic process.

Key words: Cryogenic process, European standards, measuring technology, storage tank, modules, custody transfer

ABSTRAKT

Användning av naturgas har ökat runtom i världen på grund av att energikällan är ren och påfrestningen på miljön mindre jämfört med andra fossila bränslen. Transport och förvaring sker som vätska kallad flytande naturgas (LNG). Detta sker vid en temperatur på -162 °C och tryck över 1 atm på grund av säkerhet och av ekonomiska orsaker. Efterfrågan på LNG-import har ökat med energibehovet.

Resultatet är ett ökande antal LNG-mottagningsterminaler på land för import av LNG. LNG förvaras i lagringstankar och innan leverans till slutanvändaren förångas den till naturgas i en återförgasningsanläggning. Efter förångningen levereras naturgasen till slutanvändaren via rörledningar. Detta är dock inte möjligt för alla slutanvändare på grund av geografiska hinder. Då kan man istället bygga en LNG-satellitterminal. En satellitterminal är en mindre version av en mottagningsterminal som innehåller alla nödvändiga processer och anläggningar för att ta emot, lagra, förånga LNG och leverera naturgas till slutanvändaren. LNG fraktas med tankbilar till satellitterminalen.

Det viktigaste med övervakning och kontroll av LNG-processer är att det utförs säkert och gäller för alla LNG-anläggningar. Därför måste styrsystemet vara tillförlitligt och designat så att detta gäller hela vägen från processens mätpunkt till kontrollrummet. Exakta data måste levereras från mätinstrumentet och ju mer tillgänglig information, desto bättre.

Syftet med denna avhandling är att granska mätinstrument som används i en standard LNG-satellitterminal, analysera behovet av mätinstrument och hitta nya mätmetoder eller instrument som uppfyller kraven på de olika mätpunkterna. Därtill undersöks kontrollsystemets och mätinstrumentets kommunikation och anslutning för att bedöma deras tillförlitlighet och säkerhet samt för att överväga ekonomiska perspektiv. Slutligen presenteras instrumentspecifikationerna utgående från erhållna resultat.

Avhandlingen innehåller en teknisk översikt över nuvarande och nya övervakningsmetoder för kryoteknik. Metoderna har granskats om de är lämpliga för övervakning. Internationella riktlinjer har också inkluderats för att hjälpa till med valet av mätinstrument och hur de installeras samt rekommendationer för design av LNG-processer. Resultaten i avhandlingen ökar förståelsen av processen att designa övervakningen och kontrollsystemet i en LNG-anläggning.

Nyckelord: Kryoteknik, Europeiska standarder, mättekniker, lagringstank, moduler, överföring av flytande naturgas

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

α	Temperature coefficient
ε	Dielectric constant
$\dot{Q}_{max}$	Maximum flowrate
$\dot{Q}_{min}$	Minimum flowrate

Abbreviations

AAV	Ambient air vaporizer
ATEX	Explosive atmospheres
BOG	Boil-off gas
CCS	Constant current source
CMFM	Coriolis mass flow meter
CT	Custody transfer
DCS	Distributed control system
DN	Diameter nominal
DP	Differential pressure
DPT	Differential pressure transmitters
ESD	Emergency shutdown
EN	European standard
FBG	Fiber Bragg grating
HAZOP	Hazard and operability studies
HEX	Heat exchanger
HTF	Heat transfer fluid
I/O	Input and output
IFV	Intermediate fluid vaporizer
ITS-90	International Temperature Scale of 1990
MID	Measuring instruments directive
MMQ	Minimum measure quantity
MPE	Maximum permissible error

NG	Natural gas
LNG	Liquefied natural gas
P&ID	Piping and instrumentation diagram
PBU	Pressure build-up unit
PFD	Probability of failure on demand
PID	Proportional, integral and derivative
PIT	Pressure indication transmitter
PRT	Platinum resistance thermometer
Radar	Radio detecting and ranging
RTD	Resistance temperature detector
SIF	Safety instrumented function
SIL	Safety integrity level
SIS	Safety instrumented system
TC	Thermocouple
TFM	Turbine flow meter
USFM	Ultrasonic flow meter

1 INTRODUCTION

Natural gas (NG) is found in large quantities and is the cleanest fossil fuel sustainable for combating the concern of global warming (Reddy et al., 2019). Most regions of the world use NG as a clean energy source. It can be stored and transported as liquefied natural gas (LNG) at a temperature of −162°C and pressurized above 1 atm for financial and safety considerations (Hong et al., 2019). The increase of NG worldwide, compared to other fossil fuels, is because of less pollution and higher heating capacity. The demand has increased significantly in the past few years as power plants have replaced the fuel with the efficient use of NG. This trend will continue to rise and the need for LNG import is necessary to supplement the growth (Pattanayak & Padhi, 2018).

LNG receiving terminals are being constructed worldwide due to the continuously increasing demand of LNG. An LNG receiving terminal located onshore or offshore, as a barge or a floating storage regasification unit, is needed for transporting the LNG from the carrier and supplying it to end-users. LNG is stored in storage tanks at the LNG receiving terminal. Prior to delivering LNG to the end-user, LNG is vaporized through a regasification process. Vapor continuously evaporates from LNG due to heat absorption in the storage tank and in the cryogenic pipelines during unloading. The vapor is called boil-off gas (BOG) which can cause safety problems in the LNG facilities since pressure increases with the generated BOG (Park et al., 2012). After being vaporized it is transported by long distance pipelines for distribution to the end-users. However, this is not possible for all potential end-users. For scattered or isolated populations, factories, or power plants located at geographical hurdles, it is uneconomical to build pipelines if the demand is low. Ensuring the gas supply for potential end-users can be done by direct LNG distribution with the use of mobile equipment. Distribution of LNG by road is used in cases where the existing pipeline grid is either incomplete or under capacity (Chrz & Emmer, 2007).

Ensuring access and availability is necessary for the use of mobile equipment delivering LNG. An LNG satellite terminal can be built where the gas infrastructure is poor but the potential demand of NG as a fuel for industries is substantial (Wärtsilä, 2018). Storing and transporting NG is economical in its liquid form, whether via LNG carriers or trucks to remote locations for end-users (Mokhatab et al., 2014f). Direct deliveries of LNG to end-users by an LNG satellite terminal are still in an early phase but continue to increase worldwide (Chrz & Emmer, 2007).

Monitoring LNG processes is critical for safety in any LNG facility and it is necessary to have a reliable monitoring system for predicting and preventing process related issues (Hong et al., 2019). The system should be designed to handle changes, specifications, and the environment in an economic and safe manner. Performance is controlled by the system as well as by the process (Chawankul et al., 2005). With a well-planned system, risks of operational problems, losses and redesign for new process can be reduced (Michelsen et al., 2010). Availability of precise data is essential for LNG processes. Whether it is related to unloading, storage, or distribution, correct information needs to be delivered to the control room for the process to perform correctly (Wärtsilä, 2018).

This thesis is meant to offer process design engineers a better understanding of measuring instruments in an LNG process. These can be general understanding of terms, design guidelines, selection, or installation of an instrument. It can also be used to clarify why a specific instrument is used for monitoring a part of the process in current design. Therefore, this thesis is meant to give background knowledge. The main objectives of the thesis are as follows: review the standard pressurized LNG satellite terminal piping and instrumentation diagram (P&ID) and list requirements on all instruments. Analyze the real need for each instrument. Find new methods and instruments that meet the requirements of the different measuring points. Review the control and instrument communication/connection from a reliability, safety and economical point of view. Lastly, finalize instrumentation specifications according to findings.

This thesis will focus on the control systems of storage, regasification, and unloading/loading of an LNG satellite terminal. Flaring, odorization, and send-out will not be mentioned. These systems are in the form of modules and instrument sizing should be considered but not limited to the size. All the new methods that were found cannot be applied for LNG processes. However, the new methods found are used in processes for other cryogenic liquids. Therefore, the methods are theoretically applicable for LNG processes. The focus will be on intelligent instruments, meaning digital instruments which are connected to the control system and can transfer data information. Limitations to flow measurements were made due to the amount of available flow meters. All possible meters for cryogenic measurements are mentioned briefly. However, the focus will be on those used for custody transfer and common methods for flow measurement of LNG.

2 THEORY

This chapter includes information about LNG, safety from a process perspective, the processes and the main equipment in an LNG satellite terminal, the control system, the measuring instruments, custody transfer of LNG and finally standards and regulations for instruments, installations and processes in LNG facilities.

2.1 LNG characteristics

The LNG properties varies with its composition, which depends on the gas source. Methane is the main component, but other hydrocarbon components are found as well (Mokhatab et al., 2014a) and can be seen in Table 1. The table includes examples of the LNG composition, the boiling point, molecular weight, density, and volume at atmospheric pressure. The variations of the composition will affect the properties and therefore, typical values are used for LNG.

Table 1. Example of LNG compositions and properties – adapted from (Technical Committee GSE/38, 1997)

Properties at boiling point at atmospheric pressure	LNG example 1 Light	LNG example 2 Medium	LNG example 3 Heavy
Molar content (%)			
Methane	97.5	93.9	87.2
Ethane	1.8	3.26	8.61
Propane	0.2	0.69	2.74
Butane	-	0.27	1.07
Pentane	-	0.09	0.02
Nitrogen	0.5	1.79	0.36
Wärtsilä Methane number	94	83	69
Molecular weight (kg/kmol)	16.41	17.07	18.52
Boiling point temperature (°C)	-162.6	-165.3	-161.3
Density (kg/m^3)	431.6	448.8	468.7
Volume of gas measured at 0°C and atmospheric pressure (m^3/m^3)	590	590	568

The LNG is noncorrosive, colorless, and odorless at atmospheric pressure. In its gas form when used as a fuel, it is considered as a clean source of energy due to its low carbon emission and low particle emission compared to other hydrocarbon fuels. It is nontoxic, but if leaked into an uncontrolled environment it can lead to suffocation and ignition can occur with the right concentration of air (Mokhatab et al., 2014a).

As mentioned above, the properties of LNG varies with the composition and as seen in Table 1, the properties have deviations compared to typical properties. The typical boiling point is -162°C for the liquid. The liquid volume is 600 times smaller compared to natural gas and the density falls between 430 and 470kg/m^3 (Mokhatab et al., 2014a). LNG is commonly classified according to the density but can also be according to heat value, Wobbe index, methane, or nitrogen amount (Dobrota et al., 2013). In Table 1, the lighter LNG has a higher methane number and lower density compared to the heavy LNG. The methane number has been calculated using the Wärtsilä methane calculator, based on the molar content of the LNG examples. An important attribute of LNG is the dielectric constant, which is needed for certain instruments. The LNG dielectric constant is on average $\varepsilon = 1.75$ and it is utilized to detect LNG (Paillou et al., 2008). Knowledge of the LNG properties and behavior is crucial for a successful design, operation, and process of all types of LNG facilities (Mokhatab et al., 2014a).

2.2 Safety

LNG safety is the number one priority for LNG facilities and several factors contribute to this safety. First, safe and secure operations have been developed for the LNG processes. Second, the LNG properties are well understood, and the design of the processes have been tested through multiple years of operation. Third, standards have been developed for the LNG industry and they are continually improved to ensure LNG safety (Mokhatab et al., 2014a). LNG hazards are still a concern, and the responsibility to prevent incidents should not be understated and is the focus when designing an LNG operation. The main hazards are fire, explosion, freeze burns, embrittlement of materials, and confined spaces hazards (Mokhatab et al., 2014d).

The main safety features at an LNG facility are primary containment, secondary containment, plant safety system, and separation distance. LNG storage tanks have a primary and secondary containment, meaning double tank walls. The primary containment is in contact with LNG and requires to be designed and tested for cryogenic use. The task of the containment is to remove BOG, prevent entry of air, frost heave, withstand filling, emptying, cooldown, and heating operations. Secondary containment is designed for a capacity greater than the volume of the primary containment. An insulation system is located at the inner wall and is constructed of materials with a low thermal coefficient which does not embrittle in the case of contact of LNG. Secondary containment devices are also included such as tank level gauge, cooldown temperature sensors, and leak detection (ABS Consulting Inc., 2004). This is discussed further in Chapter 2.6.

Explosion risk is reduced by storing the LNG above atmospheric pressure so that air is not leaked into the tank (ABS Consulting Inc., 2004). In order to determine the risk of explosion, a hazardous area needs to be established. A hazardous area is an area in which explosive gas atmosphere is expected or present. In this case special precautions for construction, installation, and use of equipment need to be considered. A hazardous area can be divided into zones 0 – 2 for an LNG satellite terminal and can be seen in Table 2. Determining the zones for the presence of explosive gas atmosphere depends on several factors, e.g., flammable substance, sources of release, elimination of release, and grade of the release. The approach for the classification can be found in EN 60079-10:2015 (European Committee for Electrotechnical Standardization, 2015b).

Table 2. The zones and the definition of hazardous areas for an LNG satellite terminal. Information adapted from (European Committee for Electrotechnical Standardization, 2015b) into a table.

Terms	Definition
Zone 0	An area in which an explosive gas atmosphere is present continuously, for long periods or frequently.
Zone 1	An area in which an explosive gas atmosphere is likely to occur periodically or occasionally in normal operation.
Zone 2	An area in which an explosive gas atmosphere is not likely to occur in normal operation but, if it does occur, it will exist for a short period only.

Plant safety systems are designed with two layers of protection, a prevention system which prevents loss of containment, such as pressure relief valves, and an emergency system which includes multiple layers of emergency protection (Mokhatab et al., 2014d). These are discussed in Chapter 2.4.

Separation distance means that the location of storage and processes needs to be a at minimum distance away from each other at the terminal site. This can be done with risk analysis tools such as qualitative methodologies. From a process perspective, hazard and operability studies (HAZOP) are an important method to identify risks in the process system. HAZOP is a systematic risk assessment examination of designed operations and consequential effects on the facilities (Crowl & Louvar, 2019). The HAZOP team includes designers and operators to review a given process. Piping and instruments are reviewed in sequential order and each piece of equipment is evaluated in case of operational problems. The equipment is documented by key cautions, controls, and needs for improvement (Mokhatab et al., 2014d).

2.3 LNG satellite terminal

The LNG satellite terminal plays the role of transporting the LNG from the tanker and supplying it to industries by pipelines (Mokhatab et al., 2014a; Park et al., 2012). It is a small station where LNG is delivered in trucks, stored in tanks, and vaporized at site (European Committee for Electrotechnical Standardization, 2019). It is usually a single-use type of terminal, e.g., providing gas for a power plant. However, it can also be multi-use which includes, e.g., send-out, truck loading, and bunkering. The size range of the terminal is 100 – 20,000 m^3 and the storage tank is usually the most expensive part of the terminal. Therefore, it is defined according to its size. The type of tank used is mainly bullet tanks, and the terminal capacity is determined by tank size, frequency of refilling, and operational specifications of the power plant. A 50 MW baseload plant with an average of 12 days between refilling requires a storage capacity of approximately 5000 m^3 (Wärtsilä, 2018).

The main functions are unloading, storage, vaporizing, gas quality adjustment, LNG recovery, and pressurizing (European Committee for Electrotechnical Standardization, 2019). The main process units in a Wärtsilä LNG satellite terminal are truck loading/unloading, storage tank, regasification, and metering station (send-out and odorization). These units are designed and delivered in the form of modules (Wärtsilä, 2018). These units can be seen in Figure 1. Imported LNG is stored in its liquid state in the storage tank at the terminal. For the LNG to be delivered to the customer, it needs to be vaporized into NG through a regasification process before being sent-out to the power plant. LNG continuously evaporates due to heat absorption from storage tank walls and pipelines due to warmer ambient environment compared to cryogenic storage of LNG. The evaporated gas is called boil-off gas (BOG). The BOG can cause safety problems in the LNG facilities because of the pressure build-up and temperature that increases with the generated BOG (Park et al., 2012; Shin et al., 2007). If the BOG is not treated in time the structure of the tank will be damaged and cause dangers (Shin et al., 2007). The safety valves of the storage tank will open, if the pressure is too high. The BOG will then be released into the atmosphere, resulting in economic loss and pollution (C. Liu et al., 2010). Therefore, handling of BOG is required, but since BOG is the same as NG, it can be released directly to the power plant in order to prevent dangerous situations (Wärtsilä, 2018). However, other solutions exist (e.g., BOG condensation process) which condensates and recovers BOG by utilizing LNG cold energy. The LNG cold energy is the energy released when it is vaporized. The cold energy is carried away by air or the heating system of the vaporizer. Solutions to recover the cold energy has been investigated in order to reduce the heat loss in the overall vaporization process and combining it with other LNG processes (Yuan et al., 2019).

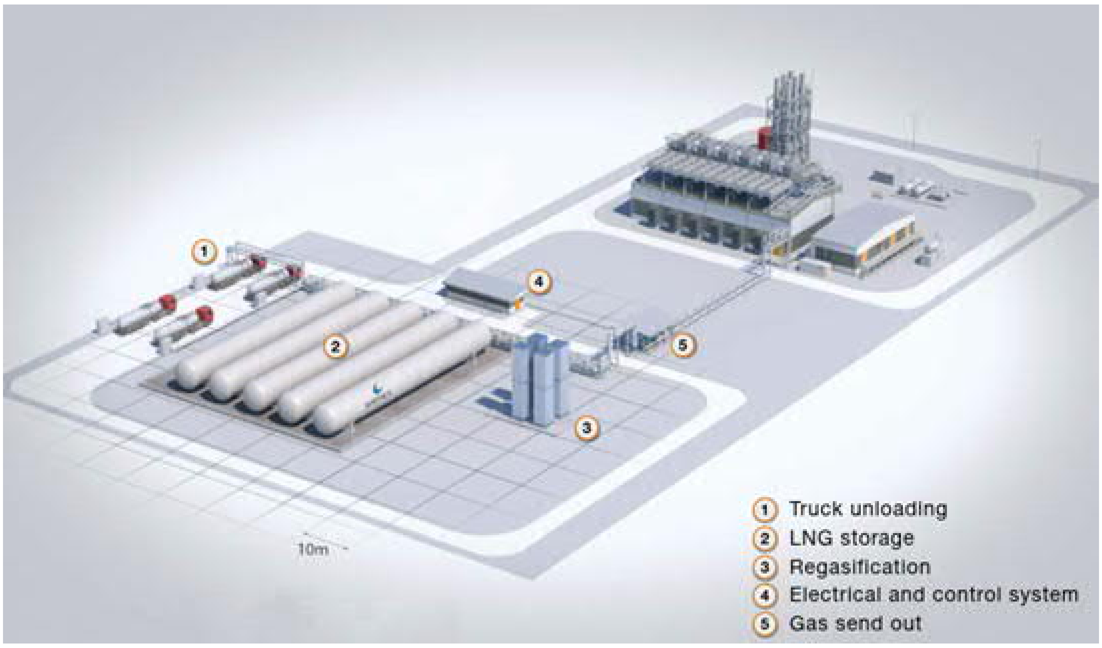


Figure 1. A Wärtsilä LNG satellite terminal used for a power plant – adapted from (Wärtsilä, 2018).

The unloading of LNG depends on the size of the truck but the unloading bay is typically designed to unload LNG at 100 m^3/h or less (Mokhatab et al., 2014c). The typical process description for a satellite terminal starts with the LNG being pumped from the truck to the storage tank. To balance the volume of the pumped LNG from the truck, a small amount of LNG is vaporized and returned. This is done through an atmospheric vaporizer or pressure-build up unit (PBU). The gas (BOG) inside the storage tank can also be used and be sent via a vapor return line to the truck. The gas flow rate is controlled by the trucks pressure.

The periods when the storage tank is in holding mode and there is a high pressure in the tank, the BOG can be sent out. The BOG is warmed prior through a heat exchanger (HEX). When the LNG is to be sent out to the customer, it must be vaporized to NG before delivery (Chrz & Emmer, 2007). Nitrogen is used to sub cool the HEXs, the tank storage, and pipe system prior to commissioning. Nitrogen is also used for purging the transfer system after the unloading phase is completed (Mokhatab et al., 2014c). A typical process of the satellite terminal is shown in Figure 2.

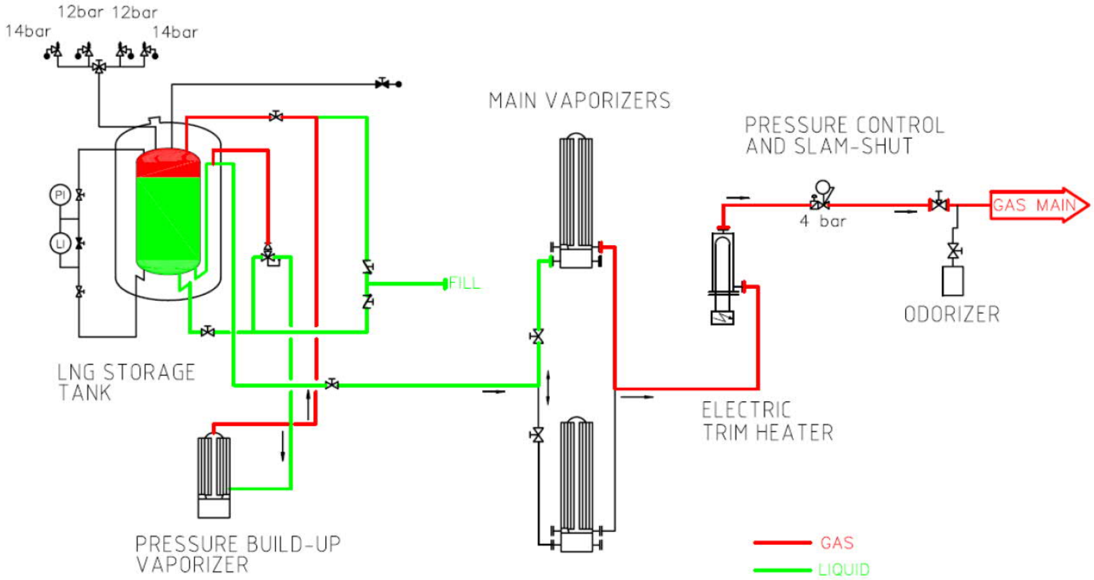


Figure 2. A flow schematic of an LNG satellite terminal (Chrz & Emmer, 2007). The LNG is unloaded at "FILL" and enters the bottom or the top of the storage tank. It can also be sent directly to the PBU. The gas inside the storage tank can be sent to the truck to balance the volume of the unloading. There is another separate pipe leading to the PBU to increase the pressure which then leads back to the top of the tank as gas. Prior to the LNG being sent out to the customer it is vaporized, heated and odorized. The storage tank includes a monitoring system and a safety release valve to the atmosphere.

2.3.1 Modularization

Due to increasing developments in remote locations, the modularization concept has been applied to LNG processes. The concept is used where site construction space is limited, labor mobility is difficult, or have a sensitive environment, (Tanabe & Miyake, 2010). The concept is to design and build self-supporting, transportable structures which include main components, equipment, and piping. For complex LNG plants this can be difficult but for small-scale LNG this is an excellent option. Module design is different compared to normal design. Limitations of the module size and weight require safety design to be planned well and redistribution of the process equipment compared to normal design. The design should occur from the ground up and the redesign of the process is difficult and time consuming (Mokhatab et al., 2014e).

Modules are meant to be cost-efficient, while in order to ensure cost-efficiency. The design needs to be innovative. The workflow must be redefined compared to normal design and needs to consider all levels from design to installation. A successful module should produce improved labor productivity, safety, quality, environmental footprint, operations, maintenance, reduced startup time, and cost. In order to achieve a successful module, these guidelines should be followed. Cooperation from all project team members and owner personnel should be involved from the start to ensure module configurations for operations and maintenance requirements. The basic concept of process and piping design of modularization for the design must be known as well. The design of the module cannot be finalized without knowledge of the details and fabrication methodology. The design to create a module will take longer but the quick plug-and-play connection should reduce the project schedule (Mokhatab et al., 2014e)

2.3.2 LNG loading and unloading

When LNG consumers are located inland, the LNG needs to be delivered by truck or train in the form of road trailers, ISO cryogenic containers, or smaller delivery units. The unloading of the LNG trucks is done at a truck loading bay and the main purpose of this unit is to unload the LNG to the storage tank. There is also the possibility to load the truck with LNG if needed (Mokhatab et al., 2014a). The unloading and loading can be done using pumps, PBU, or by pressure differential transfer between truck and storage tank (Chrz & Emmer, 2007; European Industrial Gases Association, 2015; Sharafian et al., 2019). An example of LNG unloading with PBU, pump, or both can be seen in Figure 3. Typical operating pressure is between 0.4 to 0.6 MPa but depends on specifications (Chrz & Emmer, 2007).

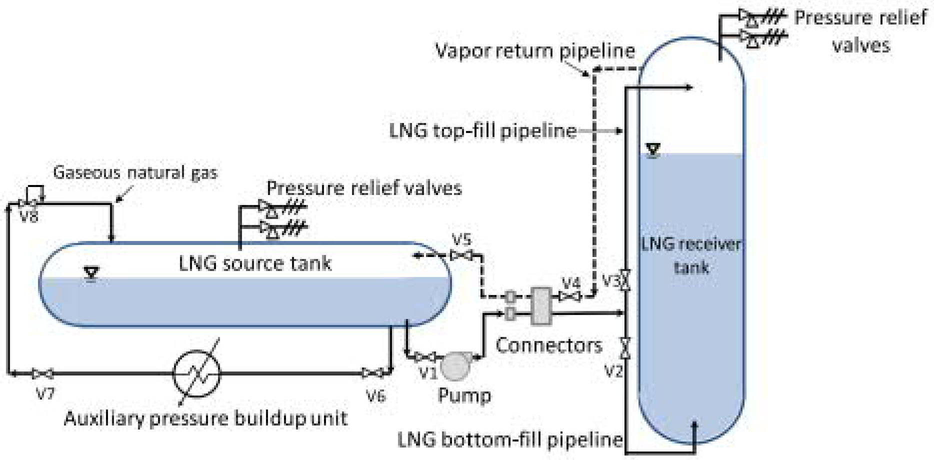


Figure 3. The truck to storage tank transfer with/without vapor return by using a pump, PBU or both (Sharafian et al., 2019). The PBU and its pipe system is removed when using the pump and the pump is removed when using the PBU.

The truck is connected to a flexible filling hose or loading arms. Depending on the loading rate and the capacity of the arms, multiple arms can be used and there can also be a vapor return arm and spare arm (European Industrial Gases Association, 2015; Mokhatab et al., 2014a). Vapor return can be added to the transfer system. This sends vapor from the storage tank to the truck, reduces the pressure in the storage tank before the unloading, and keeps a steady flow rate throughout the unloading process. This process is important when the transfer system only relies on a PBU. The unloading process cannot be started if the storage tank pressure is too high. If there is no vapor return, the pressure will increase in the truck and reduce the pressure difference of the truck and the tank, leading to a reduction in flow rate and an increase in the unloading time (Chrz & Emmer, 2007; Sharafian et al., 2019). During the unloading the operation is continuously monitored by both the truck operator, who has access to an interface panel, and the control system using measuring instruments. For custody transfer, a flow meter or a weigh scales can be used (European Industrial Gases Association, 2015). After the unloading is completed, nitrogen purging is used in order to drain the remaining LNG in the arms (Mokhatab et al., 2014a) and the system is depressurized before the truck can be disconnected from the fueling system (European Industrial Gases Association, 2015).

2.3.3 Storage tank

Deciding the tank for storage is project-specific and should address site conditions, design criteria, safety, geological considerations, environmental requirements, and regulations. The two main types of tanks are in-ground or above ground storage tanks. For above ground storage there are three types of tanks: single, double, and full containment tank (Mokhatab et al., 2014a). Bullet tanks are commonly used when storing smaller volumes of LNG. These are vacuum insulated pressure vessels which can be vertical or horizontal depending on site size and safety concerns. They are modular, flexible to install, and can be arranged in any desired amount depending on the storage capacity. These tanks are designed and operated so that no BOG compressor is required (Wärtsilä, 2018).

The vessel consists of an inner vessel, an outer vessel, perlite-vacuum, inner supports, outer supports, LNG spray line and LNG inlet/outlet, as seen in Figure 4 (Chrz et al., 2005; Wärtsilä, 2018). The inner vessel is composed of a self-supporting cylindrical container made of 9% nickel steel or stainless steel and the outer vessel is composed of carbon steel. In the annular space there is vacuum pressure and perlite is used for insulation. This construction is made in a way that the LNG will still be contained within the outer vessel, if the inner vessel breaks. It also limits the dispersion of vapor (Mokhatab et al., 2014a). This ensures that LNG can be kept in the tank for several weeks without any withdrawal or needing to be vented. With a small consumption of LNG the pressure is reduced quickly in the storage tank (Chrz & Emmer, 2007).

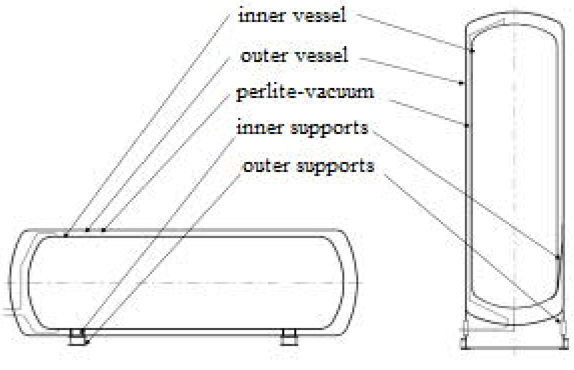


Figure 4. Bullet tank storage for LNG – adapted from (Chrz et al., 2005).

There are four modes of operation for the storage tank: holding mode, the period when there is no truck unloading/loading, unloading mode, the period when the storage tank is being filled, loading mode, the period when the truck is being filled, and send out mode, the period when the satellite terminal produces the NG for the power plant. Gas can be sent out during all the modes if needed (Mokhatab et al., 2014a).

Operating pressure can be up to 3.5 MPa (European Industrial Gases Association, 2015) but is designed at around 1.25 MPa (Chrz & Emmer, 2007). There are multiple operating variables that need to be ensured to maintain storage tank pressure. The fill connections of the storage tank can be top or bottom and are permitted by internal piping. Bottom loading is used if lighter LNG is loaded to enhance mixing and to increase the storage tank liquid level. If the LNG is heavier, it should be loaded from the top via a spray device or splash plate to promote flashing, mixing with the inventory of the tank, and to reduce the storage tank pressure. By using both top and bottom filling at the same time, the LNG flow in the process will increase. Transfer line and tank cooldown is also required to ensure the reliability and continuous use of the LNG process (Mokhatab et al., 2014c). There is no danger of rollover in a vacuum insulated vessel (Chrz et al., 2005). Rollover is when two different densities of LNG mix together and result in a large amount of vapor causing pressure build-up. Lastly BOG is the main issue when it comes to LNG storage. However, as mentioned previously, BOG is not an issue with bullet tanks since the BOG volume production is less than 0.2% per day and the storage tank is capable of handling the pressure build-up (Mokhatab et al., 2014c; Wärtsilä, 2018). To increase the pressure in the tank, a PBU is used to vaporize LNG (European Committee for Electrotechnical Standardization, 2002). A portion of the LNG is sent to the PBU, where it is evaporated in a HEX. When evaporated, the vapor is sent back to the top of the storage tank to create a higher pressure (Sharafian et al., 2019).

2.3.4 Regasification

The regasification units main functions are to convert LNG to NG trough vaporization and to increase the temperature of the gas before being sent out to the end-user (European Committee for Electrotechnical Standardization, 2019). The design of the vaporization system is determined by the site selection, environmental conditions, regulations, and operability. Large LNG import terminals use two types of vaporizers, mainly open rack vaporizer, and secondly submerged combustion vaporizer. Additionally, there are ambient air vaporizers (AAV), shell and tube exchange vaporizer, and intermediate fluid vaporizer (IFV) (S. Liu et al., 2019; Xu et al., 2018).

The AAV and the IFV are both common vaporizers used in an LNG satellite terminal. The AAV is the preferable vaporizer due to its low operating cost and environmental reflection (Mokhatab et al., 2014a).

The IFV is a closed loop process with an intermediate heat transfer fluid (HTF). This is used to transfer the heat between the LNG vaporizer and the heat source. The HTF is either ethylene glycol, propylene glycol, or hydrocarbons. The heat transfer occurs in a shell and tube HEX. The glycol-water IFV has a compact design due to the high heat transfer coefficient. Warm glycol-water fluid is used to heat the LNG (Xu et al., 2018). A pump is used to circulate the HTF in the system and a storage tank is placed upstream of the pump to accommodate the volume of the fluid during operations. Multiple options can be used to heat the HTF. It depends on what is available at site, e.g., fired heater, air heater, waste heat recovery, or seawater exchange (Mokhatab et al., 2014a). The process system is shown in Figure 5.

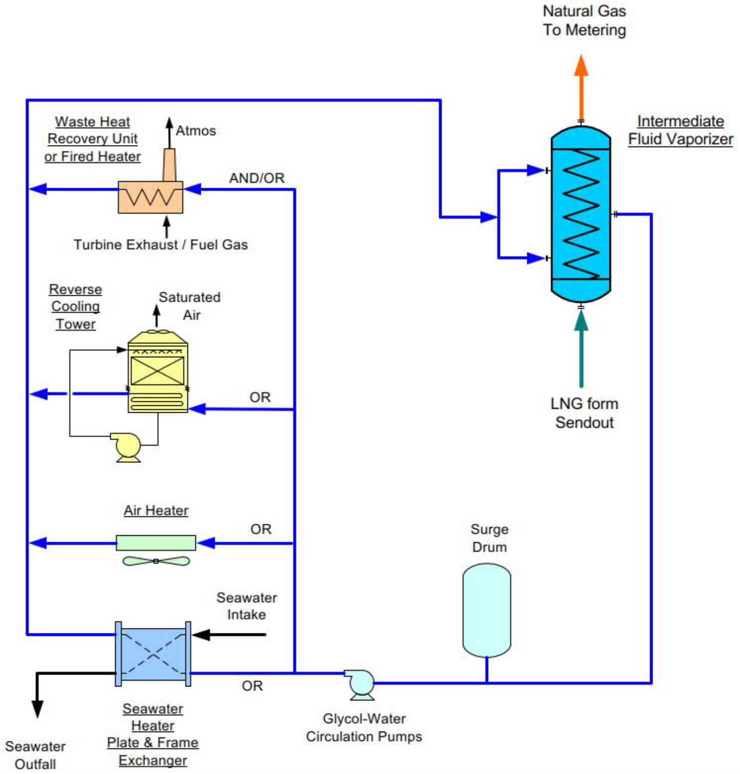


Figure 5. An example of the IFV process (Mokhatab et al., 2014a). A pump is used to circulate the glycol-water (HTF) in the process. A surge drum is located upstream of the pump. The heat source HEX is the located downstream of the pump where the glycol-water is heated. The warm glycol-water is then pumped towards the IFV and transfers the heat to it in order to vaporize the LNG to natural gas.

Instead of glycol-water, hydrocarbons can be used as the HTF, e.g., propane or butane. This type of IFV utilize seawater as the heat source and the vaporized HTF condensates on the LNG HEX. By using this type of HTF, freezing can be prevented which can be encountered with other types of HTF. This type of system has its limitations as it can only be used where seawater is available and can be a significant investment while the glycol-water can be used anywhere with the appropriate heat source (Egashira, 2013; Mokhatab et al., 2014a).

The AAV extracts heat from the ambient air in order to evaporate LNG and do not require a separate heating system like the IFV. It is considered more environmentally friendly because of this and is cost competitive. However, a greater amount of AAVs is needed in order to achieve the same effect compared to the IFV. This will require more space at the site. For satellite terminals direct air vaporizers are used but there are AAVs which utilize an intermediate fluid as well. The air exchange can be natural draft or forced air operation. Typical AAV design can be seen in Figure 6 and consists of vertical and long direct contact HEX tubes that facilitate downward air draft. This is due to there being colder and denser air at the bottom which is heavier than warm and less dense air (Mokhatab et al., 2014a).

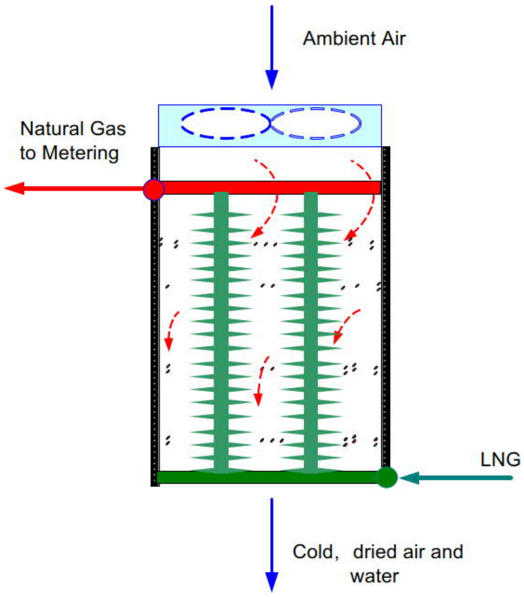


Figure 6. Typical AAV schematic (Mokhatab et al., 2014a). LNG flows through a series of surface heat exchangers. The ambient air flows downward in the AAV and heats up the LNG to NG. The cooled air and water condensate exit the AAV at the bottom and the NG is sent to the customer.

The water condensation buildup can be collected and used as service water. In order to prevent the ice buildup on the surface of the HEX tubes, periodic defrosting is required multiple times daily. The longer the operating cycle of the AAV, the longer the defrosting time (S. Liu et al., 2019). The defrosting can be done by the natural draft of air or by air fans. The use of air fans will only slightly decrease the defrosting time. However, it will help with the dispersal of fog generated from the AAV as well as with the visibility. At locations with a warm humid temperature, the fog generation will occur and its impact on the environment should be accounted for. The fog is generated when the cold air from the vaporizer meets the warm and moist ambient air. The fog can create visibility issues and interfere with the process. The AAV is advantageous in equatorial regions with a hot climate and where the ambient temperature is high throughout the year. The IFV is preferred in subequatorial areas where winter temperature will affect the ambient air temperature (Mokhatab et al., 2014a).

2.4 Control system

A control system is needed in order to operate the processes at an LNG satellite terminal. From the selection of field sensors to available information in the control room, the choices for control and automation system impact the profitability and effectiveness of an LNG operation. A control system which is well designed and maintained will reduce start-up time, avoid forced shutdowns, keep operating and maintenance cost low, uphold environmental compliance, and support operation safety and security. The main functions of the control system are to ensure a safe and reliable operation as well as optimize the process (Mokhatab et al., 2014b)

Safety is the most important objective in the automation. Design and functionality of process automation is directly related to this. To achieve this, the process variables need to be maintained in the safe operating limits which is performed by the base and advanced regulatory loops in the system. The alarms and trips in the distributed control system (DCS) are designed to warn operators or act during violations of the safe operating limit. The emergency shutdown (ESD) system is designed to safely shutdown the operation or satellite terminal in case of significant violations detected (Mokhatab et al., 2014b).

Smooth and stable operation is another important objective of the automation. This is achieved by the base regulatory controls. The designs and tuning of these control loops are critical to the stable operation. For operation optimization the advanced regulatory and process controls can be used to enhance the operation to be as beneficial as possible (Mokhatab et al., 2014b).

Traditionally the design is performed sequentially where the process is designed first. Later, the control system is designed, meaning the engineers do their work separately (Michelsen et al., 2010). The meaning of control design is to achieve the best dynamic performance, i.e., to maintain a specific control variable at a setpoint. This is ignored during the design phase as the process design engineer works on selecting the best process flow with the minimum capital and operation cost based on steady state considerations. Later on, the control engineers will have to optimize the dynamic performance for the given design (Chawankul et al., 2005). In order to achieve the best possible control system for any given process, an integrated design method is required for the process and control system. With the use of an integrated method, both the design and the operation can be improved (Michelsen et al., 2010).

2.4.1 Distributed control system

DCS, or basic process control system, includes instrumentation, input/output devices, control devices and operator interface devices which execute control and indication functions, permit transmission of control, measurement and operating information to and from single- or multiple-user at specific locations which are connected by single or multiple communication links (Liptak, 2003).

As mentioned above, the key role of the DCS is to maintain the various process variables for smooth and stable operation during day-to-day operations in the satellite terminal with the use of regulatory controls and loop management (Mokhatab et al., 2014b). The base regulatory control is the main control layer, ensuring the operation variables being maintained. These consist of proportional, integral, and derivative (PID) control loops. These PID control loops regulate the pressure, temperature, and flow in the process with a response time of one second or less (Mokhatab et al., 2014b). Advanced regulatory control handle loops that are challenging and cannot be handled by regular PID control loops. These can be, e.g., cascade and override control. The cascade control is when there is a master and slave controller. The override control is when there are competing control objectives and an output from a loop is given priority over another output (Mokhatab et al., 2014b).

Loop management is used to supervise the processes in the satellite terminal. This includes controller monitoring where the performance of the PID loops are monitored on a continues basis. Controller tuning is done with various tools in order to identify the tuning parameters of the PID control loops. It is also used to optimize the controller with either setpoint tracking or disturbance rejection. Remote monitoring is utilized to identify and troubleshoot any field related problems. The system can also be accessed remotely with a smart device if the system allows for it via ethernet or internet at any location (Mokhatab et al., 2014b).

Real-time event management provide information for performance and tracking. This can be used to improve the lifecycle of the process. It can also be used for alarm management. Alarms indicate abnormal conditions in the process. If an alarm occur, the operator will need to do adjustments of the process in order to prevent a trip or a shutdown of the process (Mokhatab et al., 2014b).

2.4.2 Intelligent field instrument

The meaning of a device or an instrument is that it is designed for direct or indirect measurement, monitoring, or control of a variable. This includes primary elements, indicators, controllers, final control elements, computing devices, and electrical devices such as annunciators, switches, and pushbuttons. The meaning of field is that the instrument is in the vicinity of its primary element or final control element (Liptak, 2003). Intelligent relates to the instrument being connected to the control system to transfer data such as process and equipment information to enable process control, asset optimization, and safety functionalities (Mokhatab et al., 2014b). These instruments are usually connected to a local control panel which connects to the control system. By monitoring the process, the instrument senses the magnitude of one or more variables for the purpose of deriving useful information. This can be used for analyzes, indication, or alarm. (Liptak, 2003; van de Kamp, 2006).

It is important to understand the difference of a sensor, a transmitter, and a transducer. A sensor is a separate or integral part of the instrument that senses the process variable value. It assumes a corresponding predetermined state and generates an output signal indicative of or proportional to the process variable. A transmitter senses the process variable through a sensor or measuring element and has an output whose steady-state value varies only as a predetermined function of the process variable. The sensor can be an integral part as indirect pressure transmitter or separate as in thermocouple temperature transmitter. Lastly, a transducer is a part of the instrument which can be a primary element, a transmitter, a relay, or a converter that receives the information in the form of physical quantities, modifies the information, or its form if required and produces a resultant output signal (Liptak, 2003).

Instruments can be invasive or non-invasive and intrusive or non-intrusive. If transducer is in contact with the fluid, it is invasive, and if it is not in contact, it is a non-invasive sensing. If the transducer is protruded into process flow or changes the flow profile, it is an intrusive method, and if it does not change the flow profile, it is a non-intrusive method (Basu, 2019d).

The use of intelligent field instruments increases safety, reliability, and productivity in the processes with precise measurement, and with the use of multivariable field instruments, the number of instruments can be reduced. The more information available from these instruments, the easier it is for the control room operator to manage the system. The instruments can be connected via fieldbus, a two-way industrial network communication system for real-time control, or remote I/O where the instrument is connected via cable to a local control panel so that the system cannot be altered by software. These instruments are capable of self- and process-diagnostics to ensure that the data transferred is reliable (Mokhatab et al., 2014b). Reliability is the probability that an instrument will perform its objective adequately, for the period specified and under the operating conditions specified (Liptak, 2003). It is important that the instrument used is capable of this and a high reliability is to be expected of any system. Operators with the use of a human machine interface can easily pinpoint locations of errors. Operators can also use instrument diagnostic tools to perform troubleshooting. Alerts can be generated to enable operations and maintenance of equipment or process conditions in LNG processes (Mokhatab et al., 2014b). Typical response time according to EN 61298-1 is defined as 150 – 180 milliseconds (ms), where dead time is typically 50 ms and time constant of 100 – 140 ms (Basu, 2019g).

2.4.3 Accuracy, repeatability, and sensitivity

Accuracy, repeatability, and sensitivity are terms that needs to be understood, when dealing with instruments. The purpose of all measurements is to obtain the true value. The error of the measurement is the difference between the measured and the true value. It is impossible to know the exact error since it is impossible to measure a value without an uncertainty. However, it is possible to state the limits of the true value. The term accuracy, more precisely inaccuracy or uncertainty, is often misunderstood (Liptak, 2003).

Accuracy is the ability of the measuring instrument to indicate values closely approximating the true value of the quantity measured. Uncertainty is the true value of the measurement that cannot be determined but estimated by statistical analysis. Uncertainty can also be the range which the true value can be found. Precision can be described by repeatability. Repeatability is the closeness of several measurements of the output quantities, where the input and operating conditions are the same (Basu, 2019a). Sensitivity is the smallest amount of change that can be detected by an instrument (Rys, 2011).

The accuracy terminology is illustrated with the help of Figure 7. The spread of the dots located on the upper right corner represents the random error of the measurement. The distance from the mean random error to the bullseye is the systematic error. The systematic error is a displacement of the measured value from the true value, which can be reduced by calibration. Repeatability is the range from the furthest points of the dots and cannot be reduced. The dot on the lower left corner is an illegitimate error which can be eliminated. The uncertainty is defined as the sum of the random error and the systematic error. There is no need to know the true value of the measurement if the purpose is to maintain the process conditions. The goal is then to reduce the random error without worrying about the systematic error. This is common for many industrial installations. However, if determining the true value is needed, the repeatability is insufficient. The total accuracy can be obtained by reducing both the random and the systematic errors. This is achieved by recalibration (Liptak, 2003).

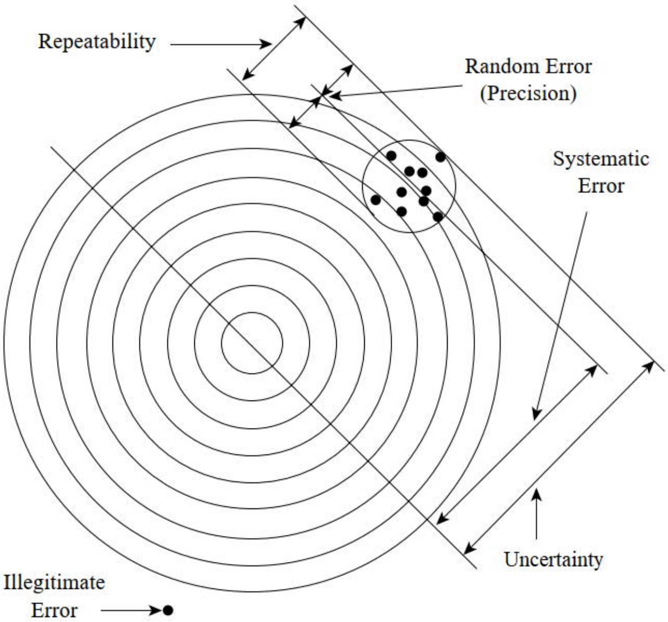


Figure 7. Accuracy terminology in the form of a shooting target. Adapted from (Liptak, 2003). The bullseye represents the true value of the measurement. The dots represent the measurement of the instrument. The distance between them represents the uncertainty of the overall measurement.

2.4.4 Emergency shutdown system

The ESD system, or the safety instrumented system (SIS), is designed to protect personnel, equipment, processes, and environment by reducing the likely hood or the impact of an identified emergency event. This system is independent of the DCS and include safety instruments. However, both systems can use the same instruments during certain conditions. The main components of the ESD system are sensors that collect the necessary information to determine an emergency, i.e., storage tank overfilling. Logic solvers are used to determine the actions based on the information from various instruments. The logic solvers have a high reliability and provide fail-safe operations. The output of these transfers to the final control elements to implement the required action. Final control element implements the actioned from the logic solver to ensure the safety of the process. It can also include communication and ancillary equipment (European Committee for Electrotechnical Standardization, 2017a; Mokhatab et al., 2014b).

A small proportion of leaked LNG in the process can cause loss of containment as a result of an explosion or a fire incident. The ESD system in the LNG satellite terminal is used to automatically stop the LNG process and isolate leakage sections. Therefore, the ESD system is considered an important system and requires attention. To improve the reliability of the equipment and the operational procedures, the root cause of undesired failures are investigated (Cheng et al., 2009).

The ESD system is based upon specific criteria's and built upon safety instrumented functions (SIF), which are used to maintain a safe state of the process in the case of a specific hazardous event. The SIF is designed to achieve a required safety integrity level (SIL), which is the ability of the ESD system to perform the required SIF when required. The SIL consists of levels 1 to 4 and the higher the number, the higher safety integrity. The SIL is determined by the probability of failure on demand (PFD) of the instrument used for the ESD system. The higher the SIL, the lower the PFD, the lower the frequency of a dangerous failure causing a hazardous event (European Committee for Electrotechnical Standardization, 2017a).

In order to achieve the required SIL and SIF, an overall safety lifecycle is found in EN IEC 61508-1. The safety lifecycle can be seen in Figure 8 and should be followed in a systematic manner to ensure the lifecycle of the ESD system (European Committee for Electrotechnical Standardization, 2010).

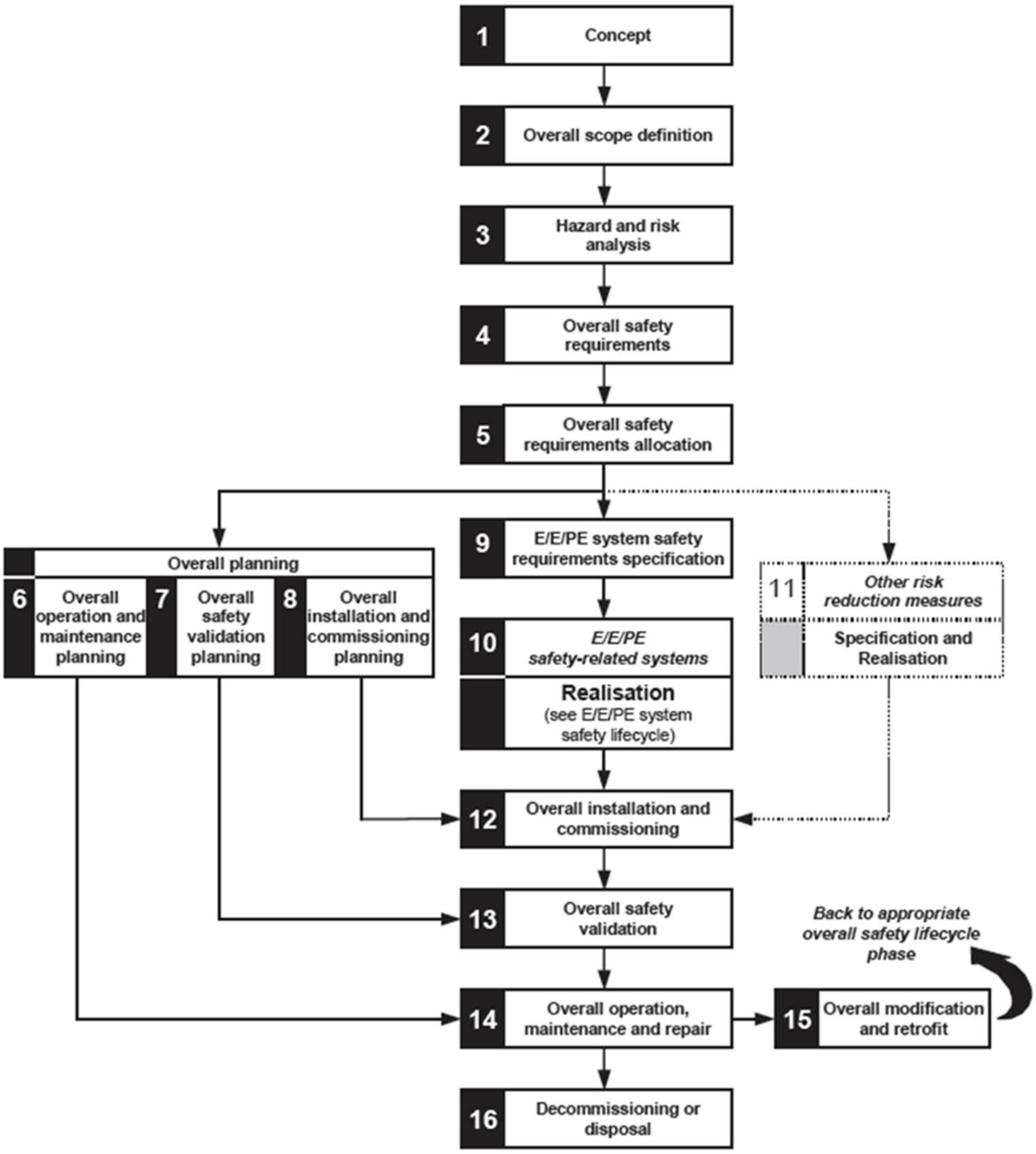


Figure 8. Overall safety cycle (European Committee for Electrotechnical Standardization, 2010).

The descriptions and the responsibility of the steps are shown in Table 3.

Table 3. Overall safety lifecycle, an overview - adapted from (European Committee for Electrotechnical Standardization, 2010).

Lifecycle step	Description	Responsibility
1 Concept	Develop an understanding of the control system and the environment.	Process design team
2 Overall scope definition	Determine the boundaries of the control system and the scope of the HAZOP.	Process design team
3 Hazard and risk analysis	Determine the hazards, hazardous events and situations related to the process and control system.	Process design team
4 Overall safety requirements	Develop the safety requirements, functions, and integrity based on the HAZOP.	Process design team
5 Overall safety requirements allocation	Allocate the safety requirements, functions, and integrity for designated SIS, SIF and other	Process design team

	reduction measures. Selection of components.	
6 Overall operation and maintenance planning	Develop a plan to operate and maintain the SIS, ensuring the required functional safety is maintained.	Safety instrument supplier
7 Overall safety validation planning	Develop a plan for the overall safety validation of the SIS.	Safety instrument supplier
8.1 Overall installation planning	Develop a plan for the installation and commissioning of the SIS to ensure the required functional safety is achieved.	Safety instrument supplier
9 SIS safety requirements specification	Define the SIS safety requirements in terms of SIF and SIL to achieve required functional safety.	Process design team
10 SIS realisation (both HW / SW)	To create the SIS conforming to the specifications.	Safety instrument supplier
11 Other risk reduction measures, specification and realisation	To create other risk reduction measures according to the safety function and safety integrity requirements of the system.	Safety instrument supplier
12 Overall installation and commissioning	To install and commission the SIS according to achieve the required functional safety.	Process design team / Customer / Safety instrument supplier
13 Overall safety validation	Validate the SIS according to the specifications for overall safety and considered the safety requirement allocations.	Process design team / Customer / Safety instrument supplier
14 Overall operation, maintenance and repair	Ensuring that the functional safety of the SIS is maintained to the specific level. Ensure the technical requirements, maintenance, and repair of the SIS are specified and provided for future operations.	Customer
15 Overall modification and retrofit	To define the procedures that are necessary to ensure that the functional safety of the SIS is appropriate during and after the modification and retrofit phase has occurred.	Customer
16 Decommissioning or disposal	Define the procedure that are necessary to ensure the functional safety of the SIS during and after activities of decommissioning or disposing of the process.	Customer

In order to ensure the requirement of the SIL, calculations must be done. The calculations are based on supplier data. The supplier must provide the following information: failure rates of the components, mean time to failure, safe failure fraction, and test intervals. Based on the SIL calculations, the safety function operation mode is defined as a high or a low PFD, which the instrument must achieve. In order to determine the PFD, the following values are needed from the supplier: periodic proof of testing, failure rate of safe failures (1h), failure rate of dangerous failures (1h), failure rate of dangerous detected failures (1h), and failure rate of dangerous undetected failures (1h). An instrument is proven reliable if there is enough operational experience in a restricted area, a specified functionality and documented evidence. The supplier must follow a quality management system (VDMA, 2009).

2.5 Custody transfer

Custody transfer (CT) applications are mainly used in oil and gas industries. It is a special flow measurement, where the fluid flow is defined as a metering point and measured for sales transaction. The accuracy is the most important aspect as any errors or uncertainties can be expensive for either parties. Therefore, this is highly regulated, involving governments, notified bodies and contractual agreements between CT parties (Basu, 2019a). The measuring system can be of the empty hose or the full hose method (International Organization of Legal Metrology, 2007) and includes flow conditioning, pressure, and temperature measurement on the CT pipe referred to as stream. The use of steam flow computers, meter prover, prover automation, density measurement, sampling measurement, flow computation, and quality measurement are also required (Basu, 2019a). An example of the set-up is shown in Figure 9.

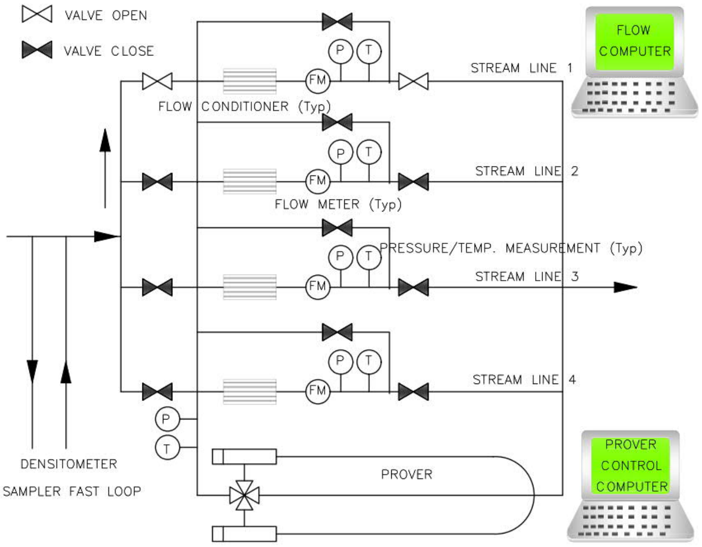


Figure 9. Custody transfer measurement with multiple streamlines (Basu, 2019a). The streamline includes multiple meters monitoring the line. The streamlines also includes a flow conditioner, safety valves and by-pass valves.

The following flow meters are accepted for CT of LNG by American Gas Association: Coriolis, ultrasonic, and turbine flow meters. The first one measure the mass flow and the others measure the volumetric flow. All the flow meters used for CT need to be approved by a notified body (Basu, 2019a; International Organization of Legal Metrology, 2007; The European Parliament and the Council, 2014). The three meters and the orifice plate can be used for CT of NG. The orifice plate restrict the flow in a pipe and calculates the mass flow based on the pressure in the pipe (Basu, 2019a). The

CT can also be done by weighing the total mass of the LNG trucks before and after the unloading with a mass flow meter found in the unloading process (The European Parliament and the Council, 2014). All the flow meters mentioned are discussed in later chapters.

2.5.1 Cryogenic flow measurement

Due to a greater demand for cryogenics and liquified gases in the past years, there have been an increased demand for effective measurement. At cryogenic conditions, the liquid offers little lubrication for moving parts, and thermal shock of fluids is problematic for transportation. Keeping elements cold, below boiling point, and ensuring that the materials are in their purest form is challenging. Special treatment is needed because of the temperature and two-phase behavior. Because of the presence of bubbles within the cryogenic liquid, there will be interference on the precise measurement. The major constraints associated with cryogenics are the two-phase nature of the liquid, the selection of materials for the operating temperature, the calibration at the operating temperature, and the density correction for volumetric flow measurement and temperature correction factors (Basu, 2019f).

The selection of the correct meter is of extreme importance and the following points need to be considered. Quality, design, and calibration must be of the highest standard, with independent verifications. The meter must be precision crafted with the best available materials and able to handle harsh conditions, including a wide range of temperatures. Reliability, material quality, workmanship, proper installation, and calibration are key influences for a reliable operation. No moving parts in the meter are preferred over moving parts. Therefore, meters with moving parts should have quick fault detections and spare parts. The turbine flow meter should be equipped with a specially designed turbine rotor that spins freely, ensuring the precision. Monitoring displayed in real time is a must for high-quality meters. Independent calibration provides a greater level of accuracy and reliable operation (Basu, 2019f).

2.5.2 Measuring instruments directive

Measuring instruments directive (MID) is a directive that specifies the requirements of the measuring system for CT of liquids and gases. It provides the requirements for all applicable meters, surrounding system, installation, operation, and verification procedures (Hägg & Sandberg, 2017). In order to use the instruments for CT, they need to be MID certified, which means that the total system needs to have a high enough accuracy rating (International Organization of Legal Metrology, 2007). MID certification requirements are discussed in Chapter 2.6.3.

2.6 Standards for LNG design

The design of any LNG facility needs to follow design standards, national, and local regulations. These include, e.g., material selection, design, safety operations, and technologies. European and American standards are commonly used around the world, and American standards can be applied in Europe and vice versa. An international work group was formed in 2006 under the International Organization of Standardization. Their main task is compatibility and harmonization of LNG standards between all countries (GIIGNL The International Group of Liquefied Natural Gas Importers, 2019). The main standard to follow for onshore design is EN 1473 "Installation and Equipment for LNG Design on Onshore Installations". This is a risk-based standard that focuses on achieving a desired level of safety for the LNG facility. Additional standards are also available and used for LNG onshore design (Mokhatab et al., 2014d) and can be found in Chapter 5.5. The standards include requirements for measuring instruments, installations and process specifications. These specifications are mentioned below.

2.6.1 Standards for instruments in LNG facilities

All electrical equipment shall be installed in non-hazardous areas. If this is not applicable, it should be installed in the area with least likelihood of an explosive atmosphere (ATEX) (European Committee for Electrotechnical Standardization, 2014b). All electrical equipment, instruments, and installations in hazardous areas shall be followed according to EN 60079. The required number of instruments needed is determined by HAZOP and reliability studies. Enough instruments shall be installed to commission, operate, decommission in a safer manner (European Committee for Electrotechnical Standardization, 2019), and include safe process control within operation ranges and safe operations in the event of alarm or shutdown (National Fire Protection Association, 2019). The instruments used are liquid level indicators, pressure indicators, and temperature indicators. The accuracy of instruments used for LNG is not specified. The only attribute given is that the accuracy shall be sufficient for the purpose of the instrument (European Committee for Electrotechnical Standardization, 2019).

The following requirements are needed for selection of the appropriate electrical equipment: classification of the hazardous area including the equipment protection level requirements. The classification of protection group or subgroup for electrical equipment in the presence of gas, vapor, and dust. The specification of the temperature class protection and ignition temperature of the gas or vapor present in the facilities. The minimum ignition temperature of dust cloud and layer in surrounding area is needed. The whereabouts and intendent use of the equipment must be specified. Finally, external influences and ambient temperatures are required for the selection. Certain output parameters for radiating or ultrasonic equipment cannot be exceeded. Unintended ignition from radiating and heating from ultrasonic equipment need to be considered, such as sunlight reflection and energy release (European Committee for Electrotechnical Standardization, 2014b).

2.6.2 Standards for instruments when measuring NG

Pressure and temperature sensors with their according NG installations shall comply with EN ISO 15970 (European Committee for Electrotechnical Standardization, 2015a). The accuracy of these instruments is divided into four classes (A-D). The class is based upon type of installation, capacity, and maximum permissible error (MPE). Accuracy class A or B are suited for satellite terminal because pressure and temperature measurements are done on pipeline. Accuracy class A has an uncertainty less than or equal to 1.2% and class B has an uncertainty greater than 1.2% and less than or equal to 2.5% (European Committee for Electrotechnical Standardization, 2015a).

The pressure can be measured with an absolute pressure sensor or a gauge pressure transmitter and typical selection is capacitance, strain gauge, or resonant sensors. Capacitance and strain gauge are discussed in Chapter 3.2.1 and 3.2.4, resonant sensors are not mentioned in this thesis. With the use of intelligent transmitters, the signal is measured electronically, converted to digital format, sent to be stored in a microprocessor and can be transmitted in a suitable format to instruments. For analog transmitters, 4 to 20 mA is used for current and voltage outputs. To avoid measurement errors, the installation shall be installed according to ISO 2186 and manufacturer specifications. The piping between the process and transmitter shall transmit the process variable accurately. The general requirements are to place the taps on the top or the side of the pipeline. The mounting of the transmitter should be beside or above the taps so that the liquid drains into the process. Impulse piping should be as short as possible, to enable independent activities of environmental conditions. The slope of the impulse line should be at least 0,08 m per meter downward towards the process connection. The impulse pipes should be large enough to avoid friction and ingress of moisture. Lastly, the impulse pipes should prevent sediment deposits and should never be for sampling. For differential pressure transmitters (DPT), both impulse legs should be the same temperature. The height difference between the sensing point and sensor shall be as short as possible to avoid the effect of gravity on the measurement. For maintenance, the connection shall include a valve in order to prevent a shutdown of the whole process and the transmitter should be accessible (European Committee for Electrotechnical Standardization, 2014a, 2015a).

The resistance thermometer detector (RTD) is the most common measuring instrument for temperature of NG. Errors caused by noise due to long wires, between the sensor and the device, requires extra wires to compensate the noise. The transmitter converts an analogue electrical signal to a digital signal which is transmitted for processing (European Committee for Electrotechnical Standardization, 2014a). The RTD is discussed further in Chapter 3.3.1. A cylindrical sensing element is used for temperature measurement. For invasive measurements, a thermowell should be used to protect the sensing element. The thermowell is also intrusive. Heat losses will occur via the probe due to thermowell but can be reduced with applying thermal insulation. For a non-invasive and non-intrusive measurement, a pipe clamp or a welded pocket can be used. There is no information in the standards on how these should be installed. The pipe clamp is the cheapest option and the thermowell is the most expensive (European Committee for Electrotechnical Standardization, 2014a). The accuracy is higher for the invasive measurement compared to the non-invasive. The accuracy for invasive measurement depends on the homogenous temperature distribution and the adiabatic compression at high velocity. The accuracy of the non-invasive methods depends on residual heat load, vacuum and flow conditions, and thermal resistance between the sensor and the fluid integral measurement of the surface temperature of the piping. The accuracy of a non-intrusive measurement is between 1 – 2%. The reliability of the instrument for the non-invasive measurement is higher than the invasive measurement due to the risk of leakage (Müller & Süßer, 2010).

The thermometer probe shall be mounted in a thermowell to protect it from corrosion, vibration, or excessive pressure and give easy access to the unit. The thermowell shall mechanically resist static and dynamic loads caused by the gas flow (European Committee for Electrotechnical Standardization, 2014a). The installation can be seen in Figure 10.

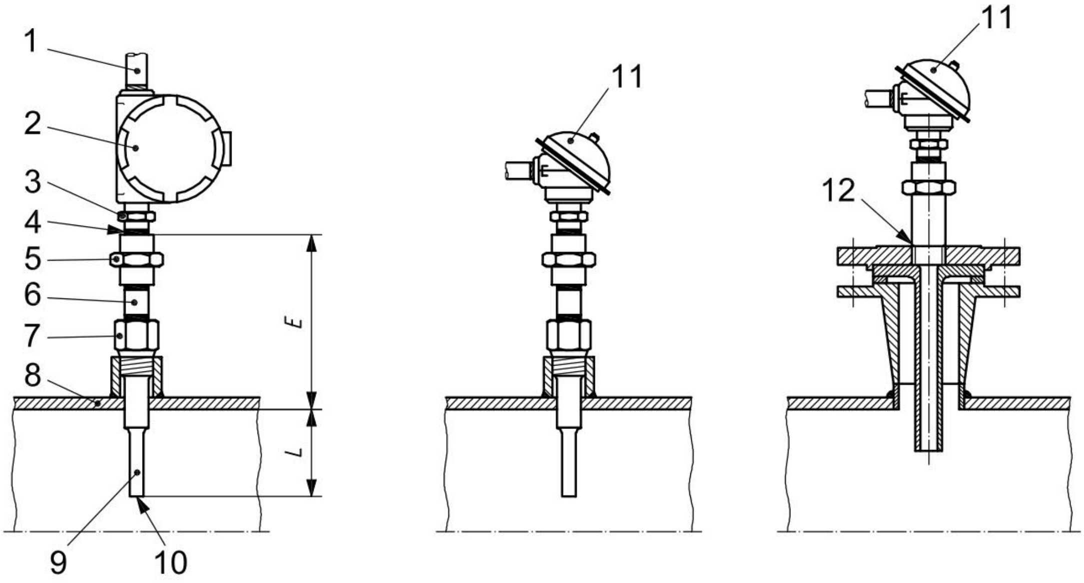


Figure 10. The RTD installation. (1) Power input, (2) transmitter, (3) sensor hex, (4) sensor adapter, (5) union of coupling, (6) extension nipple, (7) thermowell hex, (8) wall of pipe, (9) sensitive portion of sensor, (10) thermowell, (11) connection head, (12) thread, (E) extension length and (L) immersion length (European Committee for Electrotechnical Standardization, 2014a).

The RTD should be mounted vertical to the pipe wall to prevent vibration of the probe. The temperature transducer should be electrically isolated to prevent disturbances. Thermowells should not be installed near each other to prevent downstream probes to endure stress as a result of vortex, shedding and vibrations. The spacing of the thermowells should be radially around the pipeline. To ensure a good temperature measurement, the thermowell shall protrude one third of the inside diameter measured from the inner wall for DN 50 and above. For DN 300 and above, the design of the thermowell can restrict the depth of insertion and is usually 75 to 100 mm. For smaller pipes where the insertion becomes larger than three quarters of the inside diameter, the thermowell shall be inserted in a pipe bend or obliquely at 45° to the flow direction. Precautions should be taken regarding external temperature conditions to ensure that the measured temperature is the same as the gas in the pipeline. Thermal insulation around the pipe and RTD at a length of 5D on both sides should limit the effects (European Committee for Electrotechnical Standardization, 2014a)

2.6.3 MID certification

There are a limited number of standards for installation and selection of instruments for loading and unloading onshore with a truck. The NFPA 59A include requirements for loading and unloading facilities but focus more on bleed connections, isolation, and emergency valves (National Fire Protection Association, 2019). However, as mentioned in Chapter 2.5, there are requirements for the measuring system during CT. The operating conditions of the measuring system is determined by minimum measure quantity (MMQ), flow rate ($\dot{Q}_{max}$:$\dot{Q}_{min}$), type of liquid, pressure range, temperature range, Reynolds number, design of the system corresponding to the environment, and voltage supply (International Organization of Legal Metrology, 2007). The flowrate of cryogenic liquids for meter and measuring system shall have a minimum ratio $\dot{Q}_{max}$:$\dot{Q}_{min}$ of five to one. The properties of the liquid to be measured by the instruments should be specified, which are temperature, pressure, density, or viscosity (The European Parliament and the Council, 2014).

There are five accuracy classes for meters, and cryogenic liquefied gases measured at a temperature below -153°C are in the 2.5 class, which is the lowest accuracy class.

For associated measuring systems, the accuracy class is the same. The accuracy for quantities equal or greater than 2 liters or kilograms, a meter has an MPE of 1.5% and a measuring system of 2.5%. The associated measuring instruments' accuracy for temperature measurement is ± 1.0°C, pressure less than 1 MPa: ± 50 kPa, from 1 to 4 MPa: ± 5%, over 4 MPa: ± 200 kPa and density ± 5 kg/m^3 (The European Parliament and the Council, 2014). For liquid measurement the tank shall ensure a constant level either visible or detectable at the beginning and the end of the measurement operation. The level is constant when it settles within a range corresponding to a quantity no more than the minimum specified quantity deviation. This is applicable for truck unloading (International Organization of Legal Metrology, 2007). The instruments should have a high durability and be suitable for the measurement. Gas undetectable in the liquids should not lead to an error variation greater than 0.5%. However, the error variation is not allowed to be smaller than 1% of MMQ (The European Parliament and the Council, 2014).

If no gas release is occurring in the liquid upstream of the meter, the need of a gas elimination device is not required. Gas indicators should be placed downstream of the meter. In an empty hose it may be in the form of a weir-type sight glass and used as the transfer point. The transfer point is located downstream of the meter in delivery systems and upstream in receiving systems. The empty hose and the full hose system are the only allowed systems. The empty hose means a system which ensures the emptying of the delivery hose after each measuring operation. In the full hose system, the delivery end has a free end and the closing device must be installed as close as possible to the end. The meter and the pipework between the meter and the transfer point shall be kept full of liquid during measuring and shutdown periods. If this is not met, the filling of the measuring system up to the transfer point shall be affected manually or automatically and be monitored. A venting device shall be placed to eliminate gases. If the reversal of flow could result in errors, a non-return valve shall be installed (International Organization of Legal Metrology, 2007).

In the empty hose measuring system the downstream pipework of the meter, and if necessary, the upstream pipework, shall have a high point, so that all parts except the hose in the measuring system remain full. Emptying of the delivery hose is ensured by a venting valve. However, it can be replaced with a pump or compress gas injector which is operated automatically. If this is impossible due to technical or safety reasons, the measured quantity should be smaller or equal to the minimum specified quantity deviation. It should not be possible to bypass the meter in normal conditions. A manually controlled outlet may be available for purging of draining but should prevent passage of liquid during normal operations. If there is a risk of overflowing the meter, a limiting device shall be provided and shall be installed downstream of the meter with sealing possibilities. The position of multi-way valves shall be visible and located by notches, stops, or fixing devices. Deviations from this are permissible if the position of controls form an angle of 90° or more (International Organization of Legal Metrology, 2007).

The measuring system shall be designed according to metrological functions and MPE is not exceeded. Non-interruptible processes shall be designed so that significant faults do not occur or so that the facility can detect significant faults and prevent them. The system shall automatically correct a malfunction, only stop the faulty device, and have a visible or audible alarm for the operator that continues to alarm until the malfunction is corrected (International Organization of Legal Metrology, 2007).

For measuring systems for liquefied gases under pressure, only the full hose measuring system is authorized. However, if a device is installed to compensate the delivered quantity by a quantity of vapor returned in the gas line or compensation is made by automatic calculation, a connection between the gaseous phase of the truck tank and the receiving tank is permitted. In both cases the liquid flow shall be prevented from the truck tank to the receiving tank by the gas return line. The design shall ensure that the product remains in liquid state during the measurement. A thermometer well and pressure measuring device shall be installed downstream and close to the meter for verification purpose. Safety valves can be installed to prevent high pressure. If located downstream they shall open to the atmosphere or have a pipe system connected back to the receiving tank. If located upstream they should not be connected downstream to prevent bypass of the meter. If the operation requires detachable hoses, they shall remain full of their quantities, but they are not mandatory if there is a vapor return line (International Organization of Legal Metrology, 2007).

2.6.4 Standards for storage tank instruments and processes

Storage tanks shall be installed with instruments to ensure overfill and overpressure protection. To monitor the level of LNG, the level instrument needs to have continuous measurement of the fluid level and high-level detection (European Committee for Electrotechnical Standardization, 2019). If an overflow pipe is installed it should be placed at least at the same level as the high-level detection (European Committee for Electrotechnical Standardization, 2002). Pressure instrument should allow for continuous pressure monitoring, and detection of high pressure must be done by an independent instrument (European Committee for Electrotechnical Standardization, 2019).

2.6.5 Standards from control system point of view

The system shall include safety control, process control and all the instruments shall be functionally tested prior to operation. Some instruments can have individual shutdown signals. The control system shall have a high reliability, configured to fail-safe, and data transmission shall be designed to maximize reliability. The reliability of the instruments is measured by the instruments to be able to maintain normal operations. Instruments related to safety operations require redundancy when maintenance is required. Threshold detectors which have a safety function are to be independent of the process measurement. Temperature transmitter shall be installed in vent stack and flare line downstream of relief valves to trip the ESD system in case of liquid detection (European Committee for Electrotechnical Standardization, 2019). The safety system shall check the instruments for their availability, suitability of the measuring range, correct performance of operation, safety operation, appropriate arrangement, safe venting location and their performance in the event of a power cut or loss of pneumatic supply (European Committee for Electrotechnical Standardization, 2003).

For the ESD system, all SIF must be identified with their input and output signals. The communication interface needs to ensure that any failure shall not affect the ability of the ESD system to achieve or maintain a safe state of the process. The communication interface shall be robust in order to withstand electromagnetic interference including power surges. The connection interface shall be suitable for instruments referenced to different electrical ground potentials, meaning alternate mediums, e.g., fiber optics. The connections between the instruments and the ESD system shall have a response time within the process safety time. The process safety time is the time period between a failure occurring in the process or the DCS alarming a hazardous event, and the occurrence of the hazardous event if the SIF is not performed (European Committee for Electrotechnical Standardization, 2017a).

The maximum allowable response time of the ESD system starts when the process is at trip condition. It ends when the final elements reach their safe state and are still able to prevent the hazard. A response time of one minute or less is considered adequate for each SIF unless otherwise noted (European Committee for Electrotechnical Standardization, 2017b). Instruments should be selected and installed to minimize failures that result in inaccurate information due to the operating environment. Corrosion, freezing of materials in the pipes, suspended solids, polymerization, coking, temperature extremes, pressure extremes, and finally condensation in dry-leg and wet-leg impulse lines should all be considered (European Committee for Electrotechnical Standardization, 2017a).

3 CRYOGENIC MEASURING TECHNOLOGY

This chapter includes parameters for the standard satellite terminal, the measuring methods for cryogenic processes, the information and attributes needed for comparing the measuring methods. The comparison of the methods is done in order to determine the best fit for the process. The parameters of the LNG satellite terminal are shown in Table 4. The parameters are based on Wärtsilä's internal design parameters used in a standard pressurized LNG satellite terminal. These are used to determine if an instrument is suitable for monitoring the LNG process.

Table 4. Specifications of the LNG tank and the design operating conditions.

Removed due to confidentiality

3.1 Cryogenic measuring methods

The range of low temperatures is referred to as cryogenic. The range is not defined in literature but general agreement is temperatures less than -153°C and are, e.g., liquid nitrogen, hydrogen, and methane (Shokrani et al., 2013). The methods found as possible measuring methods for monitoring cryogenic processes, can be seen in Table 5. These methods are according to literature and vendors. The flow measurements have been divided into three groups as there are multiple ways of measuring the flow rate.

Table 5. The process variables to be measured and the methods available.

Measurement of process variable	Measuring method
Pressure	Capacitive, inductive, reluctance, piezoresistive, and piezoelectric pressure sensor.
Temperature	Resistance temperature detectors, semiconductor, diode, thermocouples, capacitance, and fiber Bragg grating temperature senor.
Level	Capacitive, superconductive, optical fibers, acoustic wave, differential pressure, weighing, guided wave radar, and radiometric level detection.
Flow, mass	Capacitive, Coriolis, microwave, optical, virtual, angular momentum, thermal or calorimetric, hot-wire anemometer, and dual turbine flow meter
Flow, volumetric	Positive displacement, turbine, ultrasonic, and vortex shedding
Flow, differential pressure	Orifice, venturi, and laminar flow element

If the method deviates from the parameters of the LNG satellite terminal, the method will not be investigated further. To determine which method is the best fit for the satellite terminal, information and attributes are needed. The information and attributes are method description, research, or commercial availability, technical specification, accuracy, measurement range, transmitter, installation method, reliability, cost, advantages, and disadvantages. These will be used to compare the measuring methods. For the flow meters only Coriolis, turbine, ultrasonic, and orifice will be discussed thoroughly. This is because they are the most common methods used for LNG flow measurement. They can also be used for CT of LNG, expect orifice, as mentioned in Chapter 2.5. The other flow measurement methods found will only be mentioned briefly.

3.2 Pressure measurement

The pressure is an important parameter to monitor in cryogenic applications (Arpaia et al., 2018). This is monitored to prevent overfilling, leakage in a storage tank, ensuring high enough pressure in pipelines, or detecting pressure drop in a process (Roos & Myers, 2015). A common and easy method for measuring pressure at cryogenic temperatures is to install a capillary line between the pressure location and pressure transducer at ambient temperature. This method is however limited in measurement of static pressure and at low pressure ranges. Most commercial pressure sensors are designed for use at ambient temperature and cannot be used at cryogenic temperatures (Radebaugh, 2016). The five methods presented below are exceptions and are commonly used at cryogenic temperatures.

3.2.1 Capacitive

The operating principle in a capacitive pressure sensor is the measurement of movement of an elastic element. An example of the capacitive pressure sensor can be seen in Figure 11. The element is exposed to the process pressure on one side and to the reference pressure on the other side. Absolute, gauge, or DP can be used depending on the reference pressure. These sensors are used as secondary standards for low absolute or low DP operations (Liptak, 2003).

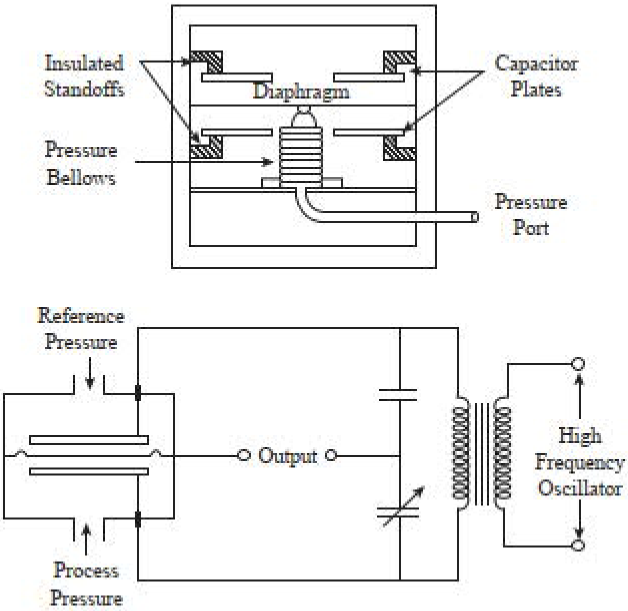


Figure 11. A capacitance pressure detector with two capacitor plates (Liptak, 2003). The pressure of the process will cause changes on the diaphragm. The change can be detected by an oscillator and is then converted into capacitance.

These sensors have an accuracy of ±1 to 2% of span. Depending on the elastic element they can operate between pressure ranges of 80 Pa to 35 MPa (Liptak, 2003). According to Radebaugh (2016) capacitive sensors in the range of 20 – 50 pF have a 5% change of sensitivity when cooled from 27 to -269°C.

Two research articles on capacitive pressure sensors for cryogenic conditions were found, the first a DP sensor and the second a gauge pressure sensor. The first one has a sensitivity of 0.02 Pa/Hz$^{(1/2)}$ with changing of less than 10% from a temperature range from -270 to 27°C (Swanson et al., 2001). The second one was tested in conditions of temperature ranges from -196 to 100°C and pressure range of 0 to 5 MPa. The measurement systems had an accuracy of 1% (Lago et al., 2014).

The advantages are a high accuracy, rangeability, linearity, and fast response time. The disadvantages are the temperature sensitivity, the short leads from the sensor, a high output impedance, sensitivity to stray capacitance, sensitivity to vibration, low overpressure capability, and sensitivity to corrosion (Liptak, 2003). A coaxial cable between the sensor and the electronics is required. The capacitive pressure sensor is a common type of pressure sensor used for cryogenic temperatures in laboratory environment. However, it is not commercially available for cryogenic temperatures

(Radebaugh, 2016). Therefore, information regarding installation method, transmitter, and reliability has not been found. They can however be used to measure the temperature of NG and the installation method is described in Chapter 2.6.2.

3.2.2 Inductive

Two kinds of magnetic pressure transducers have been tested for use in cryogenic applications (Arpaia et al., 2018). These magnetic phenomena are induction and reluctance. Inductance utilize the amount of electromotive force in an electric circuit while reluctance is the resistance to magnetic flow. These utilize the magnetic phenomena in converting the elastic movement of a sensor into an electric signal. When the pressure sensor detect a pressure change the inductance or reluctance will change in an electric circuit (Liptak, 2003).

An inductive pressure sensor use inductance to convert the flexing of a diaphragm into the linear movement of a ferromagnetic core. The movement of the core is used to vary the induced current generated by an AC power primary coil on another secondary coil (Arpaia et al., 2018). A schematic representation is shown in Figure 12.

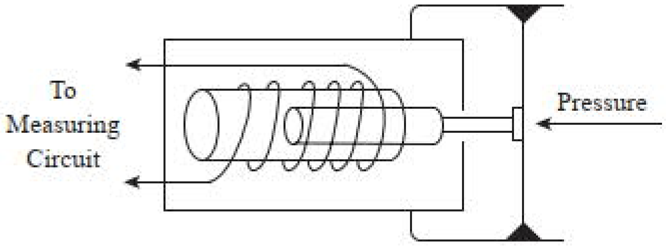


Figure 12. Schematic of an inductance pressure transducer (Liptak, 2003).

Academic researchers have developed a superconducting pressure gauge and controller system to stabilize pressure within 1 mPa in the pressure range of 0 – 3 MPa at temperatures below -267°C for liquid helium (Geng et al., 2000). The transducer is based upon another academic research project using a superconducting technique called “superconducting quantum interference device” or SQUID magnetometer (Pobell, 2007). A rod is attached to the center of the diaphragm which supports a superconducting plate. A spiral-superconducting coil is in proximity and the SQUID magnetometer measures the magnetic field change caused by the pressure change

(Figure 13). A disadvantage with this method is the lack of immunity toward external magnetic fields (Arpaia et al., 2018). A commercial inductive pressure sensor for cryogenic conditions has not been found.

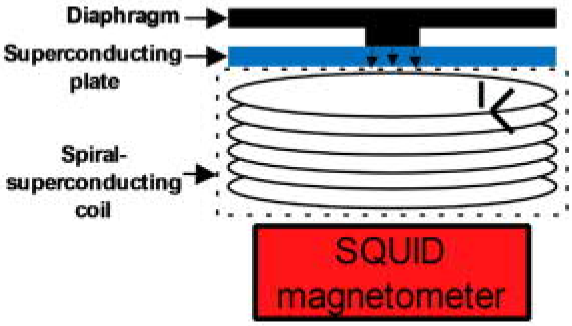


Figure 13. General architecture of the superconducted transducer for pressure measurement (Arpaia et al., 2018).

3.2.3 Reluctance

As mentioned in the previous chapter, the reluctance pressure sensor is a magnetic pressure transducer. Electrical reluctance is the equivalent of electrical resistance in a magnetic circuit (Liptak, 2003).

The sensor has inductive coils on both sides of the diaphragm (Figure 14). The magnetic reluctance is the function of the gap between the diaphragm and the “E” core. When the DP is zero, the magnetic flux in the coils have equal reluctance. When pressure is applied, the reluctance will change the inductance of the two coils and is measured by using an AC bridge where the output voltage is proportional to the pressure (Liptak, 2003; Pavese & Beciet, 2012; Radebaugh, 2016).

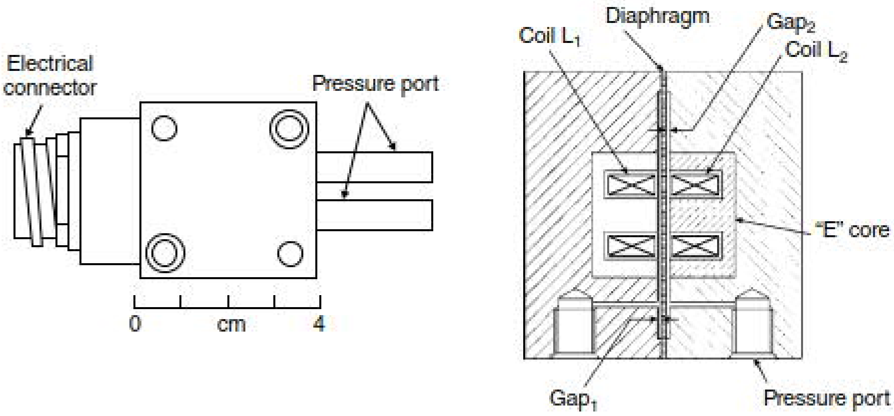


Figure 14. Reluctance pressure transducer and cross section (Radebaugh, 2016).

Commercial reluctance transducers are available on the market. For cryogenic applications an all welded construction is the only viable option (Radebaugh, 2016). Radebaugh (2016) reports of various models of reluctance transducers that have been tested for cryogenic conditions with positive results. However, these have been tested at a pressure below 100 kPa. From 27 to -196°C, the transducers showed a decrease of 12% in sensitivity at the mentioned pressure. One case of a pressure test at 5 MPa is presented, and the result is a large deviation from linearity at a low temperature of -269°C. No result of a test between the pressure range of 0.1 to 5 MPa has been found.

The calibration and the vibration test of the reluctance pressure transducers are reported in a research article with successful results. However, the same problem as above is that the pressure range is below 1.4 MPa. A 6% decrease in sensitivity was presented when the temperature was dropped from 27 to -231°C. After repeated temperature cycling, the pressure transducer had an accuracy of ±1% in liquid helium (Kashani et al., 1990).

The advantages are as follows: the applicability to a wide temperature range, a good dynamic response of measurements, low sensitivity to shock and vibration, and high output signal. The disadvantages are sensitivity to temperature, requirement for AC excitation and susceptibility to magnetic fields (Liptak, 2003; Validyne Engineering, 2020). The cost of the transducer has not been found. The general installation procedure is as follows: the transducer should be mounted on a flat and vertical surface to prevent strain of the transducer body. By mounting the transducer above the pressure point, less dirt is trapped in the system and the interior is cleaner. For gauge pressure measurement, a simple shutoff valve should be installed on the pipeline for the maintenance of the transducer. For DP measuring, two shutoff valves need to be installed on both sides of the pressure source to the transducer. A bypass valve need to be installed parallel to the transducer as well as a drain valve (Validyne Engineering, 2020).

3.2.4 Piezoresistive

The piezoresistive pressure sensor or strain-gauge sensor is the most common commercial pressure sensor and can detect absolute, gauge, and DPs. It utilize a strain gauge to measure the deflection of a diaphragm from the pressure on one side (Radebaugh, 2016). The piezoresistive material changes the resistance value when it is compressed or strained. The sensor connects the diaphragm to four piezoresistors, installed as a Wheatstone bridge (Figure 15). The resistance is converted into voltage variations and correlates to the pressure on the diaphragm (Arpaia et al., 2018; Liptak, 2003)

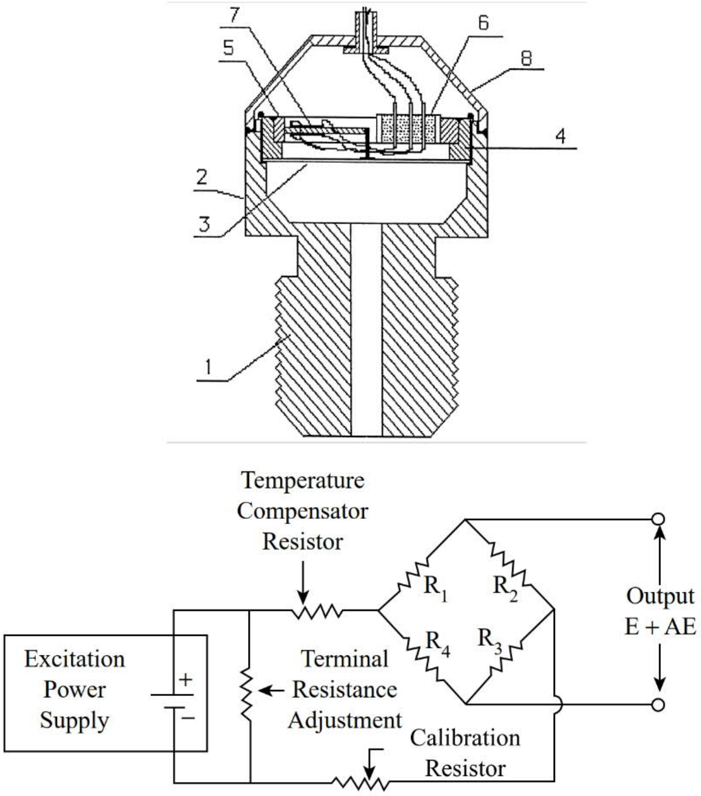


Figure 15. Piezoresistive pressure sensor for cryogenic media: (1) pressure channel, (2) housing, (3) membrane, (4) cartridge clip, (5) strain unit, (6) metal-glass contact unit, (7) cantilever with two strain gauges and (8) cover with a Wheatstone circuit (Maryamova et al., 2000 and Liptak, 2003).

The use of the piezoresistive sensor has grown due to a technique called Micro Electro-Mechanical Systems. The technique is used to make the sensors small, inexpensive, have a low power usage, and a fast response time. With the proper selection of materials, the sensor can be used at cryogenic temperatures. Research efforts have been made to make them suitable for low pressures and wide temperatures (Arpaia et al., 2018; Radebaugh, 2016).

Piezoresistive sensors have been designed and manufactured to measure the cryogenic fluid pressure with an accuracy of 0.25% up to 30 MPa for liquid hydrogen (Shams et al., 2001). Other sensors have also been reported for use in cryogenic conditions with operating ranges of 0 to 10 MPa and -231 to 27°C (Maryamova et al., 2000). The cost of the transducer is between €450 to €1,600 and for equipment €70 to €1,400. The cabling can be done with a four-wire conductor, shielded or twisted pair. The sealing surface must be smooth and free from irregularities when mounting the transducer. The use of excessive torque during the installation or improper placement of the sealing can lead to distortion and the sensitivity of the instrument is affected (Carter et al., 2018).

This type of transmitter is also safety certified according to IEC 61508 series, meaning it has a high reliability and SIL. The transmitter is also approved for ATEX areas. The transmitter should be installed as close to the process as possible with a minimum amount of piping for best accuracy. The transmitter is usually only capable of handling an ambient temperature of -40°C, therefore, cannot be in contact with the fluid. The transmitter should be installed parallel to the ground and if it is mounted on its side, the coplanar flange must ensure proper venting and draining. The process flanges should be mounted with enough clearance for process connections (Emerson Automation Solutions, 2017).

For liquid measurement the impulse piping should be placed to the side of the line to prevent depositions on the transmitter process isolators. The transmitter should be beside or below the taps to ensure the gas can vent into the process line. Drain/vent valve should be mounted upward to allow gases to be vented. For gas measurement, the impulse pipe taps should be on the top or the side of the line, and the transmitter should be beside or above so the liquid will drain into process line. The installation procedure in Chapter 2.6.2 can be used, but the slope of the impulse pipe should be upward. The piping between the process and the transmitter must accurately transfer the pressure to obtain accurate measurement. Five possible sources for errors can be pressure transfer, leaks, friction loss when purging, trapped gas in liquid line, and density variations between the legs (Emerson Automation Solutions, 2017).

3.2.5 Piezoelectric

When the piezoelectric pressure sensor is exposed to pressure, the sensing element in the form of crystals will produce an electric potential and a flow of the electric charge is presented (Figure 16). With an amplifier this charge is converted into a voltage output but will decay with time. Therefore, this sensor cannot measure the static pressure but instead measure the pressure change or the dynamic pressure (Liptak, 2003; Radebaugh, 2016).

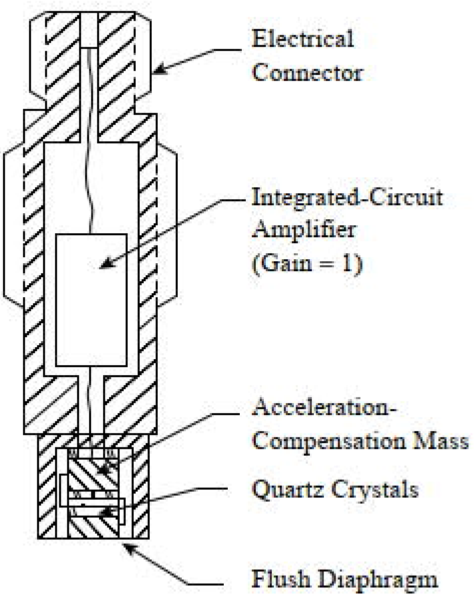


Figure 16. Piezoelectric pressure sensor (Liptak, 2003).

The materials of the sensor and the installation method are suitable for cryogenic use. Commercially available sensors can be found for temperatures down to -196°C and operate at a pressure range between 0.3 to 35 MPa. The accuracy for the sensor is low. Typical error is 5% and it can be 0.07%/°C which results in low accuracy at low temperatures (Radebaugh, 2016).

The advantages are their small size, a high-speed response time, a rugged construction, and self-generated signal. The disadvantages are limitations on dynamic measurement, temperature sensitivity, and a special cabling and output amplifier is required (Liptak, 2003). The price of the transducer is between €600 to €5,500. The price of the equipment is between €360 to €3,000. This is because the required coaxial cable is expensive. The transducer is installed in the same way as for the piezoresistive transducer but it is smaller in size as it eliminate a case-mounting (Carter et al., 2018).

3.3 Temperature measurement

The modern temperature scales follow the International Temperature Scale of 1990 (ITS-90). The scale extends from -208 to 1085°C and is a near approximation to a true thermodynamic temperature scale. Most commercial thermometers for cryogenic temperatures are resistors, thermocouples, diodes, or capacitors. These are mentioned below with the addition of fiber Bragg grating sensors, which have been developed for cryogenic temperatures. A good thermometer should be stable over time and have a high sensitivity. It should also have a fast response time when dealing with dynamic measurement (Radebaugh, 2016).

3.3.1 Resistance temperature detector

The RTD is based upon increasing electrical resistance of conductors with increasing temperature. The RTDs are made of pure metal and the most common one is made of platinum. A standard platinum resistance thermometer (PRT) can be seen in Figure 17. The PRT is the international standard for temperature measurement between the triple point of hydrogen (13.8 K) and freezing point of antimony (904 K). It can be found commercially for ranges between -200 to 850°C (Liptak, 2003).

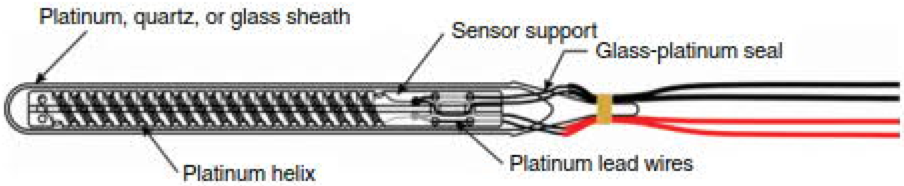


Figure 17. Cross section of a capsule type standard platinum resistance thermometer (Radebaugh, 2016).

The relationship between the temperature and the resistance changes of an RTD is referred to as an alpha curve. The PRT has a temperature coefficient which can be calculated by using Equation (1). In order to satisfy the ITS-90 conditions, the temperature coefficient should fulfill the European standard curve (DIN IEC 60751) found in Equation (2). For the best accuracy, the actual temperature coefficient should be specified (Liptak, 2003; Radebaugh, 2016).

$$\alpha = \frac{R_{100} - R_0}{100 * R_0} \tag{1}$$

Where

α = Temperature coefficient
R_0 = Resistance of RTD at 0°C
R_{100} = Resistance of RTD at 100°C

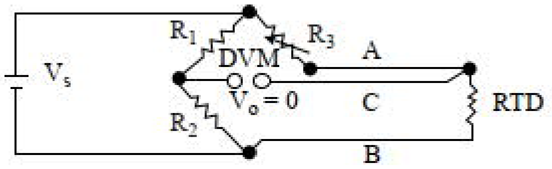
This technically has units (Ω/Ω°C) because the 100 in the denominator represents a 100°C temperature change but conventionally α is dimensionless (Radebaugh, 2016).

$$\alpha =\geq 0.00385\,\Omega/\Omega\,°C \tag{2}$$

The instrument used with an RTD must be configured to use the same alpha curve or significant errors will occur. For an industrial PRT, the resistance at 0°C is 100 Ω and can be of three different tolerance grades (A, B and C). The A-grade has the least uncertainty of ±0.47°C at -200°C and ±0.13°C at 0°C (Liptak, 2003; Radebaugh, 2016).

In order to determine the process temperature, the change in total resistance of the RTD must not be affected by anything other than the process temperature. In order to achieve this, two- to four-lead wires are installed between the RTD and the transmitter. The two-lead wire application is rare since the error introduced by the lead wires may cause significant errors. This is avoided for installations where a high accuracy is required (Liptak, 2003).

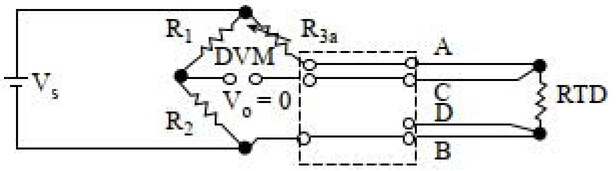
When using three-lead wires, the accuracy is increased, but terminal corrosion and loose connections can still create significant errors. A 1 Ω difference for a PRT can cause an error of 2.6 °C. In Figure 18, the three-lead wire connection can be seen. Wires A and B are connected to different halves of the bridge therefore the total lead resistance will be the difference between B and A. The connection to devices with three wire extension cables will produce errors that will wary with the environmental conditions. For high-precision measurements the four-lead wire connection should be considered as it completely eliminates the lead wire effect (Liptak, 2003).



When bridge is balanced: R1 + R3 + A + C = R2 + B + RTD + C
If R1 = R2 this becomes: R3 = RTD + B + A = RTD

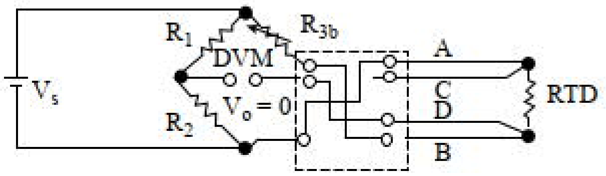
Figure 18. Three lead wire connection. The lead wire effect is reduced to the difference between lead wire A and B (Liptak, 2003).

The total lead resistance will be eliminated by using the four-lead wire connection. The RTD can either be connected to a null-balance bridge or a constant current source (CCS). The null-balance bridge connection is shown in Figure 19. It operates by making alternate null-balance measurements in the two configurations which cancels out the lead wire effect. This method is complex and expensive. The other method achieves the same accuracy and is inexpensive. The CCS with a four-lead wire connection can be seen in Figure 20. The bridge is replaced by a digital voltage meter which only measures the resistance of the RTD. The digital voltage meter is insensitive to the lead wires since there is no current flowing through them. The lead resistance will not contribute to any errors since there is no voltage drop measured (Liptak, 2003).



Switch in Position "A"

R1 + R3a + A + C = R2 + B + RTD + C
When R1 = R2:
R3a + A = B + RTD



Switch in Position "B"

R1 + R3b + B + D = R2 + A + RTD + D
When R1 = R2:
R3b + B = A + RTD

Figure 19. Four lead wire connection using null-balance bridge. The connection results in the lead wire effect being eliminated (Liptak, 2003).

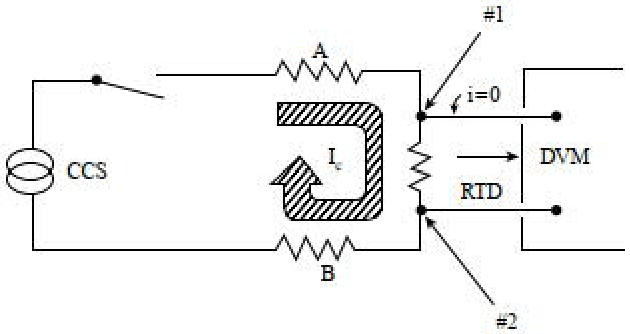


Figure 20. Four lead wire RTD connected to CCS and DVM readout (Liptak, 2003).

The three wire RTD is used for industrial processes, but for cryogenic processes the use of the four wire RTD is recommended due to their high precision measurement. In order to protect the RTD from its surroundings, a protective thermowell and fixed length leads are recommended (Liptak, 2003). In Figure 21, the typical thermowell protection with an assembled RTD can be found. The best location to have the RTD is on top of the thermowell which can be seen in the figure. The location eliminates lead-wire and noise effects. If the placement of the RTD is impossible, the lead wires should be twisted and shielded (Liptak, 2003). In Figure 22 two types of surface mounted RTDs can be seen and in Figure 23 the alternative surface mountings are shown.

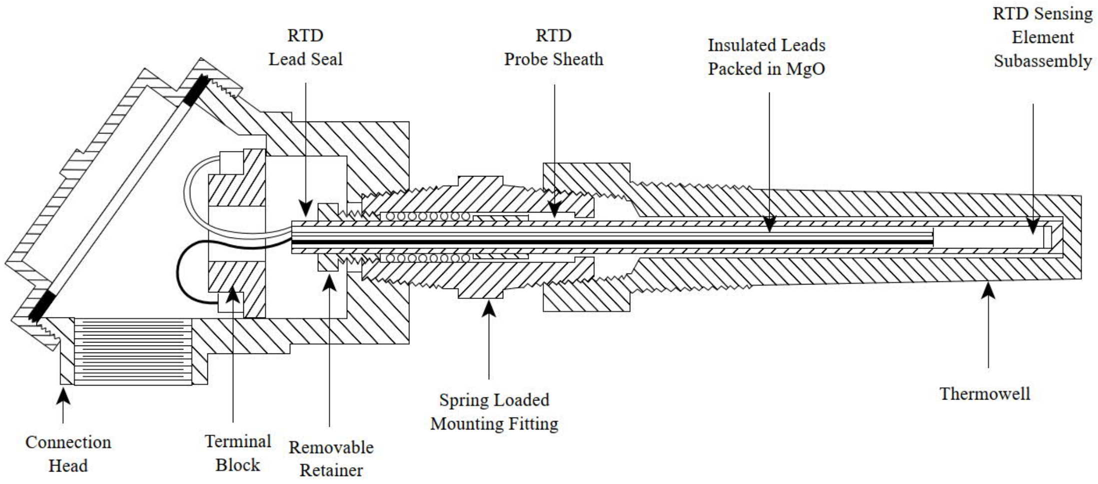


Figure 21. Commercial RTD and thermowell installation (Liptak, 2003).

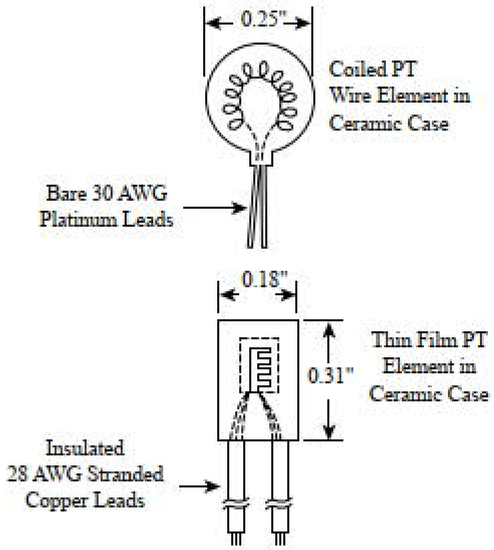


Figure 22. RTD surface temperature sensors (Liptak, 2003).

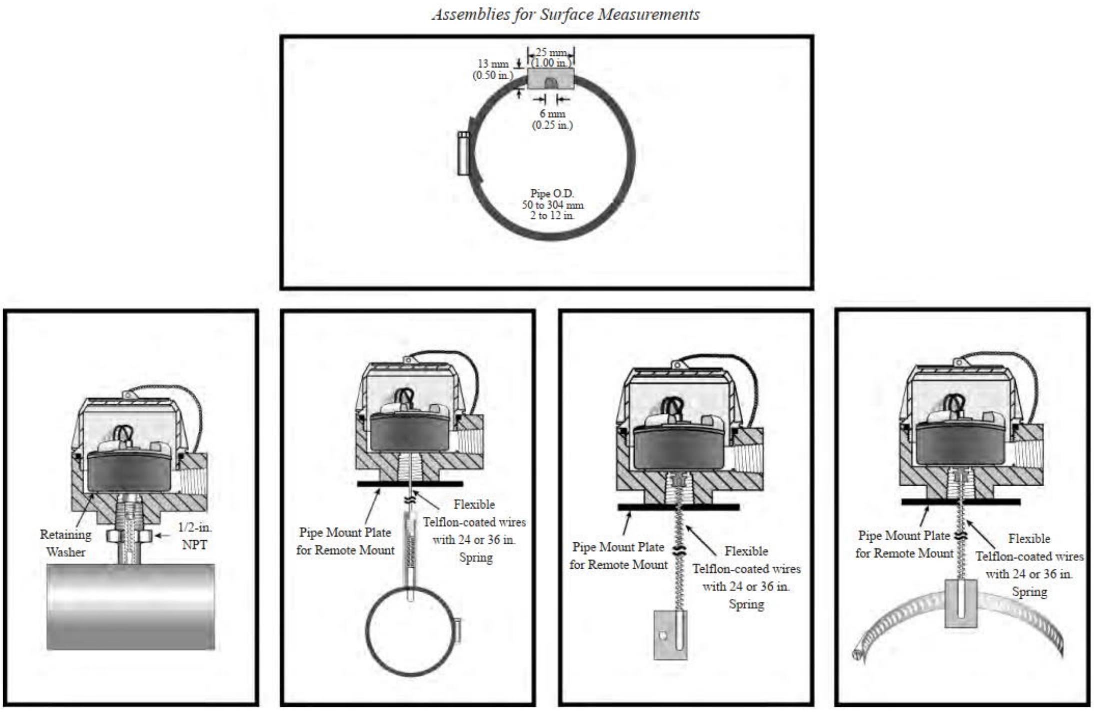


Figure 23. Alternative mounting for surface mounted RTD and thermocouple (Liptak, 2003).

In Table 6, the performance of the RTD transmitters are summarized. Intelligent transmitters have better performance but still have a minimum error. The digital output provides better performance than the analog output. The Intelligent transmitters are flexible meaning they can be used for multiple thermocouples and RTD elements. They also have self-diagnostic and self-calibration. The RTD transmitter can also be included with dual RTDs, which provides temperature differentials, high/low capability, or redundant backup. The dual method is unfortunately only available for three lead wire connections because of the limited terminal connection. These transmitters have a wide variety in universal input, configuration, and protocol selection (Liptak, 2003).

Table 6. Performance capabilities of platinum and RTD transmitter. When two error values are given, refer to higher value unless "R" meaning of actual reading. Adapted from (Liptak, 2003).

Performance criteria	Standard Platinum element	Smart Digital output	Smart Analog output 4-20 mA
Inaccuracy	±0.15% or 0.08°C	±0.035% or 0.1°C	±0.05% or 0.1°C
Repeatability	0.05%	±0.015% or 0.1°C	±0.025% or 0.1°C
Zero shift	±0.1%	±0.06% R or 0.1°C	±0.1% R or 0.1°C
Span shift	±0.1%	-	-
Supply voltage variations	±0.2% or 0.01°C	-	0.005%/V
Ambient effect (55°C)	±0.75%	Included above	±0.1%

The RTD has a high accuracy, stable operation, and sensitive thermal abilities. That is why it is used to define parts of ITS-90. A disadvantage with RTDs is the error produced by self-heating which increases with the size and resistance of the RTD. Other disadvantages are as follows: a higher cost, more fragile construction, and bigger size compared to thermocouples. An RTD sensor with a transmitter and thermocouple can range between the price of €300 to €1,800. This depends on the level of intelligence and features of the instrument (Liptak, 2003).

The transmitter can be installed on top of the thermowell or it can be field mounted with a threaded sensor. The thermowell should be attached to the measuring point of the pipe or the process container wall. For the on top installation, the transmitter should be assembled to the sensor and an extension is added in accordance to the transmitter being in the range of the ambient temperature. For field mounted installation, necessary extension nipples and adapters to the thermowell should be attached, sealed and then the wire to the sensor should be connected to the remote transmitter. Lead-wires should be attached from the sensors to the transmitter. The lead-wires should be thermally anchored at multiple points between the ambient temperature to ensure that no heat conduction occurs for the sensor. The temperature transmitter is SIL certified (Emerson Automation Solutions, 2018).

3.3.2 Semiconductor

The semiconductor-like resistance thermometer has an operational temperature range between -173 and -270°C (Radebaugh, 2016). This temperature range is lower than the LNG boiling point and the design parameters of the LNG satellite terminal. The PRT is a proven superior temperature measurement for the design temperature and most semiconductors does not follow a standard response curve as the PRT do. Therefore, the semiconductor-like resistance thermometer will not be investigated further.

3.3.3 Diode

Diodes are two-terminal electronic devices that allow the current to flow in only one direction. There are two types of diode thermometers that can be used for cryogenic applications, silicon (SI) diodes and germanium (GaAlA) diodes. Originally, the SI diode was limited to a temperature range of -51 to 149°C, but special SI diodes have been researched and manufactured to handle the same range as for GaAlA diodes, which are -251 to 43°C (Liptak, 2003; Radebaugh, 2016). The GaAlA diode is shown in Figure 24.

The diodes are sensitive, linear and have an accuracy of 0.2% at cryogenic temperatures. The sensor can detect small temperature differences, has a high accuracy, available in small sizes, and low cost. The SI diode follows a standard temperature curve while the GaAlA diodes must be individually calibrated therefore increasing the cost. Magnetic fields effect the SI diode measurement. A calibrated diode with packaging, mounting for cryogenic use and monitoring readouts cost approx. €1300 (Liptak, 2003; Radebaugh, 2016). No installation method has been found for the diodes or the type of transmitter used.

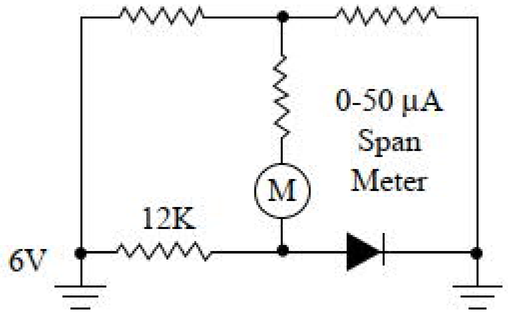


Figure 24. GaAlA diode thermometer circuit (Liptak, 2003).

3.3.4 Thermocouple

A thermocouple (TC) utilizes the thermopower or the Seebeck Effect. The assembly includes two different types of wires which are joined together at one end, referred to as the hot end. The other end, cold end, is connected to an instrument measuring the Seebeck voltage or the open circuit voltage. The voltage appears from the temperature difference of the two ends and the Seebeck coefficients of the two wires (Liptak, 2003; Radebaugh, 2016).

A 0°C reference junction is the most common type of TC which is show in Figure 25. However, the reference junction can be at any temperature. TCs are characteristic for measuring a small temperature differences and the set-up can be seen in Figure 26. Several types of metal combinations can be used for the TC and are decided by melting points, reaction to various atmospheres, thermoelectric output, electrical conductance, stability, repeatability, cost, and ease of handling and fabrication (Liptak, 2003; Radebaugh, 2016). The most common types of TCs used for cryogenic temperatures are shown in Table 7. The table includes information such as the type, wire pair, temperature range, standard error, advantages, and disadvantages.

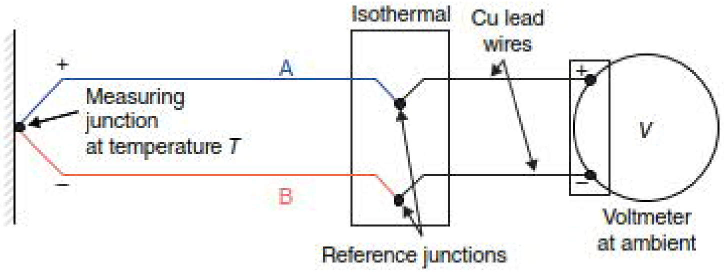


Figure 25. Schematic overview of TC measurement with 0°C reference (Radebaugh, 2016).

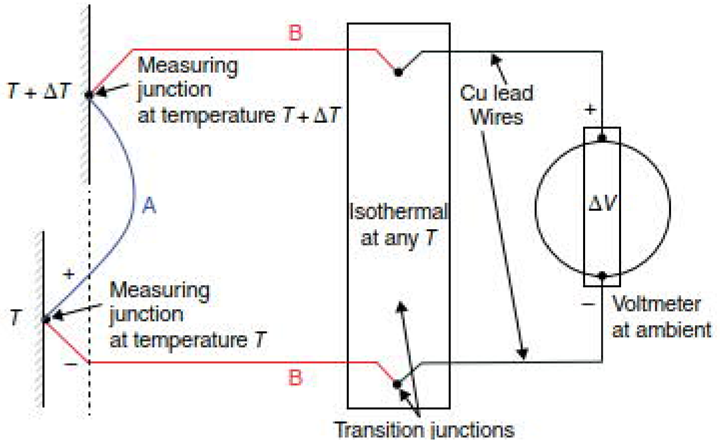


Figure 26. Schematic overview for small temperature difference (Radebaugh, 2016).

Table 7. Thermocouples used at cryogenic temperatures. Adapted from (Liptak, 2003; Radebaugh, 2016).

Type	**Positive wire**	**Negative wire**	**Temperature range K**	**Standard error**	**Advantage**	**Disadvantage**
E	Chromel	Constanatan	[3, 1173]	1.5K	Highest V/°C	Larger drift than other metal couples
J	Iron	Constanatan	[63, 1073]	1.5K	Most economical	Brittle below 273.15K
K	Chromel	Alumel	[3, 1573]	1.5K	Most linear	More expensive than T or J
T	Copper	Constanatan	[3, 673]	1% of T	Good resistance to corrosion from moisture	Smaller temperature range

The TC is manufactured with a protective outer sheath which uses the insulating material to electrically separate the TC from the sheath. The sheath also provides environmental and mechanical protection. The TC require an electrically isolated measuring circuit. The TC insulation will breakdown with time and measurement errors will occur. Therefore, an instrument with full isolation should be used to eliminate the possibility of the breakdown. The accuracy of the TC depends on the wire material and should be made from the same coil of wire to ensure the accuracy. TC types for cryogenic use have specific extension wires which are designed to be installed at the cold junction of the loop. A Thermowell is supplied to protect the TC from mechanical damage, the fluid and its environment (Liptak, 2003). The assembly of the thermowell for the TC can be seen in Figure 27 and the mounting techniques is shown in Figure 23.

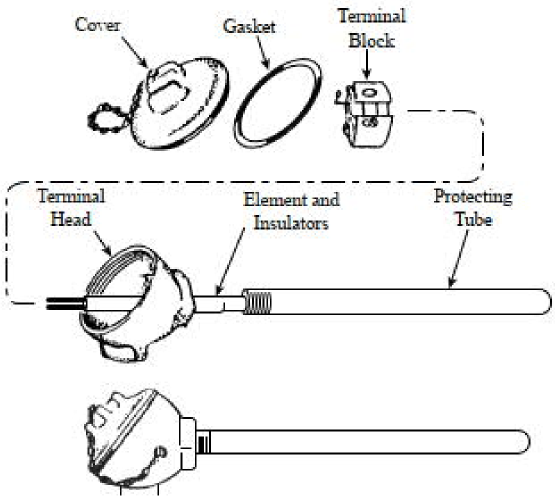


Figure 27. TC and thermowell installation (Liptak, 2003).

The transmitter, the protocol, and the flexibility of the TC are similar to the properties mentioned in 3.3.1. With the use of extension wires for cryogenic processes issues are associated and the best alternative is to have the transmitter on top of the thermowell, which can be seen in Figure 28. It can be expensive to have the transmitter on top of the thermowell since the cost of the cabling can be high from the TC to the control room. The transmitter is ATEX proof and has an accuracy of 0.05% of full range (Liptak, 2003).

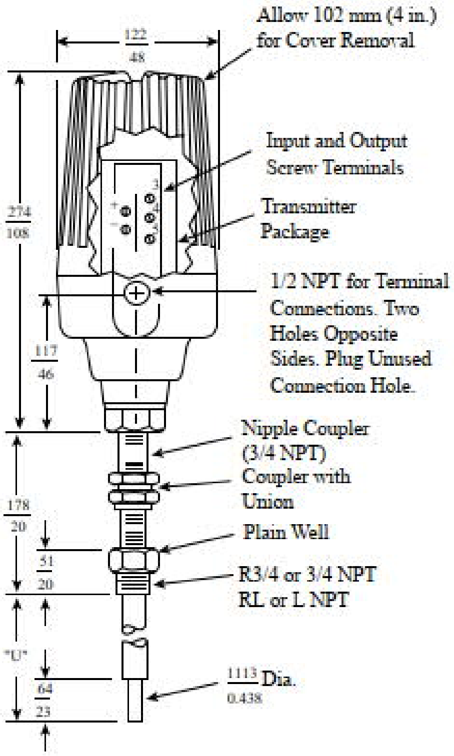


Figure 28. Thermocouple with transmitter mounted on top of thermowell (Liptak, 2003).

The advantages are as follows: low cost, large variety of sizes, ruggedized construction, versatile installation, wide temperature range, accurate readings, and fast response time. The disadvantages are a weak output signal because of its sensitivity to disturbance, the requirement of amplifiers, and the fact that calibration errors are induced over time. The largest size of lead wire should be used for the measurement. Stress and vibrations should be avoided in the process. The price of the thermocouple element, including the transmitter and the thermowell, is between €700 and €1,800. This depends on the design and additional features (Liptak, 2003). The method of installation is the same as for the RTD, found in Chapter 3.3.1.

3.3.5 Capacitance

The capacitance thermometer has a temperature range between -271 and 27°C and a high accuracy. It is mostly used for applications where a strong magnetic field is present (Radebaugh, 2016). For that reason alone, it will not be investigated further since the magnetic field is not an issue for the processes of an LNG satellite terminal.

3.3.6 Fiber Bragg grating

The FBG sensor uses optical technology where the Bragg wavelength shifts are measured to establish the temperature of a treated section on the core fiber material. When exposed to UV light, the specified Bragg wavelength related to its grating period is reflected from the source light. As the temperature changes, the Bragg wavelength shifts which correlates to the measured temperature. The FBG sensors have not been applicable for cryogenic use (Liptak, 2003), but with the help of research a solution developed for cryogenic use has been found for monitoring in the LNG storage tank (Hong et al., 2019). The basic principle of the gratings, the wavelength of the reflected spectrum, and the design of the FBG sensor can be seen in Figure 29.

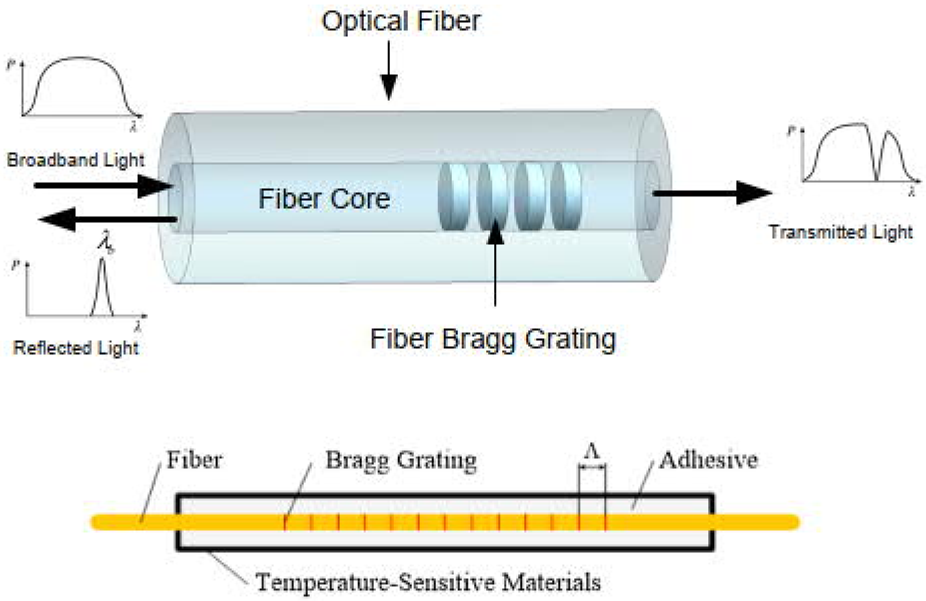


Figure 29. Operation and design of an FBG sensor for cryogenic use (Hong et al., 2019).

The reason for developing the FBG sensor for cryogenic tank monitoring is because traditional electric sensors has a high risk of explosion caused by sparks. Optical fiber sensors are therefore a suitable option given their dielectric nature (Hong et al., 2019). The sensor has been tested in a tank with 3 m^3 liquid nitrogen at 2 MPa because of the safety hazards of LNG and RTD sensors are used as reference and validation. The test proved that the FBG sensor could be used in a temperature range of -190 to -80°C for LNG tank monitoring with an accuracy of ± 0.35°C at the lowest temperature. The test also proved that there is a linear relation between the wavelength and the temperature (Hong et al., 2019). The equation for determining the temperature is shown in Equation (3).

$$T = k_i(\lambda - \bar{\lambda}_i) + \bar{T}_i \ (\bar{\lambda}_i < \lambda < \bar{\lambda}_{i+1}) \quad (3)$$

Where

T = Temperature (°C)

$\bar{T}_i$ = Constant at interval temperature (°C)

λ = Wavelength (nm)

$\bar{\lambda}_i$ = Constant at wavelength at segment number (nm)

$\bar{\lambda}_{i+1}$ = Wavelength at next segment number (nm)

k_i = Constant at segment number

i = Segment number, every 10°C of temperature range

The constants can be determined from the correlation of temperature and the reflected wavelength. The FBG sensor can effectively measure the temperature in an LNG tank and it has similar dynamic performance as to an RTD sensor. However, they are not commercially available but will be in the near future (Hong et al., 2019).

3.4 Level measurement

There is no ideal level measurement technology. In a perfect world all measurements would be nonintrusive and noninvasive (Liptak, 2003). This is however not practical and the determining of the liquid level can be a problem (Radebaugh, 2016). Selecting a level instrument should be based on the affecting factors and the desired qualities of the instrument. In practice there is a tendency to select a DP sensor and the performance is what it is. This is often not the best solution. This type of instrument can run into problems for low pressure tap handling. If the level indication must be independent of density, radar, or capacitive measurement can be used (Liptak, 2003). An example utilizing radar for pressurized bullet tank is shown in Figure 30. The following chapters include DP sensor, radar, capacitive, and five other level measurement methods for cryogenic use.

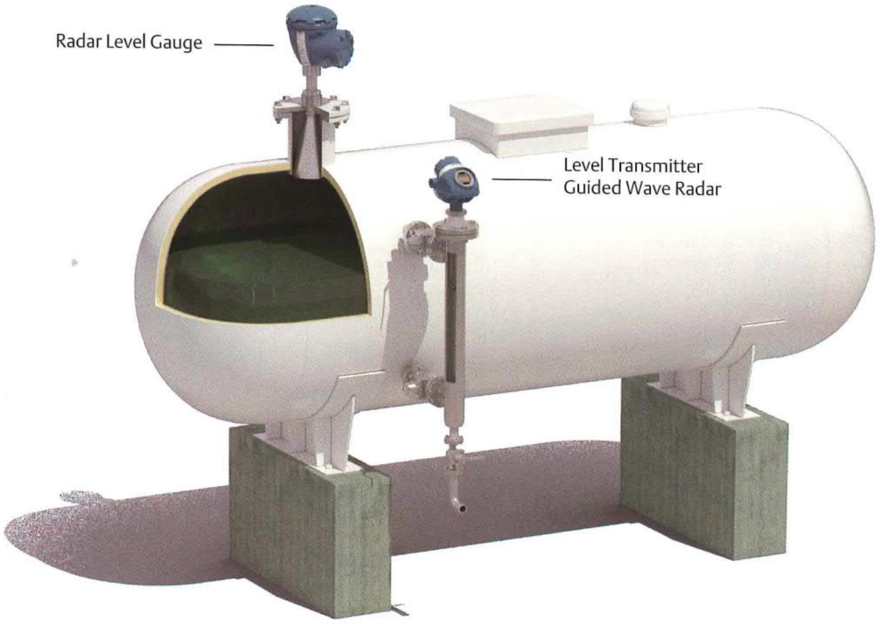


Figure 30. Tank gauging configuration for pressurized horizontal tank. Adapted from - (Hägg & Sandberg, 2017)

3.4.1 Capacitive

A capacitive sensor allow for continues measuring of the liquid and utilizes the difference in the dielectric constant for liquid and gas state (Matsumoto et al., 2011; Sawada et al., 2003). It can also be used for level detection and the capacitance is decided by the medium (van de Kamp, 2006) and is formed when a level sensing electrode is installed in a tank. The electrodes of the sensor refer to one plate of the capacitor and the second plate is the tank wall or the reference electrode. As the medium level changes, the electrode is displaced by the different dielectric constant of the gas/liquid phase and a charge in the capacitance occurs. The capacitance is proportional to the dielectric constant and as the medium level raises the parallel plates will increase the capacitance as a function of height. The transducer is designed in the form of two coaxial tubes isolated from each other as seen in Figure 31 (Arpaia et al., 2018).

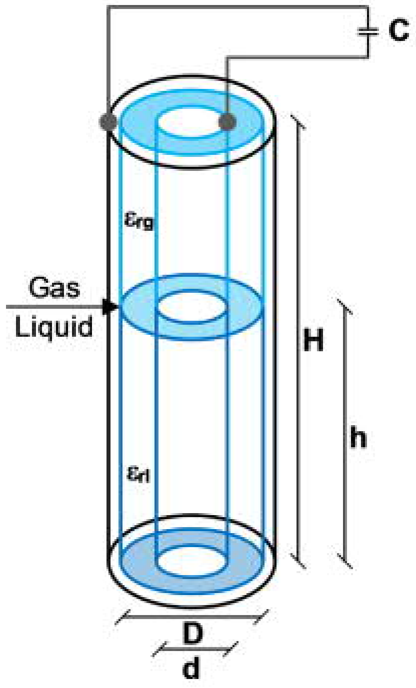


Figure 31. Capacitive transducer for liquid measuring. C is capacity, H is height of the transducer, D is the outer diameter of electrodes, d is the inner diameter of the electrodes, h is the height of the cryogenic liquid, ϵ_{rl} *and* ϵ_{rg} *are the dielectric constants of the liquid and the gas (Arpaia et al., 2018)*

The accuracy of the capacitive sensor depends on the transducer and the electronics used (Celik et al., 2001) but can be down to a sub-millimeter of a meter (Matsumoto et al., 2011). The measurement is affected by temperature, distance between electrodes and contamination of the dielectric material (Arpaia et al., 2018). Research has been made to increase the accuracy, the sensitivity of the capacitive sensor, and for use of different types of cryogenic liquids, e.g., liquid nitrogen, helium, and hydrogen (Celik et al., 2001; Matsumoto et al., 2011; Medeova et al., 1998). This method is commercially available and used for liquid nitrogen (Radebaugh, 2016) and also in petrochemical industries (van de Kamp, 2006). Therefore, this method is applicable for LNG, but no information has been found on it being used for LNG tank level measuring.

3.4.2 Superconductive

Conductive sensors cannot be used at cryogenic temperatures and for this reason superconductive sensors have been developed. The superconductive sensor works by applying current through a superconducting wire. The wire is partially absorbed in the liquid. The part of the wire which is in the gas state will function as normal while the liquid state part of the wire will be superconducting. Due to the liquid part staying superconducting, the wire resistance is proportional to the length above the liquid (Arpaia et al., 2018). A simplified schematic can be seen in Figure 32.

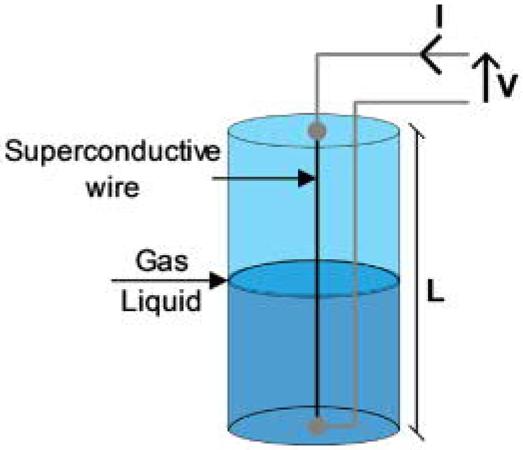


Figure 32. Principle of superconductive level measuring. (Arpaia et al., 2018).

An increase in sensitivity and a reduction of heating can be done with the proper selection of wire material, so that the superconducting wire has a critical temperature slightly higher than boiling point of the liquid (Radebaugh, 2016). Superconductive sensors are used in liquids (e.g., helium, hydrogen, nitrogen, and oxygen) (Karunanithi et al., 2015; Maekawa et al., 2015) and are commercially available (Radebaugh, 2016).

Superconductive sensors have shown higher precision and linearity compared to other sensors such as capacitive sensors. A drawback of the superconductive sensor is the heat input (Matsumoto et al., 2011) but this can be overcome with a pulsed power supply (Arpaia et al., 2018).

3.4.3 Optical fibers

Optical fiber-based sensors are immune to electromagnetic interference, chemically inert, spark-free, and can include multiple fibers in one sensor which reduces its cost. It operates by using the change of the refractive index between liquid and gas phase. A fiber optic sensor includes a LED or a laser transmitter, a sensing element, and a receiving photodiode. It can be used for both discrete and continuous level measuring. Due to cryogenic liquids having smaller refractive indexes compared to water, commercial methods cannot be used. Therefore, techniques based on light scattering of self-heated fiber immersed in liquids have been developed. Because of the larger specific heat and thermal convection rates of liquid the temperature rise is smaller than the gas. The light of the optical fiber sensor is scattered and by the temperature difference of the phases, the liquid level is detected (Arpaia et al., 2018).

As mentioned above, no commercial optical fiber level sensor has been found. However, researches have been found on the method for cryogenic use. The first method is an array of the FBG sensors which have been tested for liquid nitrogen at -196°C (Chen et al., 2011). The second one is based on Optical Frequency Domain Reflectometry (OFDR) measurement of fiber Rayleigh scattering and is shown in Figure 33. The light from the laser is split into measurement and reference. Based on the measurement light reflected from the tank, compared to the reference, the time delay between them is proportional to the liquid level. Depending on the angle of the light sent out from the optical fiber sensor, the liquid or vapor of the medium can be measured. The refractive index of the medium will reflect the light back. The response time of the measurement is different, if the measurement is from vapor to liquid or submerged in the liquid (Yang et al., 2001). This method has been tested for liquid nitrogen at -196°C and liquid helium at -270°C with an accuracy of 12 pm/°C in a 70 m deep tank (Chen et al., 2012).

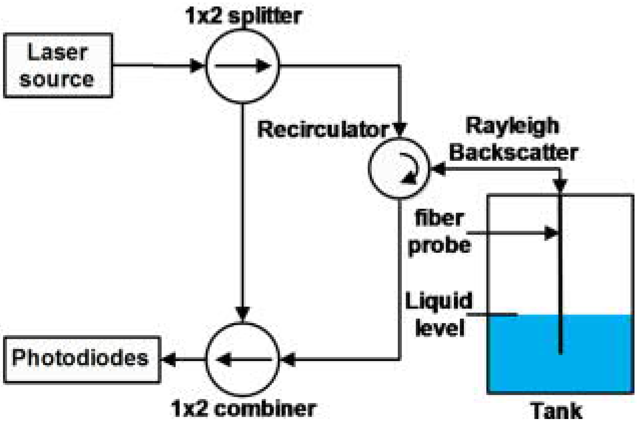


Figure 33. Schematic of fiber Rayleigh scattering method (Chen et al., 2012).

3.4.4 Acoustic wave

In literature there are several methods based on acoustic wave sensors or ultrasonic level detection for cryogenic liquid measuring (Arpaia et al., 2018; Fisher & Malocha, 2007). However, the maximum pressure limitation is below 0.5 MPa due to mechanical limitation of the sensor. The sensor can also not handle vacuum pressure (van de Kamp, 2006) and for those reasons, it will not be investigated further.

3.4.5 Differential pressure

The pressure in liquid is proportional to density and height of the liquid. Pressure is independent of volume and shape of the vessel. The reading by hydrostatic pressure at a fixed point can be used to determine the depth of liquid in a tank, if the density is known and the weight of the liquid above the fixed point is also known (Thipse, 2013). However, hydrostatic pressure can only be measured at atmospheric pressure or above in open vessels. In order to measure gauge or absolute pressure, a DP measurement is used instead (van de Kamp, 2006).

The DP can be detected by sensing two pressures separately and by calculating the difference, the liquid level is obtained. A pressure sensor based on piezoresistive pressure method is shown in Figure 34.

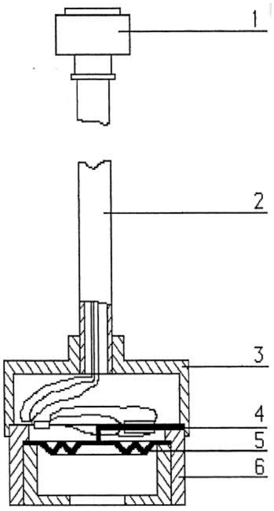


Figure 34. Differential pressure measuring level sensor for cryogenic use: (1) electrical contact, (2) drainage pipe, (3) cover, (4) cantilever, (5) membrane, (6) housing (Maryamova et al., 2000)

In practice, a single pressure difference sensor should be used to avoid measurement errors (Liptak, 2003). An example of level measuring using a single pressure difference sensor can be seen in Figure 35.

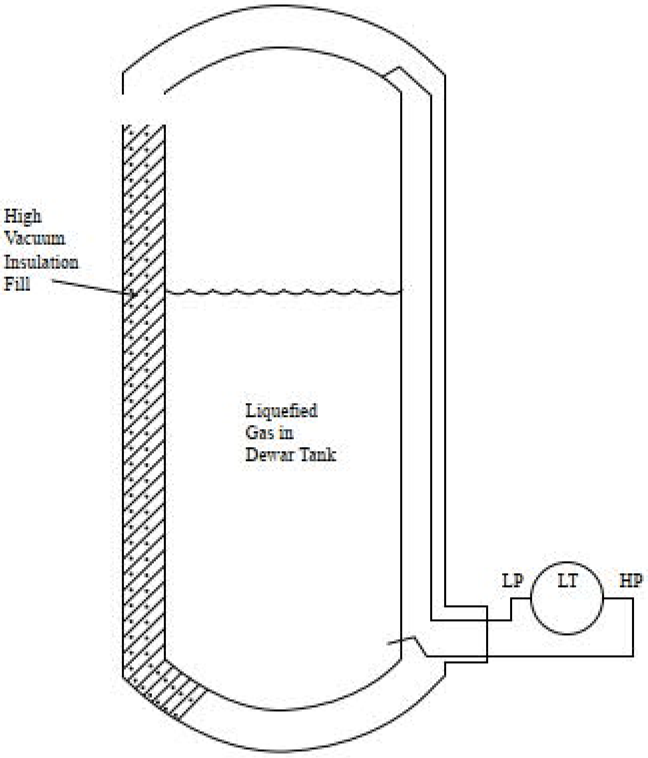


Figure 35. Cryogenic liquid level measuring in vacuum-insulated tank. LP is low pressure side, HP is high pressure side and LT is differential pressure level transmitter (Liptak, 2003).

The height range of the pressure sensor is large with a reasonable accuracy. They are not sensitive to changes in conductivity or product composition but are sensitive to the specific gravity of the liquid. The system is used to measure the pressure and the liquid level can then be calculate in the tank. It is advantageous to measure the weight of the liquid rather than the volume with this method. The system is easily assembled, the sensors are reasonably accurate and easy to calibrate if the mounting position is taken into consideration. The disadvantages of this method are the density of the liquid is needed and it can be expensive. The accuracy of the measurement is dependent on the quality of the LNG, which affects density. The density will affect the temperature, therefore, the accuracy is lowered with each step of affection (van de Kamp, 2006).

As the pressure transducer must be exposed to the pressure it is usually mounted near or at the bottom of the tank. If the sensor is mounted on extension nozzles or pipes, it must be ensured that the LNG will not crystalize or congeal in the pipe. A second transducer can be mounted to measure the vapor pressure on top of the liquid in the tank (van de Kamp, 2006). The pressure above the liquid affects the pressure measured at the bottom of the tank. To measure the true liquid level the tank, the top pressure must be subtracted from the bottom pressure. A pressure tap must be placed at the top and connected to the low side of the transmitter. The tank pressure is then equally applied and then the DP is proportional to the liquid height multiplied by the liquid specific gravity. The impulse line must be provided with a minimum of two elbows and straight minimum lengths of 500 mm in three planes in order to allow for line contraction. Otherwise, a spiral from the tube must be done to allow for contraction. The total minimum line length is 2 m. The impulse line must also be uninsulated to prevent the appearance of two-phase condition. The low-side transmitter piping will remain empty if the gas does not condensate. This is a dry leg condition which is required for DP level measuring. The range determination of the high and the low threshold for the transmitter can be calculated. The high threshold is calculated by the specific gravity of the liquid multiplied by the vertical length between minimum and maximum desired level. For the low threshold the specific gravity is multiplied by the vertical length between transmitter datum line and min level. The transmitter is ATEX certified and the cost starts at €3,000 but can be higher. The associated system can be just as expensive (Emerson Automation Solutions, 2017).

3.4.6 Weighing

Weighing the storage tank is an indirect level measuring method that can be used for cryogenic liquid. However, this method relies on the density and with LNG varying in density this becomes difficult. It also measures the weight, not the level, which requires large mechanical equipment and is expensive (van de Kamp, 2006). Therefore, this method is not investigated further.

3.4.7 Guided wave radar

Microwave technology utilizes either guided or impulse-echo method. The guided method is preferred for its ability to measure a lower dielectric value, handling vapor and has similar properties as a superconductive sensor (Liptak, 2003; van de Kamp, 2006).

Radar uses time domain reflectometry technology to detect and measure liquid levels in a tank. The radar is composed of an electric transmitter and a wave guide or a probe. A high frequency with a low amplitude pulse is sent through the probe which is immersed in the liquid. The probe impedance decreases when it reaches the liquid with the higher dielectric constant than of air or vapor and the pulse is reflected. The reflected pulse amplitude is then sampled and displayed on a time scale. Therefore, with the samples and the interval time, the liquid level can be measured (Liptak, 2003). This is shown in Figure 36.

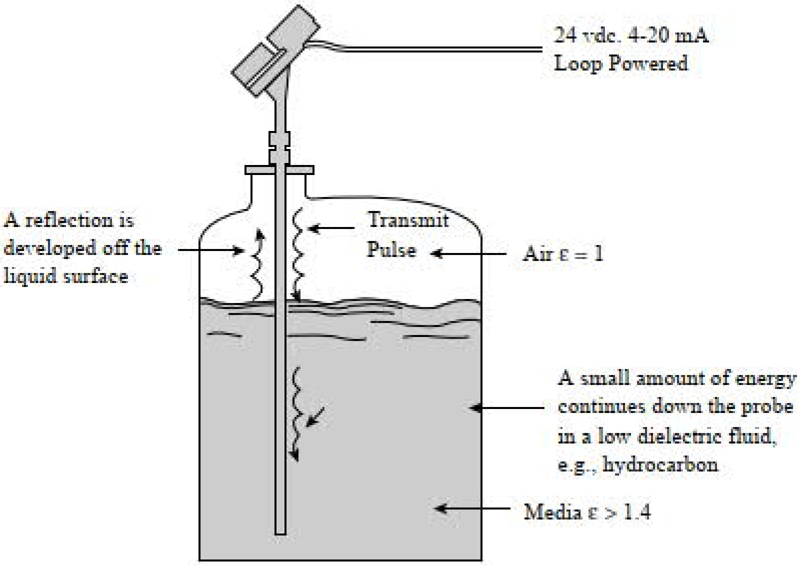


Figure 36. Guided wave radar level measurement set-up (Liptak, 2003).

The minimum dielectric constant for the measurement range is 1.4 but can be lower with special techniques. It can perform measurements at cryogenic temperature and vacuum pressures with an accuracy of 0.3 mm or 0.1% depending on which is higher. The operating tank depth can be from 0.7 to 60 m. The selection of the probe is the important aspect when deciding the radar to be used. The process conditions, dielectric sensitivity, mounting, probe length, turbulence, and hazardous area classification must all be considered. An important aspect is overfilling prevention in the tank. By only measuring at the top of the tank can be problematic and cause errors in the measurement. This is because of the risk of false reflection if the probe meets something other than the liquid and the distance to the liquid affects the accuracy. Therefore, it can be useful to have another measurement system or another radar which specifically detects high level alarm. The mounting of a radar is easy and usually it is calibrated at the factory. The radar can be used with any communication protocol (Liptak, 2003; van de Kamp, 2006).

The instrument is mounted via a standard pipe, mounting boss, or flange. To prevent deflection of the probe on to the sides of the tank, nozzle, or external coupling, the solid pin at the start of the cable must project into the tank and the nozzle diameter should be at least as wide as high. To avoid false impedance changes, the measurement range of the cable must be a minimum of 30 cm from the wall and other objects in the tank. This also applies to the filling streams of LNG. If the cable can be moved by the medium causing the probe to touch the side of the wall, the end of the probe can be tied down (van de Kamp, 2006). The price on this instrument varies but is approximately €3,400 and is ATEX certified (Emerson Automation Solutions, 2019).

3.4.8 Radiometric

This method is the only existing non-invasive level detection method. It should only be used if the transducers cannot be applicable to a tank because of extreme process or environment conditions (van de Kamp, 2006). Therefore, this method is not investigated further.

3.5 Mass flow measurement

Mass flow measurement can be obtained as an indirect measurement of the mass flow or as the product of volumetric flow and density in the process (Liptak, 2003). The mass flow of a cryogenic fluid is important for CT from the tank or the truck to the customer (Radebaugh, 2016). Mass is independent of pressure, temperature, density, and viscosity (Basu, 2019e). As mass is an intrinsic property, it is always better to measure mass flows in industrial processes but the volume flow measurement is also popular (Basu, 2019b). Mass flow measurement is deployed for critical flow applications. The reliability and the performance of the mass flow meter is important. Since mass can only be measure indirectly is it necessary to accelerate the fluid to measure the inertia effects (Basu, 2019e).

As the Coriolis flow meter is the only type of mass flow measurement allowed for CT of LNG (Basu, 2019a), the other measurements will only be mentioned briefly and are capacitive, microwave, optical, virtual, angular momentum, thermal or calorimetric, hot-wire anemometer, and dual turbine flow meter (Arpaia et al., 2018; Basu, 2019e; Radebaugh, 2016).

The capacitive flow meter measure electrical charges that appears when a liquid comes in touch of a solid, creating a charge separation area. This can be utilized for slush hydrogen but since slush is not appearing in LNG processes, this method cannot be used (Arpaia et al., 2018).

The microwave flow meter consists of two circular waveguides placed upstream and downstream of a flow pipe. The cut-off frequency of the waveguide changes with the density of the liquid that flows. By knowing the distance between the two waveguides and measuring the time between the cut-off frequency, the flow velocity is estimated. The densimeter exploits the shift of a microwave due to variations of the dielectric constant of a fluid. By using a network analyzer, the fluid density can be estimated. This is used for slush hydrogen (Arpaia et al., 2018).

Optical techniques can be used to measure the direction and the speed of a fluid. By using optical absorption and acoustic-optic signal processing, the mass flow rate can be determined for the fluid. This is used to measure the mass flow of the propellant for a rocket (Arpaia et al., 2018).

A virtual flow meter is an indirect measurement which combines data sensed by a group of sensors. It calculates the mass flow of the fluid indirectly by using temperature and pressure at the input/output of a valve. This has been used to monitor and control cryogenic superconducting operations using hydrogen as a fluid (Arpaia et al., 2018).

An angular momentum flow meter uses a rotating member with vanes which are parallel to the axis. The rotating member is powered by an electric motor. The liquid retards to the rotational speed, and the rotor speed sensed by a magnetic pickup is treated electronically to indicate the mass flow rate. The maximum flow rate is between 2 – 15 kg/s and has a pressure drop between 20 – 50 kPa. Liquid hydrogen, oxygen, nitrogen, and argon have been tested with this type of flow meter (Radebaugh, 2016).

In a thermal or a calorimetric flow meter, the fluid is heated with a constant power which causes the fluid temperature to increase. A TC measures the temperature difference of in- and outgoing fluid. The mass flow can be calculated when the specific heat of the fluid is known. This has been tested for hydrogen and helium in its gas phase at temperatures between -173 and 27°C at a low mass flow rate (Radebaugh, 2016).

A hot-wire anemometer deduces the mass flow rate from the heat transfer rates associated with a heated element. The resistively heated element has a large temperature coefficient of resistance and a large length-to-diameter ratio. The electrical power to the element varies as the element maintains a constant resistance and therefore the flow rate can be deduced from the voltage squared. This has been tested for helium gas at temperatures down to -196°C (Radebaugh, 2016).

Dual turbine flow meters are used for cryogenic service (Radebaugh, 2016) but are not popular outside of aerospace industry. This meter includes two closely coupled rotors which can operate in the same or the opposite direction. As the fluid swirls the rotor speeds can be sensed. The sum or the average speed can be used to estimate flow rate. This can be utilized for liquids and gases down to -200°C (Basu, 2019d).

3.5.1 Coriolis

The Coriolis mass flow meter (CMFM) is the most popular mass flow measurement for processes and utilizes the Coriolis effect. The liquid passes through a set of tubes, which are vibrating at a natural frequency to minimize energy requirements. The use of two tubes are the common practice, but the same result is achieved with only one tube. However, for a higher sensitivity and to facilitate the measurement, two tubes are required. The liquid flow enters U-shaped tubes and is returned to the main flow process after passing it (Figure 37). The U-tubes will vibrate and when no flow is present, the Coriolis force will be zero, as liquid starts to flow it will try to oppose the vibrations (Basu, 2019b).

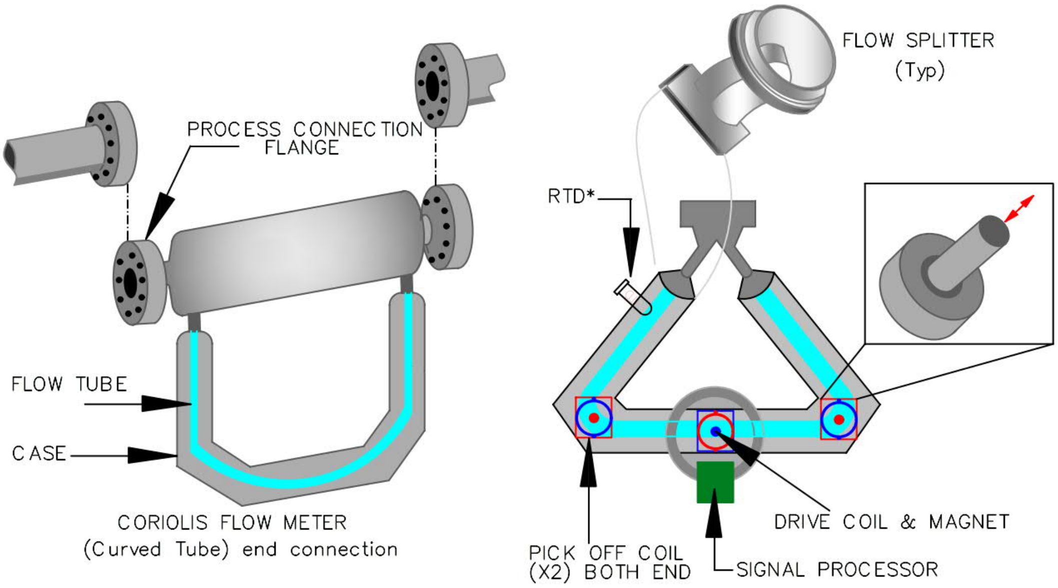


Figure 37. CMFM with main parts (Basu, 2019b)

The directions of the flow will be opposite at the inlet and the outlet. The inlet section will decelerate the movement of the vibrations and the outlet section will accelerate the movement. A phase shift will be introduced, meaning there will be a difference in time of the peak for the vibrations which is proportional to the mass flow (Figure 38). The sensor measures the motion of the flow tubes either by position, velocity, or acceleration. The time lag is measured with an electromagnetic pick off to calculate the mass flow (Basu, 2019b).

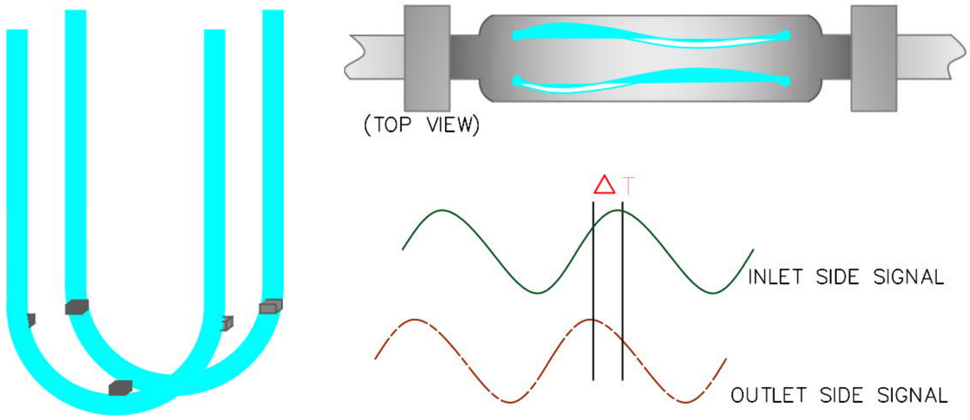


Figure 38. Flow direction of liquid in U-tubes and ΔT of inlet and outlet to measure mass flow (Basu, 2019b)

The main components of CMFM are as follows: meter body, connection flange, flow splitter, flow tubes, casing enclosing flow tube, drive coil and magnet, sensors, and transmitters. The typical CMFM is designed according to the twin-tube principle with flow splitter and tow bent meter tubes. This allows for symmetry and is unaffected by process parameters such as density, viscosity, and temperature. CMFM is an inline type meter. Vibrations will not affect the measurement or the meter housing. The flow splitter should split the flow equally. If not, the sensors located at both ends of the flow tubes will measure the displacement, so additional errors will not occur. Therefore, the flow profile is not needed, and no straight length is required. The critical points for selecting a CMFM are flow sensitivity, pressure loss, tube size, and frequency of operation. The tubes should be as short as possible to decrease pressure loss and minimize the space requirement (Basu, 2019e). Elasticity changes with change of temperature and temperature compensation is needed (Basu, 2019f).

The CMFM is designed to handle pressure up to 2.5 MPa, temperatures down to -200°C, ambient temperatures from -40 to 70°C with a relative humidity up to 95%. Typical accuracy is 0.25% and is dependent on zero stability. Zero stability is an error caused by that the Coriolis sensors will show an offset signal even when the true mass flow is zero. Zero stability is also a function of turndown ratio, the higher turndown ratio the lower accuracy but less pressure loss. Zero stability is specified for all CMFM. The relationship between these can be seen in Table 8. Typical turndown is 20:1. Transmitter can be placed remote or is an integral part of the design. The response time is less than one second and can use all kinds of protocols (Basu, 2019e).

Table 8. Relationship amongst accuracy, turndown and pressure loss (Basu, 2019e)

<table>
<tr><th colspan="6">Accuracy, turndown and pressure loss relation
Pipe size: DN 50, max flow: 70.000 kg/h, zero stability: 3.5 kg/h and accuracy 0.0005%</th></tr>
<tr><td>Turndown</td><td>60:1</td><td>20:1</td><td>10:1</td><td>2:1</td><td>1:1</td></tr>
<tr><td>Accuracy</td><td>±0.25%</td><td>±0.05%</td><td>±0.05%</td><td>±0.05%</td><td>±0.05%</td></tr>
<tr><td>Pressure loss</td><td>60 Pa</td><td>40 Pa</td><td>150 Pa</td><td>28 kPa</td><td>100 kPa</td></tr>
</table>

The advantages with CMFM are as follows: direct measurement of true mass flow, multivariable measurement, i.e., mass flow, density, and temperature with lower amount of instruments, volume flow can be computed, used for all kinds of medium, measuring flow in both directions, low power consumption, no moving parts, and no straight length requirement. The disadvantages are as follows: capital cost, limited sizes of the meter, affected by external parameters, and pressure drop. CMFM is used for different types of applications (Basu, 2019e), but is specially used for CT of LNG and for other cryogenic liquids (Basu, 2019a).

The measuring tube should be full when measuring the flow. The entrapment of gas and build-up should be avoided. Both vertical and horizontal mounting is allowed. Vertical mounting should be used for upward flow. This is preferred as it ensures a complete fill up of the measuring tube. It also ensures that dirt is drained downwards, and entrapped gas is released from the top. Downward flow is allowed if there is a restricting orifice and valve downstream to ensure the line is full. Horizontal mounting can be done head up, which is used for liquids, or head down, which is used for gas. There should be isolation valves placed up and downstream of the CMFM for maintenance or part replacement. A bypass line with a valve should be placed so that the process line remains uneffaced if the meter is inoperative. The meter housing should not be placed on a flange, and therefore, a short meter section is needed. The CMFM should not be placed near valves with frequent ON/OFF functions as it will cause pulsation and vibrations which will affect the performance. Piping should be firmly connected to prevent additional vibrations. Calibration of the instrument is done individually with water as the medium, which brings major uncertainty to other cryogenics (Basu, 2019e). Calibration of any instrument for cryogenic use is difficult as there are not many calibration facilities for cryogenics in the world. It is still recommended to test the meter in an independent laboratory for precise measurement (Basu, 2019f). The CMFM is designed to be used in hazardous areas. The cost of this type of instrument starts at €8,500 and increases depending on application type and additional functions (Instrumart, 2020b). Additional information regarding selection, design, installation etc. can be found in ISO 21903.

3.6 Volumetric flow measurement

As mentioned in Chapter 3.5, volume flow measurement is popular in industrial processes. It is possible to arrive at mass flow from volume flow by multiplying measured volume flow with the density at the operating condition. Some limitations to this approach are that correct fluid properties might not be obtainable. When changing operating conditions, temperature and pressure compensation are applied. Therefore, the mass flow computed from the volume flow will include all inaccuracies of the overall measurement (Basu, 2019e).

To compute the volumetric flow, the common method is to measure the velocity of the fluid inside the pipe and multiply the area of the pipe. The velocity profile of the fluid is a function of pipe geometry and Reynolds number. There is also a straight pipe length requirement for the flow meter which is required to achieve the required accuracy. Typical values for liquid velocity are between 0.15 and 4 m/s. The flow meter is typically fitted with flanges to be mounted to a pipe. Turbine and ultrasonic flow meters can be used for CT of LNG. However, they must be approved by a notified body and density of LNG must be established (Basu, 2019b, 2019a). Positive displacement and vortex shedding can be used for LNG processes (Arpaia et al., 2018; Radebaugh, 2016) and will therefore be mentioned briefly.

The positive displacement method uses a mechanical flow meter with moving parts. Volume is directly measured and is independent of fluid velocity, pipe inside diameters, and flow profiles. The mechanical moving parts located in the flow stream will physically separate the fluid into known volumes based on the dimensions of the meter. The known volume increments are counted or totalized (Basu, 2019b). They are used for various cryogenic applications where there is a low flow rate between 3.6 – 36 m^3/h (Radebaugh, 2016).

Vortex shedding in fluids occurs when placing a non-streamlined object in the path of a fluid with a high Reynolds number. Intervals between the vortices are constant, regardless of velocity, and the function of the diameter of the pipe. The fluid will alternately separate from one side to the other downstream. A bluff body is a cross-sectional shape that offers large resistance to incoming flow to retard it. On the bluff body where the vortex shedding occurs, the fluid velocity increases, and the pressure will decrease. On the opposite side, pressure will increase, and velocity will decrease. This will cause a net pressure on the bluff body and will be reversed as the next vortex is shed from the opposite side. This is known as Karman's principle and is utilized for vortex flow meters (Basu, 2019b). Vortex flow metering is suited for LNG measurement with a low Reynolds number. However, this has yet to penetrate the market (Basu, 2019h) as it is a comparatively modern flow measuring technology (Basu, 2019d).

3.6.1 Turbine

The turbine flow meter (TFM) is an inferential measurement which calculates the volumetric flow from temperature and pressure conditions (Basu, 2019d). It is used for CT of low-viscosity fluids which can be applied for LNG (Basu, 2019a). The TFM is used for a large variety of application areas for cryogenic liquids and gases (Basu, 2019d). The TFM is an instrument where the kinetic energy of a moving fluid is converted into rotational energy (Basu, 2019d). The process fluid flowing against the turbine causes the blades to rotate at a speed proportional to the velocity. An axially mounted rotor with blades is assembled in the flow and supported by ball or sleeve bearings on a shaft. This is found inside the TFM, as shown in Figure 39. As the liquid passes through the blades, the rotator speeds up, and the flow rate can be sensed by the magnetic pick-up. As the rotator blades pass the magnetic pick-up, a voltage pulse is generated, and a totalized flow can be calculated by the total number of pulses (Basu, 2019b).

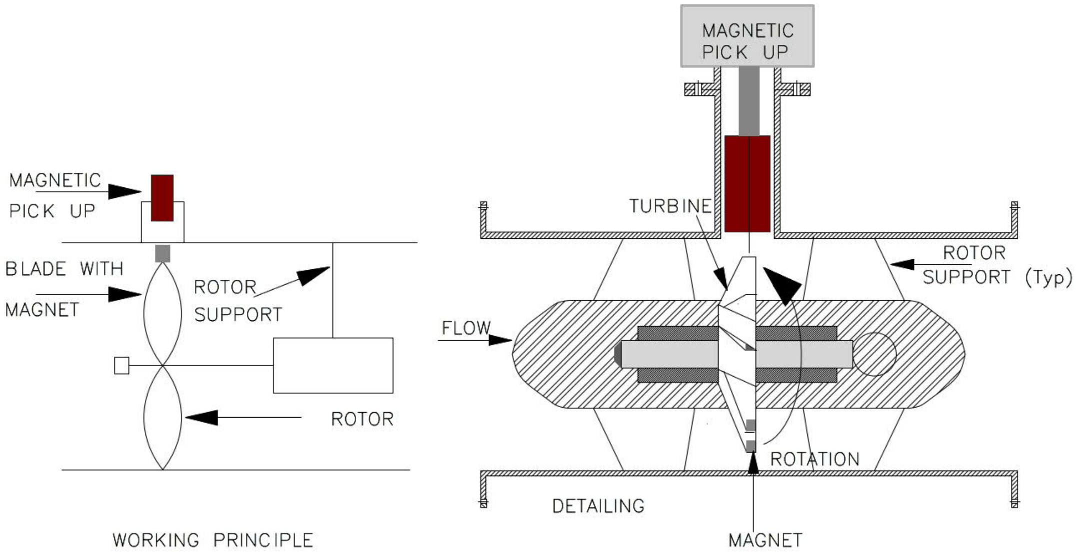


Figure 39. Turbine flow meter and working principle (Basu, 2019b).

The main parts of the TFM are the meter body, flanges for process connection, threaded electrical connector, flow conditioner (up- and downstream), hanger blade (up- and downstream), hanger hub, sharp upstream cone, rotor assembly, rotor bearings, shaft, smoother downstream cone, and top electrical enclosure. It can handle pressures up to 4.0 MPa (Basu, 2019d) and cryogenic temperatures down to -267°C (Basu, 2019f). The operational temperature range is -20 to 70°C and a relative humidity of 90% (Basu, 2019d). The accuracy rating is between 0.15 – 0.5% and can handle a range ability larger than 10:1 (Basu, 2019b). Another important parameter is the K-factor, the number of pulses per unit volume. This is dependent on the viscosity and determined by the size of the TFM (Basu, 2019d), which can be from 5 to 700 mm (Basu, 2019b).

The TFM is a well understood measurement method that is suitable for both gas and liquid. The advantages are as follows: a wide operational envelope, inline or insertion type of measurement, suitable for high pressures and low flow rates, an easy installation method, and a wide design of the electrical enclosure for safety applications and harsh environments. The disadvantages are as follows: high wear, erosion and damages due to the moving parts which affects accuracy, the long straight length requirement (U:10D/D:5D), viscosity changes of the liquid, and a robust pipe system is needed. Any vibrations of the pipe system will cause distortion to the flow profile and disturb the measurement. (Basu, 2019d)

For the installation of the TFM, the environmental considerations must be done considered. The flow direction must be followed for the mounting and a flow conditioner must be used. Shielded cables should be used and earthed. Excess torque should be avoided for the installation. The tapping points should be placed in the outlet section of the meter housing. For pressure tapping the distance is 3 x the nominal width and for temperature tapping, 5 x the nominal width. A calibration of the instrument is needed to fix the specific K-factor. The calibration of the TFM used for cryogenic liquids is hard to achieve as a comparison method of calibration is the only option. The instrument is compared with another type of flow measurement, which will increase the probability of a higher uncertainty. Since the TFM has moving parts, frequent calibration checks are needed. For more information regarding installation of TFM, ISA – RP31.1 can be advised (Basu, 2019d). The cost of the TFM depends on the size and additional applications. The starting price is €850 but can be up to €30,000 for the instrument with installation costs (Universal Flow Monitors Inc., 2020).

3.6.2 Ultrasonic

The ultrasonic flow meter (USFM) utilizes electrical properties, ultrasonic energy in the form of acoustic waves, to measure the flow rate. It is a noninvasive measurement and there are three types of USFM: Doppler type, transit time type, and correlation type (Basu, 2019d). The transit time type is used for cryogenic applications (Basu, 2019f). There are two configurations of transit time USFM as can be seen in Figure 40. In the first version, transducers are placed on opposite sides of the pipe and the transit time from transmitter to receiver, both with and against the flow direction, is measured to compute fluid velocity. In the second version, the transducers are placed on the same side of the pipe and the transit time is measured from one transducer and reflected from the pipe and returned to the receiver (Basu, 2019b).

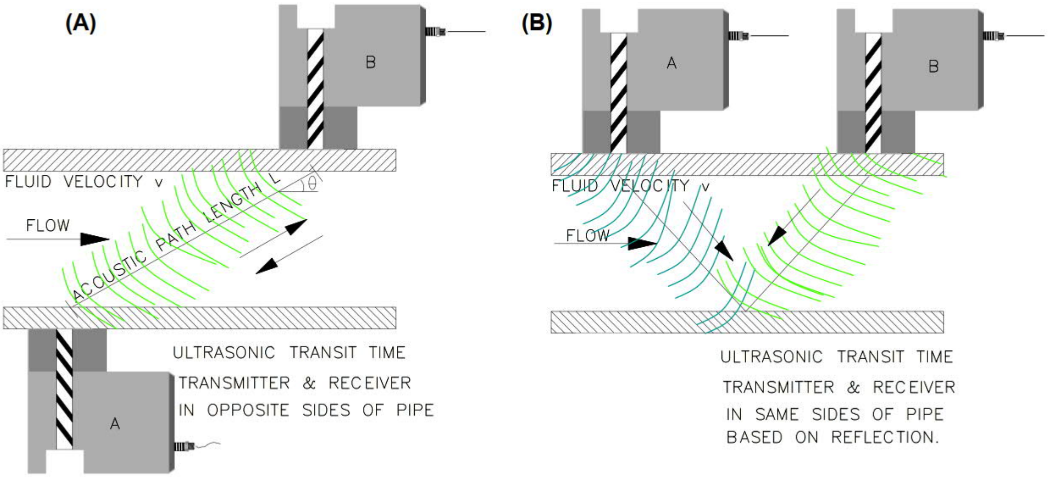


Figure 40. Transit time ultrasonic flow meter (A) different side configuration, (B) same side configuration (Basu, 2019b).

The transit time of the USFM depends on the velocity of the ultrasonic and of the flowing liquid. The flow measurement is affected by flow profile, pipe influence, environmental interference, and temperature of the fluid. The USFM consists of a set of transducers, an electrical housing, a pipe section, and/or a spool piece. The pipe section in this case means clamp type mounting. The liquid is needed for the acoustic waves to travel, therefore, the density, pressure, and temperature must be defined (Basu, 2019d).

The transducer can fit into the spool piece and be welded with the pipe or it can have a flanged type connection. The transducer is the main part of the instrument. It includes piezoelectric technology which vibrates when a current is applied. The transducer can be wetted or non-wetted. A wetted transducer is an invasive but non-intrusive method. It is shaped flat and comes in sizes of 1 to 30 cm in diameter. The connection type is a tilted diameter where the transmitter is on opposite side of the pipe or in an axial offset on the same side. The minimum diameter for the tilted diameter of the pipe is 50 mm and for axial offset, smaller pipes are used in sizes of 6 to 50 mm. A non-wetted transducer includes a clamped connection and is mounted outside on the pipe. The non-wetted method is non-invasive and used for pipe sizes above 50 mm. For smaller pipes, the transducer must be preinstalled. The location of the transducer is important for the accuracy and for the measurement to take place. A straight pipe is required, 10D upstream and 5D downstream in order to achieve an undisturbed flow profile. If a flow conditioner is used, the requirement is less strict. Transducers should be located horizontally with the pipe. It cannot be mounted at the top or bottom for horizontal pipes. This is because if there is entrapped gas at the top or containments of the liquid in the bottom the measurement will be affected. If the pipe is full, mounting on vertical pipes is allowed but downward flow should be avoided. Pressure and temperature tapings should be mounted downstream. The recommended location for the temperature probe is 3D from the flow meter (Basu, 2019d). Calibration for the instrument was not found for cryogenic liquids but it is assumed that it is like other types of cryogenic flow measurement.

The advantages are as follows: the larger the size of the USFM and pipes will result in a higher accuracy of the measurement, miniscule pressure loss due to the non-intrusive measurement, no moving parts, high overall accuracy, reliable, easy installation, both weld-on and pipe clamp type connection can be used, low maintenance, and low power consumption. The disadvantages are the cost compared to other flow meters, measurement according to the full hose philosophy only, and the measurement is affected by flow profile, deposits, or the entrapment of gas or dirt (Basu, 2019d).

The USFM is used for a large variety of liquids and gases (Basu, 2019d). It can be used for CT applications for larger quantities of NG and LNG (Basu, 2019d; Hogendoorn et al., 2007). It can handle ambient temperatures of -40 to 70°C and relative humidity of 95%. It has an accuracy between the range of 0.5 to 2%, the operating temperature range is between -200 to 80°C. It is independent of pressure and can therefore handle a high pressure. This type instrument is suitable for use in hazardous environments (Basu, 2019d). Various suppliers can be found for this instrument but no available cost of the USFM has been found. For information related to installation and selection of USFM, ISO 21903 can be advised.

3.7 Differential Pressure flow measurement

Flow rates based on a non-flow measurement is used by inferential flow meters. It is accepted for measuring gas or liquid flows. All DP flow measurements are static and have no moving parts. In head type flow measurement, a differential head is created with the help of a restriction which can be measured. The principle of the measurement is based on the pressure drop across the restriction which is proportional to the square of flow rate. The flow rate is calculated by extracting the square root of the reading (Basu, 2019b). The orifice plate measurement is the only one allowed for CT but for NG only. It is however a common method used to measure the flow of LNG (Basu, 2019a).

A venturi is a gradual tapered restriction at the inlet and outlet, referred to as the throat. It has a very high discharge coefficient and low pressure drop. The convergence and throat area is responsible for the pressure drop and is where the head type flow is calculated (Basu, 2019b). The venturi has been used for helium. Its design prevent it from being used in reverse flow, which is a possibility with the orifice plate (Radebaugh, 2016).

A laminar flow element creates a linear relationship between the mass flow rate and the pressure drop. This can be used for a wider range of flow rates compared to the orifice plate and the venturi. However, this is not commercially available and only used in laboratory environments (Radebaugh, 2016).

3.7.1 Orifice plate

The orifice plate is the most used fluid flow element in processes. An orifice inserted into a pipeline causes an increase in velocity and a corresponding decrease of pressure will occur downstream. The Vena contracta is the location in the orifice where this occurs and where the diameter of the stream is the smallest. An orifice plate is a flat piece of metal with a specified sized hole (Basu, 2019b) as shown in Figure 41.

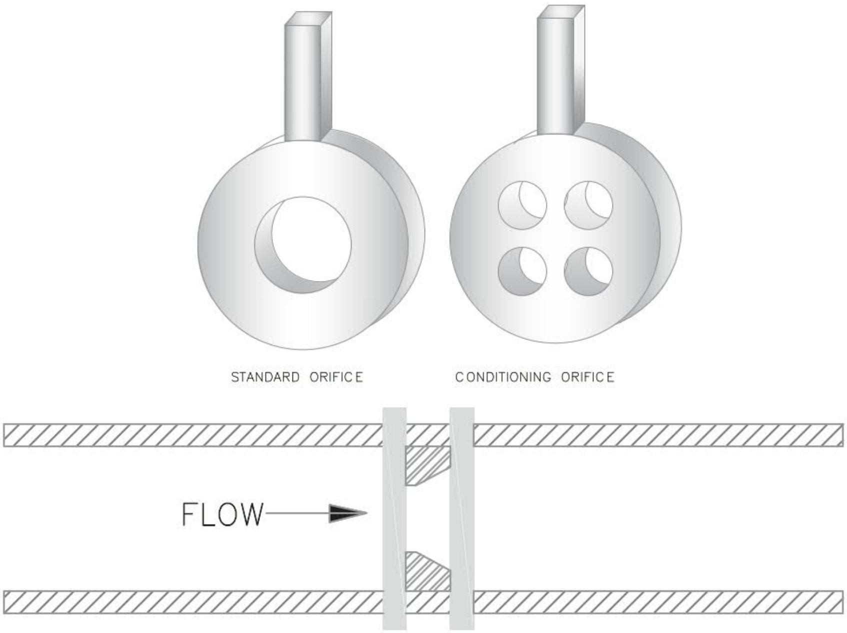


Figure 41. Orifice plate inlet pipe with standard orifice and conditioning orifice – adapted from (Basu, 2019b)

Orifice assembly includes the orifice plate, a flange or carrier ring, gasket, pressure tapping, studs and nuts as shown in Figure 42. It offers acceptable uncertainties at comparatively low costs. There are mainly four types of orifice plates: the measuring, integral, senior, and restriction. Depending on the pipe size, the thickness of the orifice plate changes. An orifice plate based on Bernoulli's theory is referred to as a conditioning orifice plate (Basu, 2019c). This is an integral orifice plate and used for cryogenic measurements (Basu, 2019f). There are some deviations from with the conditioning office compared to the standard orifice plate. These deviations are the plate thickness, orifice/beta ratio, piping requirements, and the accuracy.

The advantages of the conditioning orifice compared to the standard orifice are as follow: the self-conditioning flow which increases the performance, short straight pipe requirement (U:2D/D:2D), tight fit application, and improved wet gas applications allowing condensate to pass. It has a compact design which includes a transmitter for a higher accuracy and lower installation costs. A conditioning orifice plate includes four holes placed in a pattern, as can be seen in Figure 41. This design will make the fluid flow condition itself. It is designed to have the same beta ratio or the equivalent to a standard orifice (Basu, 2019c).

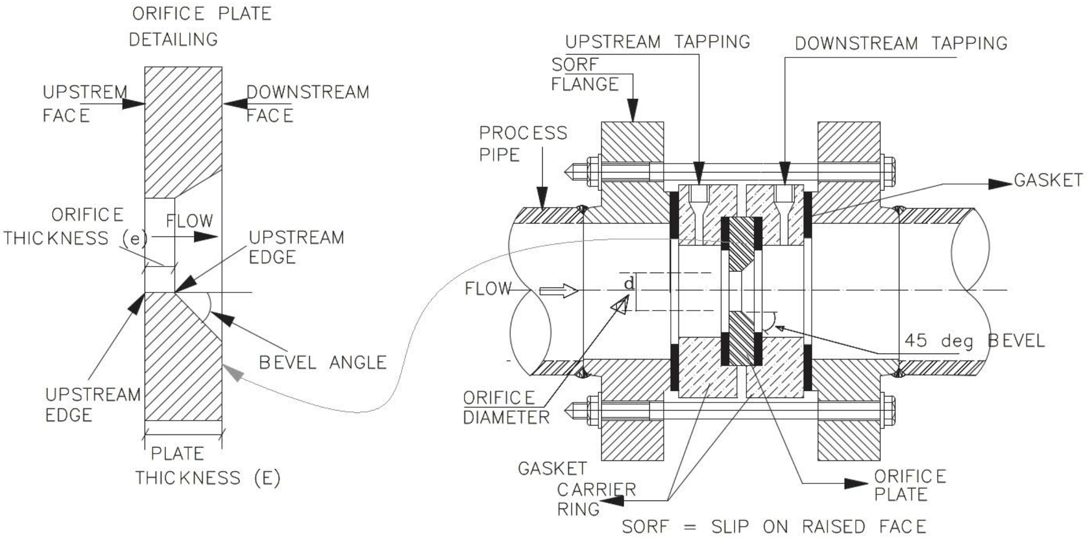


Figure 42. Orifice flange assembly and carrier ring with flange tapping - adapted from (Basu, 2019c)

The advantages of using an orifice plate compared to other flow meters are as follow: no moving parts, robust construction, available in a wide variety of size and beta ratio. It is inexpensive and the cost is similar for all sizes. It is easy to design, manufacture, install, and require low maintenance (Basu, 2019c). The disadvantage is a permanent pressure loss and therefore has a higher power requirement. The accuracy is at best 2% which is affected by the density, the pressure, and the viscosity (Crabtree, 2009). Measurement errors due to density variations will affect the differential pressure ratio and should be less than 0.25 (Liptak, 2003). This instrument is not suitable for measurement where Reynolds number is < 10.000. The size of the vent and drain hole should be < 10% of orifice diameter, otherwise corrections of the flow calculation are needed. Head type meters with connection to a DPT through an impulse line have multiple leakage points (Basu, 2019c). Large temperature gradients present concerns when O-rings, glands, welds, or dissimilar metals are present in the flow stream (Basu, 2019f).

The suggested pressure range is 0 – 25 kPa for maximum accuracy but the range can be up to 10 MPa. It has an range ability of 5:1 and the accuracy is 2 – 4% over full scale (Basu, 2019b). The design, including the transmitter, can handle fluids with temperature at the boiling point of -196°C (Basu, 2019f). The conditioning orifice utilize a smart multivariable transmitter which can measure absolute pressure, DP, and temperature (Basu, 2019g). For high accuracy flow measurement, in smaller pipe sizes, a meter run assembly design is common. This assembly is built as one unit to avoid inaccuracies. For high pressure applications, a raised face or ring type flange connection is used for mounting to the pipeline (Basu, 2019c). The starting price for the orifice plate flow meter is around €3,000 and upwards, depending on the application and process connection (Instrumart, 2020a).

Tapping points must be placed for measuring. There are five types of tapping styles which are corner, flange, radius, vena contracta and pipe tap. Corner and flange tapping are the most common practice in Europe. The corner taps are located immediately adjacent to the plate faces, between the plate and the pipe wall. Flange tap design places the tap holes every 25 mm upstream and downstream of the orifice plate. The basic mounting steps for the orifice plate are as follows: confirming the placement of the orifice in the pipe, assure proper orientation, measure the inside diameter at the tapping point, welding the orifice assembly flange connection to the pipe, ensure that cleaning, draining, and purging are applicable, ensure the pipe is unpressurized and purged, and lastly check for leaks (Basu, 2019c). For DPT to measure the process conditions, impulse lines must be installed. The line can be either an impulse tube or pipe, where the tube is the preferred option as it is cheaper. There is also no need for screws and welding. The DPT is placed above or below the source point. All transmitters are connected to an impulse line via a valve manifold which has a three- or five-valve manifold connection (Basu, 2019c), as can be seen in Figure 43.

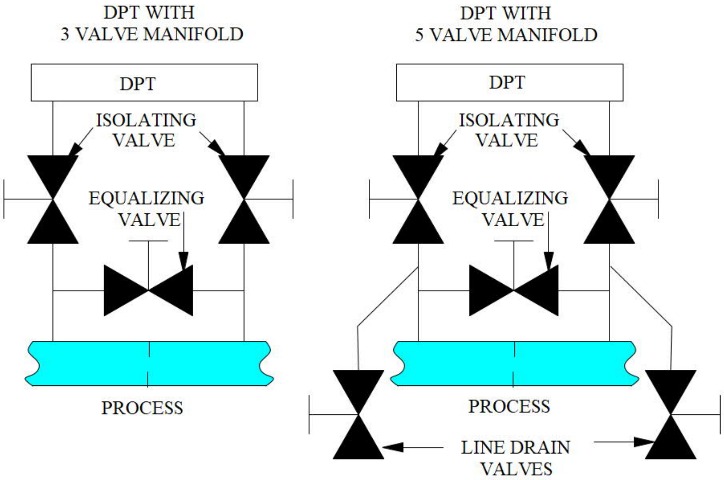


Figure 43. Valve manifold with DPT and impulse line set-up – adapted from (Basu, 2019c)

For liquid measurement, it is common for vapor and dirt to be entrapped and accumulated in the liquid. To avoid this, tapping should be done from the horizontal side of the pipe, so vapor vents up and dirt flows down. If this is not applicable, then the tapping point should be 45° to the horizontal on either side. This is only valid for horizontal pipes. The transmitter location should be below the source point, so a higher positive head is available and entrapped vapor is released towards the pipe. If the transmitter must be placed above the source point, the impulse line should be at an elevation slightly above the transmitter level and then make a downward loop connection to the transmitter. The impulse line should be as short as possible. The impulse line is upward or downward depending on the case but should be at a slope of a 2/25 gradient (Basu, 2019c).

There is a lack of calibrating equipment for operations at cryogenic temperatures. The calibration is done at room temperature and afterwards, calculations are made by extrapolating cryogenic conditions from readings at room temperatures. For a complete understanding of pressure tapping, design, placement, installation etc. for the orifice plate, EN ISO 5167-1 & -2 can be used. ISO 2186 can be used for impulse lines (Basu, 2019c).

4 MATERIAL AND METHODS

This chapter focuses on explaining the work process and the critical instruments. It also analyzes the requirements for the instruments, investigates the available measuring methods, the accuracy requirements for the instruments, and the findings of the thesis.

4.1 Reviewing the standard pressurized LNG satellite terminal

The standard pressurized LNG satellite terminal was reviewed to see which types of instruments it contains. This was required in order to analyze the need for instruments. This was done by reading the P&IDs and process descriptions for the process modules. From the P&IDs, the process line and the main equipment were established as well as the type of measurement and the location of the instrument. Based on this, a list of each module was created, including instrument name, type, model number, manufacturer, enclosure protection, atmosphere protection, design range, operating range, process connection, description of location, I/O-type, control system connection, types of signal, and if it is a critical instrument. All attributes are important in order to understand the logic of the selection and to get a complete picture of the instruments used for the process. From the process description, the procedure of the process was established. By establishing the step by step of the LNG process, the logic of the process and the measured values were determined.

Firstly, a critical instrument in this thesis is defined as an instrument that is not working as intended. Secondly, another solution would be preferred to the existing one. Thirdly, the instrument should be upgraded to present better results in a more cost-effective way regarding purchase and installation costs.

After the lists were created, a summary of the types and total amount of instruments was established for each module. Detailed information was investigated by reviewing technical specifications and data sheets of the instruments used for the modules. The parameters for the standard pressurized LNG satellite terminal were done during this time as well.

4.2 Critical instruments

A discussion with Mr. Krooks and Mr. Latvasalo was held to determine if an instrument was critical or not. Eight instruments were deemed critical out of all the instruments used for the modules. Most of the critical instruments were related to temperature measurement. The other instruments were related to level and flow measuring. This discussion was helpful as it gave insight into questions not considered earlier and guidance in order to find related information to certain instruments. It also gave a wider perspective for the search information on analyzing the real need for instruments.

4.3 Analyzing the need for instruments

After reviewing all the instruments used for the modules, it was time to understand the usage and the need. Initially, this was discussed with Mr. Krooks. The process design and instruments used were based upon HAZOP, the knowledge of design engineers, and common practice within the industry. It was decided that deeper and broader background knowledge was to be investigated. This was done by reading standards for design of onshore LNG facilities.

EN 1473:2019 is the standard used for LNG onshore installations. Within this standard there are additional standards that can be read and interpreted for design. By using the internal engineering workbench and with the help of Mr. Krooks, additional standards were found to include valuable information. Unfortunately, not all interesting or relatable standards to instrumentation or process design were accessible.

In the beginning, only information related to instruments of LNG process was searched for. Information related to the installation and the design specific for LNG process were also included with time. With the help of the determined critical components, additional information such as custody transfer, MID certification, and specifications related to control system were added. Open access information not part of standards was also searched for. However, all the information found referred to the standards. A list of requirements was created. The list includes all information found for instrumentation, installation, and process design. The list of requirements is meant to be used to analyze the real need for the instruments. The list of requirements is presented as Chapter 2.6 and the standards used can be found in Chapter 5.5.

4.4 Measuring methods for process variables

It was now time to find instruments and methods that can be used for monitoring LNG processes. The focus was originally on new methods or instruments. Theoretically, new methods can include measurements that can be applied to LNG processes. Therefore, all measurements applicable for cryogenic conditions and liquids were included as well, since the operating conditions for cryogenic liquids are similar. Unfortunately, this is not always possible in practice as certain conditions or parameters are related to a specific liquid. The method or instrument was investigated if it can be used for cryogenic conditions. The methods mentioned in this thesis are all used for cryogenic measurement. However, certain methods are only mentioned briefly as they are not applicable for LNG (e.g., capacitive flow meter) which needs to be in contact with a solid to create a charge in order to measure the flow rate.

The materials used for cryogenic instruments in this thesis are obtained from different sources, including distinguished papers and articles published by research institutions and handbooks for cryogenics, LNG and other measurements. The instrument or method is validated by extensive use in the process industry or by the academic research of institutions. The methods mentioned are either available for commercial use, for use in laboratory environments or experimental set-ups. Most of the methods are available for commercial use. The mentioning of methods used in laboratory environments or experimental set-ups are important. As technology improves, certain methods might be applicable in the future for use in the industry.

To have a clear list of technical specifications and attributes was important in order to compare the methods that were discovered. This is to determine if a method is more valuable than the other methods. The technical specification is important as it relates to the instrumentation being applicable with the operating conditions. The accuracy of the instrument is equally important due to the readings of the variables. This is to ensure a safe operation of the process controlled by the system. The advantages and disadvantages are great for understanding the instrument and if it is applicable or deviates from the design of the process. The installation method of the instrument is needed in order to know how to integrate the instrument and additional equipment with the process. The cost of the installation is also needed. E.g., is it enough to have a transmitter mounted with a pipe clamp or must it be welded with a pocket into the pipe? The kind of information and attributes can make or break the selection of an instrument. Certain attributes can lead to more problems such as, a pipe clamp is cheaper than a welded pocket. Will the accuracy still be the same? These are considerations that are important and therefore must be included.

4.5 Accuracy

The accuracy for meters and measuring systems for MID certification and CT, can be seen in Table 9. A meter is an instrument designed to measure continuously, memorize and display the quantity at metering conditions of the flowing liquid. A calculator is a part of the meter that receives the output signals from the measurement transducers, the associated measuring instruments, and displays the result. The associated measuring instrument is connected to the calculator for measuring certain quantities which are characteristic of the liquid. The measuring system includes the meter and all the devices required to ensure correct measurement (The European Parliament and the Council, 2014).

Table 9. Measuring systems accuracy for continuous and dynamic measurement of cryogenic liquids – adapted from (The European Parliament and the Council, 2014).

Measurement	Accuracy
Meters	1.5%
Measuring systems	2.5%
Calculators	0.25%
Associated measuring instruments:	
Temperature	± 1.0°C
Pressure	Less than 1 MPa: ± 50 kPa From 1 to 4 MPa: ± 5% Over 4 MPa: ± 200 kPa
Density	± 5 kg/m3

The accuracy for liquid level measurement in a storage tank has not been established. General agreement for instruments and methods for CT in LNG carrier's tanks is ± 5.0 mm or better (GIIGNL, 2015). This agreement is based upon information found in the

ISO 18132-1:2011 standard, which is used for carriers and floating storage. The ISO 18132-2:2009 has been found. This standard refers to refrigerated shore tanks for hydrocarbon fluids and could include information regarding the accuracy for liquid measurement in storage tanks. However, the standard has not been found accessible.

For the NG side in an LNG facility, the accuracy shall be better than 2% and the repeatability better than 0.6% on full scale. This applies to an ambient temperature between -20 to 40°C (European Committee for Electrotechnical Standardization, 2009).

4.6 Establishing and finalizing instruments

All the methods applicable for LNG monitoring and a comparison between them, are summarized in Chapters 5.1 – 5.4. The creation of a procedure to select an instrument to be used has been discussed. This would be in the form of a logical thought process. The procedure includes the requirements related to the instrument such as operating conditions, technical information, availability, safety regulations, and certificates. The information needs to be compared to the technical data sheet of an instrument from the supplier. An example of how this procedure would look like can be seen in Figure 44.

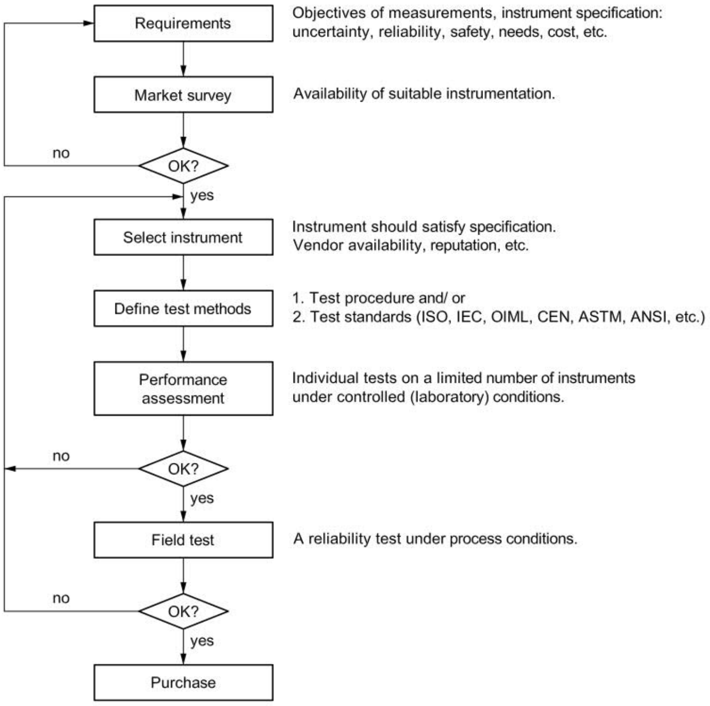


Figure 44. Example of the procedure for the requirements and selection of an instrument to be used for cryogenic monitoring (European Committee for Electrotechnical Standardization, 2014a).

5 RESULTS

The results of this thesis are meant to give process design engineers a better understanding of measuring instruments used in an LNG process. In the following subchapters, the results presented are as follows: a comparison of the instruments based on their attributes and recommendations of which instrument to be used, international standards that will help with the design of LNG processes and instrument specifications, the results of the critical instruments and finalized instrumentation specifications according to findings.

5.1 Pressure measuring methods

A comparison in terms of accuracy, measurement range, operating temperature, influence quantities, and commercial availability among the described pressure sensors are reported in Table 10. The inductive method is interesting because of its high accuracy and wide operating temperature, but neither it nor capacitive measurements can be used for cryogenic measurement since these are not commercially available.

Table 10. Comparison between sensors for pressure measurement.

Measurement principle	Accuracy %	Measurement range MPa	Operating temperature °C	Influence quantities	Commercially available
Capacitive	1.0	[0, 5]	[-196, 97]	Drift of capacitance dielectric constant	No
Inductive	<0.1	[0, 3]	[-267, 0]	Magnetic disturbance	No
Reluctance	1.0	[0, 5]	[-231, 27]	Temperature	Yes
Piezoresistive	0.3	[0, 10]	[-231, 27]	Temperature	Yes
Piezoelectric	5.0	[0, 35]	[-196, 0]	Temperature	Yes

Based on the information in Chapter 3.2, the piezoresistive pressure sensor exhibits the best use for cryogenic measurement due to it having the largest operational range with a high accuracy. Its small size, low power consumption and commercial availability makes this sensor an attractive choice and the clear favorite for LNG pressure monitoring. It is SIL certified which is important. It is favorable in price compared to the other methods. The installation method is the same as for the piezoelectric, but the accuracy is superior, and it is cheaper. It is also the most common type of pressure sensor. It is available in a wide variety of different specifications and finding the right type is likely due to the great number of suppliers.

For measurement of NG, the piezoresistive sensor is recommended as well but there is also the possibility of using a reluctance pressure transducer. The piezoresistive sensor is still preferred since it has a higher accuracy. It is difficult to compare these two, since no price was found for the reluctance pressure transducer. Depending on the type of LNG process it might be worth to have less accuracy for a cheaper measurement system.

5.2 Temperature measuring methods

Six methods for measuring cryogenic temperature were discovered but only four are redeemed as viable for LNG processes. The semiconductor-like resistance thermometer is decided not suitable for LNG since its preferred temperature range is far below the boiling point of LNG. The capacitance thermometer is also decided to not be used. This is because of the lack of a strong presence of magnetic fields in LNG processes, which is the atmosphere where these thermometers thrive.

The remaining four methods are compared in Table 11. The FBG sensor is an interesting solution for temperature monitoring in the LNG storage tank as it performs like an RTD. However, the accuracy is not as great as for the other measurements. There are also unknown factors regarding the safety and since it is not commercially available, one can only wait for the future to know if it will stay as an experimental set-up.

Table 11. Comparison between thermometers for temperature measurement.

Measurement principle	Accuracy %	Measurement range °C	Influence quantities	Commercially available
RTD	0.03	[-200, 850]	Self-heating error	Yes
Diode	0.20	[-251, 43]	Calibration procedure required	Yes
TC	0.05	[-210, 800]	Sensitive to disturbance	Yes
FBG	0.35	[-190, -80]	Accuracy	No

The diode thermometer can be cheaper than the RTD and the TC but is still not recommended because of the inferior accuracy. The set-up may be expensive and with the current accuracy it still might not be suitable compared to the other measuring instruments. It is also not suited in LNG facilities from a safety perspective, as no information has been found regarding it.

The RTD is more accurate and stable while the TC is more economical. They are both interchangeable with each other, if one method is used then the other could be used as a replacement. They have a similar installation method as well as the mounting of the sensor. In the end, the deciding factors are accuracy, safety, reproducibility, temperature range, resolution, size, cost, magnetic field, and measuring instrument. Based on these factors the RTD is the favorite choice for temperature measurement in LNG processes. The use of the RTD is also the common practice for LNG processes and the TC is more suited for experimental set-up or laboratory environments where safety is not of the greatest concern and where less accuracy is enough.

The thermometer probe of the RTD or the TC can be placed in a thermowell or a pipe clamp. If the measurement is intrusive a thermowell must be used to protect the probe from the environment. Thermal insulation must be used to reduce heat losses due to the intrusive installation method. A pipe clamp or welded pocket can be used for non-invasive and non-intrusive measurement. The difference between them is that pipe clamp is cheaper than the welding cost and a thermowell is the most expensive method. The accuracy will be higher for an intrusive measurement, but the reliability will be lower due to risk of leakage. The accuracy for a non-intrusive measurement is between 1 – 2% but will be more reliable.

5.3 Level measuring methods

Out of the eight level measuring methods mentioned earlier only five remain. Acoustic wave, weighing, and radiometric level detection were deemed not applicable for the process conditions. The remaining five methods can be seen in Table 12 where their accuracy, measurement range, operating temperature, and influence quantities are compared.

Table 12. Comparison between methods for level measurement.

Measurement principle	Resolution order of magnitude	Measurement range m	Operating temperature °C	Influence quantities	Commercially available
Capacitive	Sub-millimeter	[0, 1]	> -253	Capacitance of lead wires, pressure, temperature.	Yes
Superconductive	Sub-millimeter	[2, 8]	> -269	Magnetic disturbance	Yes
Optical fiber	Sub-millimeter	[0.7, 100]	> -269	Temperature	No
Differential pressure	Millimeter	[0.7, 50]	> -198	Pressure, temperature	Yes
Radar	Millimeter	[0.7, 60]	> -198	Dielectric constant of liquid.	Yes

Optical fiber sensors with self-heated fibers such as FBG sensors appear to be a good choice for cryogenic storage application. This is based on the technical specification in Table 12. It has been specifically designed to reduce safety concerns that are present in current level measuring methods and to be applicable in ATEX. However, it is not available for the LNG industry yet but the research investigating the method confirms the possibility of working in storage applications. Hopefully, this method will be available for commercial use in the future. If the cost is reasonable, this can be a viable option for future storage applications.

Capacitance and superconductive level sensors are used for cryogenic liquids, but no evidence on them being used for LNG have been found. The guided wave radar senses the dielectric constant of LNG in order to measure the liquid level. The use of this method has increased in recent years for monitoring the storage tank. However, there are some issues that can occur with radar and a separate high-level alarm might be needed to prevent overfilling the tank as seen in Figure 30.

The first consideration when it comes to level measurement in a tank is usually DP measuring. It is accurate, reliable and can be modified depending on the service needed. The downside of this is the handling of the low-pressure side. Depending on the ambient temperature change, the density will change, and the level reading can become inaccurate.

The best decision for level measurement is between guided wave radar and DP measuring. The DP measuring is used in a wider range of tank storage than radar, but they have similar technical specifications. The price of the instruments is similar, and both are designed according to safety recommendations. The installation of the guided wave radar is straight forward compared to DP measurement. However, there are challenges when installing a radar in a vacuum insulated tank. A chamber should be used to prevent disturbances and to isolate the measurement. The DP measurement must heed to stricter installation requirements than guided wave radar (e.g., placement of the transmitter, impulse line length, slopes, and uninsulated pipes) in order to achieve correct measurement of the liquid level. Accuracy related problems appear when the impulse line cannot ensure if the measurement is on gas or liquid phase. If the measurement must be independent of density, then radar is the clear choice. Otherwise, the choice is not that clear between which measurement is better. A lot comes down to what kind of information is known regarding the selected level measurement and what are the recommendations from the manufacturer side. Other than that, it comes down to the cost of the measuring system and the general design of the storage tank.

5.4 Flow measuring methods

The flow measuring methods CMFM, TFM, USFM, and conditioning orifice are found in Table 13. There their accuracy, influence quantities, straight length requirement, operating pressure, and operating temperature are compared. All methods are viable for flow measurement of LNG, while the orifice plate is not applicable for CT of LNG.

If CT of LNG is required, the Coriolis flow meter is the best choice. All flow meters must be approved by a notified body to be used for CT. It has the highest accuracy and is applicable for the process conditions. It is a cheaper choice compared to the other flow instruments. It has no straight length requirement and less requirements for installation in general. The TFM and the USFM require additional density measurement. They can be used for CT but may have to meet additional requirements or is approved with remarks. The TFM has moving parts which is not preferred for CT as this affects the reliability of the process. It also cannot compete with the other instruments when it comes to the lower side of ambient temperature. There are more requirements for the installation of the TFM and the USFM compared to Coriolis flow meter. The list of order for CT of LNG flow meter is Coriolis, USFM, and TFM. All meters can be found in various sizes for different pipe sizes. However, if large quantities are to be measured, the USFM is the preferred option. This is because the larger the pipe diameter, the more time for the traversing of the beam and hence a higher accuracy on the measurement. It can also be more cost-effective for the larger pipe size.

Table 13. Comparison between methods for flow measurement.

Measurement principle	Accuracy order of magnitude %	Operating pressure MPa	Operating temperature °C	Influence quantities	Straight length requirement	Commercially available
Coriolis	0.25	[0, 2.5]	> -196	Temperature and pressure	None	Yes
Turbine	0.33	[0, 4]	> -267	Wear of moving parts, erosion, and damages	U:10D/D:5D	Yes
Ultrasonic	0.35	[0, 4]	> -200	Flow profile, deposits, and entrapment	U:10D/D:5D	Yes
Conditioning orifice	2.0	[0, 10]	> -196	Density, pressure, and viscosity	U:2D/D:2D	Yes

If the meter is meant to only be used for LNG measurement, the same list of order is applied but the conditioning orifice must be included in the list. The main disadvantage with the conditioning orifice compared to the other flow meters is the accuracy. However, it is considerable cheaper compared to the other methods. In terms of size all are applicable for placement in a module, except for USFM which tend to be larger in size. All meters have their downside and careful consideration should be placed to the specific design conditions. Either Coriolis or conditioning orifice is recommended for LNG measurement. It all comes down to the accuracy specification, the design of the process, and the cost of the total design. Even if conditioning orifice is cheaper than Coriolis as an instrument, the total installation cost should be considered as well. If the best accuracy is required than Coriolis is the clear favorite.

5.5 Standards

In Table 14, the standards used in the thesis can be seen. These standards need to be taken into consideration when designing an LNG facility. The standards for the instrumentation and the control system are included as well. Limited or no requirements have been found for loading and unloading, process, and heat transfer system using intermediate HTF for regasification.

Table 14. List of standards used for this thesis and their titles.

National standard	Title	About
EN 1160 1997	Installations and equipment for liquefied natural gas – General characteristics of liquified natural gas	General information on LNG, cryogenic materials, health and safety for the LNG industry.
EN 13458-3 2002	Cryogenic vessels. Static vacuum insulated vessels. Part 3: Operational requirements	Guidelines for vacuum insulated tanks with a pressure higher than 0.5 bar.
EN 13645 2002	Installations and equipment for liquefied natural gas. Design of onshore installations with a storage capacity between 5 t and 200 t	Guidelines for storage tanks in LNG facilities.
EN 1473 2019	Installation and equipment for liquefied natural gas –Design of onshore installations	Guidelines for all processes and relating instruments for on-shore LNG installations.
EN 15001-1 2009	Gas infrastructure—Gas installation pipework with an operating pressure greater than 0,5 bar for industrial installations and greater than 5 bar for industrial and non-industrial installations—Part 1: Detailed functional requirements for design, materials, construction, inspection and testing	Guidelines for design of pressurized natural gas processes.
EN ISO 15970 2014	Natural gas – Measurement of properties – Volumetric properties: density, pressure, temperature and compression factor	Guidelines for measurements of natural gas processes.
EN 1776 2015	Gas infrastructure – Gas measuring systems – Functional requirements	Guidelines for design, construction, testing etc. of natural gas measuring systems.
ISO 18132–2 2009	Refrigerated light hydrocarbon fluids – General requirements for automatic level gauges – Part 2: Gauges in refrigerated-type shore tanks.	Guidelines for level measurement of cryogenic liquids.

ISO 2186 2007	Fluid flow in closed conduits – Connections for pressure signal transmissions between primary and secondary elements	Guidelines for pressure measurement related to flow measurement of cryogenic liquids.
ISO 21903 2019	Refrigerated hydrocarbon fluids – Dynamic measurement – Requirements and guidelines for the calibration and installation of flowmeters used for liquefied natural gas (LNG) and other refrigerated hydrocarbon fluids	Guidelines for different flowmeters used for LNG.
EN ISO 5167-1 2003	Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full – Part 1: General principles and requirements	General guidelines for flow measurement by differential pressure devices.
EN ISO 5167-2 2003	Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full – Part 2: Orifice plates	Guidelines for flow measurement by orifice plates.
EN 60079-10 2015	Explosive atmospheres – Part 10-1: Classification of areas – Explosive gas atmospheres	Guidelines regarding safety in LNG facilities.
EN 61508-14 2014	Explosive atmospheres – Part 14: Electrical installations design, selection and erection	Guidelines for installations and selection and requirements for instruments.
IEC 61508-0 2019	Functional safety of electrical/electronic/programmable electronic safety-related systems - Part 0: Functional safety and IEC 61508	Safety guidelines for instruments and devices.
EN 61511-1 2017	Functional safety – Safety instrumented systems for the process industry sector – Part 1: Framework, definitions, system, hardware and application programming Requirements	Safety guidelines for instruments and control system.
EN 61511-2 2017	Functional safety – Safety instrumented systems for the process industry sector – Part 2: Guidelines for the application of IEC 61511-1	Detailed safety guidelines related to previous standard.
EN 61511-3 2017	Functional safety – Safety instrumented systems for the process industry sector – Part 3: Guidance for the determination of the required safety integrity levels	Safety guidelines for instruments and control system.
MI-005 2014	Measuring systems for continuous and dynamic measurement of quantities of liquids other than water	Requirements for measurements related to custody transfer.

NFPA 59A 2019	Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)	American guidelines for LNG processes.
OIML R 117-1 2007	Dynamic measuring systems for liquids other than water. Part 1: Metrological and technical requirements	Requirements for measurements related to custody transfer.

5.6 Critical instruments and finalizing specifications

During the writing of the thesis, most of the issues related to critical instrument have been answered. The critical instruments were a better solution would be preferred has been presented. Questions related to the critical instruments were answered with the help of standards and information that can be found in this thesis. However, for one of the critical instruments an answer has not yet been found at this point. The problem with the critical instrument cannot be answered with just information regarding the instrument, but the equipment in the process must also be considered. In order to move further, more information is required. The answers to questions and suggested instruments for the critical instruments found were written in a separate document and will not be presented publicly in this thesis. The finalizing of instrumentation specifications according to findings can be found as the standards for LNG design in Chapter 2.6.

6 DISCUSSION

The measuring instruments presented in the results are all applicable for the monitoring of LNG processes. Not all the measurements are available for the industry as certain instruments are only reported for use in laboratory environments. Generally, the preferred instrument type presented for monitoring the process variable complies with what is used in the industry today.

For monitoring pressure, the piezoresistive sensor is the best option. This is the case for the LNG industry. It is the most common method with a high accuracy and a low price compared to other available pressure instruments. It would be great to see more research added into the inductive pressure measuring method. The research articles on the method present a promising solution for the cryogenic process industry. It is a simple method of measurement capable of handling cryogenic temperatures with an accuracy greater than piezoresistive sensors.

The selection of the temperature instrument comes down between the RTD and the TC. This is not surprising as both are common temperature instruments. They are in extensive use within cryogenic processes. They have similar attributes and installation methods, resulting in them being easily interchanged for temperature measurement. The selection comes down to the total cost of the measurement and the installation if the manufacturer provides the needed safety certifications.

The only new instrument discovered for cryogenic temperature measurement was FBG sensors. The accuracy is slightly lower than the accuracy of the RTD and the TC. It presents itself as a unique measurement utilizing optical technology. It is specifically designed for LNG storage monitoring from a safety perspective. It has only been tested for liquid nitrogen with successful results. It is a new instrument which is currently being developed. Hopefully more research and technical information will be accessible in the future. This can be a future temperature method for commercial use.

For liquid level measurement in cryogenic conditions, there are two given options, DP measurement or radar. This is not a surprise as has been the case with the other measurements. DP measurement has always been a common solution to establish the liquid level in a tank. The use of guided wave radar has increased over the years. They utilize completely different measurement methods, where the guided wave radar measures the actual liquid level and the DP measurement is used to calculate the liquid level if installed accordingly. There are certain scenarios where one method is preferred. Both methods have their own related issues. The decision comes down to the total cost of the package. With the increase of guided radar used for liquid measurement, it is worth to request quotations from manufactures.

Optical technology was not only a newfound method for temperature measurement but also a method for level measurement. This can be done with FBG sensors to measure the liquid level in an LNG storage tank. By using the refractive indexes of LNG with the time delay of the light being sent and received the level can be measured. The temperature and the liquid measurement could be done with one instrument. Therefore, reducing the cost of using multiple instruments to monitor the storage tank. At this stage it is still being developed.

For CT of LNG, the clear winner is Coriolis mass flow measurement because of the highest accuracy. It is the only one that has no problem being certified for CT compared to USFM and TFM. It is cheaper and has less requirements for the installation. For flow measurement of LNG, Coriolis is still the clear favorite compared to orifice plate. However, the cost of the orifice plate still makes it attractable even with lover accuracy compared to the other methods. Coriolis and orifice are both common methods used in LNG processes. USFM and TFM are also common but not as extensively.

Some limitations had to be made to reduce the further research of flow measurement. Only common methods were in focus. However, more information about vortex volumetric flow measurement should have been presented. It is known to be suitable for LNG flow measurement, but it was later revealed that it is possible for CT. It is a new method for CT and has not penetrated the market yet.

All methods applicable for LNG should be included in this thesis. However, there might be methods missing. These methods might be newer research methods with limited accessibility of information or outdated methods not applicable anymore. A considerable amount of time has been put into searching all methods used for cryogenics. There are articles and handbooks which mention monitoring methods for cryogenic process. However, all the methods mentioned have not been included in one single document except for instruments for flow measurement. Certain methods are only used in laboratory environment or are experimental. These cannot be used for now in the industry. They were important discoveries and they were included in this thesis as they can be future monitoring methods.

Certain attributes could not be found for some instruments, e.g., the cost and the installation method. This is due to the lack of available information that reduces the reliability when comparing instruments. The comparison of the methods could be improved by requesting quotations from manufacturers. With the design conditions and other requirements, the manufacturer could send technical information of the measuring instrument. A direct comparison of instruments could be done with the technical specification and therefore provide a more reliable result. This would also include other types of information (e.g., safety certifications, installation methods and total cost), which would give more accurate information. However, this is more time consuming. Direct contact with the manufacturer is needed and it is important that the technical information is in accordance with the design specifications for the comparison.

Based on the results, certain instruments deserve more focus than others. However, in order to achieve the results, the information needed to be documented. All possible methods were of interest and specific information related to the methods was needed.

The list of standards includes information regarding instruments, design, installation method etc. The list increases the available information, since only few standards were known from the start. Within the standards further reading is provided as they include other standards. The standards helped with finding the real need for instruments and design decision, but there are still some limitations. Certain standards can be used for certain processes. There was little to no information specified directly for LNG satellite terminal, truck loading/unloading, or cryogenic control system in general. Standards related to specific instruments were found but could not be accessible. Those standards could provide additional information.

Information and standards for CT of LNG between a carrier and a storage tank are well documented. For truck unloading to storage tank, the information is lacking or nonexisting. It can be hard to standardize this because the truck container design varies between countries. The trucks are usually operated by another company than the one running the LNG satellite terminal. The LNG satellite terminal design was originally derived from cryogenic standards. The cryogenic industry generally has fewer control and automation operations compared to LNG processes, resulting in a lack of available information. The truck loading/unloading process is often not the focus compared to other LNG processes. The LNG satellite terminal design is a new concept, hence no standard is developed for the satellite terminal and the truck transfer. A standard reflects the industry’s good practice and requires consensus. Hopefully with time, a standard will be established.

As mentioned in the results, all questions have not been answered for the critical instruments. Certain answers were found but other problems are yet to be resolved. Specific answers to problems can be hard to find. This applies especially to industry related issues, as industries might not want to report the issues. Therefore, the problem is never presented, and a solution is never considered.

7 CONCLUSIONS AND RECOMMENDATIONS

The thesis focuses on the LNG satellite terminal, but the instruments and methods presented can be used for other LNG processes. They can be used for e.g., large import terminals, liquefaction plants, and flat bottom tanks, if the operating conditions are the same. Therefore, this thesis provides measuring methods applicable for all LNG facilities.

The results reflect well onto the expectations of this thesis. The main objectives of the thesis are accomplished in one way or another with valuable results. The instruments used for the standard pressurized LNG satellite terminal were reviewed. The technical information from the instruments was established. The second objective of analyzing the need for each instrument was achieved with the help of standards in order to have a baseline of requirements. From there, why the instruments are needed can be found. The third objective of finding new methods or instruments for measuring process values was achieved as well. Several new methods were found, and the result of the best methods complies with what is currently used in the industry. Most of the focus was allocated to this part since more information was requested of the measuring method. The fourth objective, reviewing the control and instrument communication from a reliability, safety, and economical point of view, was not achieved. This was included when finding new measuring methods instead, in order to compare the methods with each other. The final objective of finalizing instrument specifications was achieved. The need for the instruments and guidelines to be followed was established. New methods were found and compared to existing methods in order to determine which is the best measuring method. Answers related to critical components were found, but not all of them were answered during the time of writing this thesis.

The thesis improves the knowledge of terms, standards and methodology for instruments to the design engineer. The focus is to give the design engineer knowledge of instruments from an instrument perspective. Usually, the LNG process is developed first, and then the instrumentation for the process is included. This thesis is meant for the design engineer to integrate the design for both the process and the instrument at the same time. This is to ensure a dynamic solution that focuses on presenting the best solution with both objectives in mind.

From the company's perspective the results are satisfying as most of the objectives have been answered. The work presented in this thesis is of value to the company. The subjects of the thesis have evolved around the information that the company requested. If more knowledge of a subject was needed, it has been investigated in order to give a more detailed description. The only objective which is not discussed extensively is the fourth objective. Here further work can be done by performing reliability calculations of the current instruments that are used in the LNG satellite terminal.

The third and the fourth objective can be investigated even further. By contacting manufacturers and receiving technical information regarding an instrument, a better result of the comparison can be achieved. Other valuable information such as an accuracy rating, an installation guide, and the total cost of the instrument can be received as well. With the technical information, reliability calculations can be made on all the instruments. This can be compared with other related measuring instrument to discover which instrument is the safest to use in the LNG process.

Further research can be done by investigating why certain measuring methods are not available for commercial use. This is interesting since certain methods have been available for years, but not implemented for the industry. The reason behind this could provide answers and would be good to have, e.g., knowing if it is related to operational performance, safety of the process, or selection of materials for the design of the instrument. Information regarding the time when instruments can be used for the industry would also be interesting to know. Can certain instrument be available within a couple of months? Is it a five-year period including test runs and other certification procedures that needs to be performed before becoming available? The answers to these questions can help when planning the control system and the design of an LNG process.

The possibility of building a test facility is something that can be performed in the future. When a suitable monitoring method has been established, a practical test should be performed to see if the theoretical information is correct. The test facility should include all the equipment in an LNG satellite terminal. It should also be possible to interchange the instruments ensuring all methods can be tested. The data received from the measuring instruments should be stored. Therefore, the data can be compared over a longer time period with measurement data from other instruments. This is of course expensive, and careful consideration should be done whether the information achieved is worth the cost.

There are new methods developed for the LNG industry as proven in this thesis, but they are not of the highest priority. Considering the technology and processes that can be researched within the LNG industry, less focus is placed onto the control system and even less on instrumentation. There are applicable measuring methods within the LNG industry which have yielded a good operational performance for a long period of time. More research on instrumentation for cryogenic conditions can be found when the operating environment is harsh, e.g., strong presence of magnetic field or space. However, the research into the instrumentation for the LNG process should be focused on as equally as on improving the overall performance of the LNG process. After all, the safe operation of an LNG process is the most important factor within the industry.

SVENSK SAMMANFATTNING

Optimering av mätinstrument och kontrollsystem för en standard trycksatt LNG-satellitterminal

Naturgas är en ren energikälla jämfört med andra fossila bränslen. Den kan förvaras och transporteras som flytande naturgas (LNG) vid en temperatur på -162 °C och ett tryck på över 1 atm. Detta av ekonomiska orsaker, volymen för LNG är 600 gånger mindre än för naturgas, och säkerhetsskäl, explosionsrisken minskar med ett högre tryck och förhindrar att luft läcker in. Byggandet av mottagningsterminaler för LNG har ökat under de senaste åren. En mottagningsterminal har som uppgift att ta emot LNG som transporterats av hangarfartyg, förvara, återförgasa och leverera naturgas till slutanvändaren via långa sträckor med rörsystem.

Av geografiska skäl kan inte alla tänkbara slutanvändare nås via långa rörsystem, och därför används LNG-satellitterminaler. En satellitterminal är en småskalig mottagningsterminal. Den innehåller samma processer och utrustning som en större mottagningsterminal men LNG levereras med hjälp av vägtransport till satellitterminalen.

Övervakningen av LNG-processer är viktigt för säkerheten i alla LNG-anläggningar. Det är nödvändigt att ha ett pålitligt övervakningssystem för att förutse och förhindra problem som är processrelaterade. Tillgängligheten av noggranna mätdata från processens mätinstrument är viktigt och korrekt information ska överföras till kontrollrummet för att kunna kontrollera processerna.

Syftet med denna avhandling är att ge en bättre förståelse av mätinstrumenten som används för en LNG-process. Målet är att undersöka vilka mätinstrument som används i en standard trycksatt LNG-satellitterminal. Vidare analyseras kraven på och behovet av mätinstrumenten. Avsikten är att hitta nya mätmetoder eller mätinstrument för övervakningen av LNG-processer. Därtill undersöks kontrollsystemets och mätinstrumentens kommunikation för att bedöma deras tillförlitlighet och säkerhet samt för att överväga ekonomiska perspektiv. Slutligen ska specifikationerna för mätinstrumenten presenteras utgående från erhållna resultat.

Alla processer i LNG-satellitterminalen beskrivs inte i föreliggande arbetet, utan endast förvaring, återförgasning och påfyllning. Processerna levereras som nyckelfärdiga moduler och därmed måste mätinstrumentens storlek beaktas. Alla tänkbara mätmetoder som kan användas för kryogenisk temperatur nämns kortfattat och undersöks för att bestämma om de kan tillämpas i LNG-övervakning. Gällande flödesmätare begränsades undersökningen till att omfatta de flödesmätare som är vanligast och som kan användas för överföring av LNG.

En LNG-satellitterminal är en liten terminal för mottagning av LNG, förvaring och återförgasning som allt sker inom satellitterminalen. Den används ofta i kombination med ett gaskraftverk. Storleken på satelliteterminalen definieras enligt förvaringstankarnas storlek och kapaciteten ligger mellan 100 och 20 000 m^3. De utgör den dyraste kostnaden för satellitterminalen. Processen i satellitterminalen börjar med att LNG levereras med tankbilar. Tankbilen ansluts till mottagningsmodulen med hjälp av slangar och förvaringstanken påfylls via ett trycksatt rörsystem. Den maximala flödeshastigheten är 100 m^3/h och styrs av trycket som är ca 1 MPa. Trycket i systemet kontrolleras med hjälp av en pump eller en tryckökningsenhet.

Förvaringstanken är cylinderformad, vakuumisolerad och antingen horisontellt eller vertikalt installerad beroende på säkerhetsanalyser. Flera förvaringstankar kan användas för att öka förvaringskapaciteten. Tanken består av ett inre och yttre kärl för att kunna förvara LNG säkert. Om det inre kärlet går sönder kommer LNG fortfarande att förvaras inuti tanken. Konstruktionen förhindrar också spridning av naturgas som förångats i förvaringstanken.

Då LNG ska levereras till slutkunden sänds LNG till förångningen. Här värms LNG upp och blir till naturgas igen. Den vanligaste typen av förångare i LNG-satellitterminaler är en luftförångare eller förångare med mellanliggande värmeväxlare. Förångare med mellanliggande värmeväxlare är ett slutet system med en värmeöverförande vätska från en värmekälla. Vätskan är vanligen en blandning mellan vatten och glykol vilket ger en hög värmekoefficient. Värmekällan kan vara upphettat vatten, ånga eller spillvärme beroende på vad som finns tillgängligt. Luftförångaren extraherar värme från omgivande luft och kräver inte en mellanliggande värmeväxlare. Luftförångaren föredras för att den har konstaterats vara miljövänligare och billigare. Däremot krävs flera stycken för att uppnå samma effekt.

Kontrollsystemet är uppbyggt att vara så säkert som möjligt. Det består av ett processkontrollsystem och nödstoppssystem. Processkontrollsystemet består av mätinstrument och apparater som övervakar och reglerar processerna. Huvuduppgiften för detta system är att upprätthålla processens variabler och en stabil process. Processvariablerna är tryck, temperatur, flöde och vätskenivå. Nödstoppssystemet är uppbyggt av säkerhetsinstrument och är ett separat system. Dessa instrument har som uppgift att förhindra uppkomsten av problem och stoppa processerna vid ett nödalarm. Säkerhetsinstrumenten innehåller olika funktioner som måste uppfyllas för att upprätthålla en säker process vid en eventuell fara. Dessa funktioner består av säkerhetsintegritetsnivåer från 1 – 4. Nivån indikerar hur bra säkerhetsinstrumentet hanterar processen vid en fara. En högre siffra indikerar en lägre risk för att det uppstår en fara. Säkerhetsintegritetsnivåerna kan beräknas och ska bekräftas av tillverkaren.

Mätinstrument används för direkt eller indirekt mätning, övervakning och kontroll av processvariabler. Digitala mätinstrument kan uppkopplas till kontrollsystemet för att överföra noggranna mätdata. Mätinstrument som kan utföra flera typer av mätningar är att föredra. Det är viktigt att förstå skillnaden mellan mätinstrument som används. Till exempel om det är en detektor, sändare eller elektronisk omvandlare. Med ett digitalt mätinstrument ökas säkerheten, tillförlitligheten och effektiviteten i en process.

Överföring av LNG är vanligt inom LNG-industrin. För detta krävs speciella flödesmätare med en stor noggrannhet. Det kringliggande systemet kräver också en stor noggrannhet. Andra krav och regler måste också följas. Dessa och själva överföringen av LNG övervakas av myndigheter och anmält organ.

Den standard trycksatta LNG-satellitterminalen undersöktes för att ta reda på vilka mätinstrument som används. Information om dessa dokumenterades för att kunna hänvisa till vad som är kraven för mätinstrumenten. Samtidigt konstaterade det att det finns avvikande mätinstrument. Med avvikande mätinstrument avses de mätinstrument som inte fungerar som förväntats, ett annat mätinstrument föredras eller mätinstrumentet ska leverera noggrannare mätdata och vara kostnadseffektivt. Totalt var åtta mätinstrument avvikande för LNG-satellitterminalen och majoriteten av problemen var relaterade till temperaturmätning. Övriga problem gällde nivå- och flödesmätning. Dessa avvikande mätinstrument medförde att informationssökningen måste utvidgas för att analysera varför instrumenten är nödvändiga.

För att analysera behovet av mätinstrument behövdes information. Informationen innehåller behovet, valet, konstruktionen och installationen för varför mätinstrumenten används. Det framkom att valet av mätinstrument baserade sig på riskanalyser, designingenjörens egen kunskap och normer inom branschen. Bredare kunskap om ämnet krävdes och därmed granskades tillgänglig information i nationella standarder för LNG-anläggningar.

EN 1473:2019 är en standard för landbaserad konstruktion av LNG-anläggningar. I denna standard kunde övriga standarder hittas som kunde användas för att få information relaterad till mätinstrument. I början söktes endast information relaterad till mätinstrumenten. Detta utökades till att inkludera information så som installationsmetoder och konstruktion av LNG-processer. På grund av de avvikande mätinstrumenten krävdes information om överföring av LNG, krav på mätsystem och specifikationer för kontrollsystemet. Alla använda standarder och resultat av informationssökningen återges i detta arbete.

Undersökningen av nya metoder för övervakning av LNG-processer utvidgades genom att tillämpa mätinstrument som används inom kryogena processer. De flesta kryogena mätinstrument kan användas för LNG med vissa undantag. Alla tänkbara metoder nämns i detta arbete men om metoden inte kan tillämpas för LNG utesluts den. Metoderna eller mätinstrumenten är tagna ur tekniska handböcker och vetenskapliga undersökningar. Vissa metoder är väl etablerade inom branschen medan andra endast är experimentella eller används i laboratorium. För att undersöka vilka metoder som passar bäst för övervakningen undersöktes olika egenskaper. Dessa egenskaper är tillgänglighet, teknisk information, noggrannhet, mätområde, driftområde, installation, tillförlitlighet och kostnader. För- och nackdelar undersöktes också.

Totalt har fem metoder för tryckmätning hittats och alla är anpassade för LNG. Sex metoder hittades för temperaturmätning men endast fyra som lämpar sig för LNG. Åtta nivåmätningsmetoder hittades men endast fem rekommenderas för nivåmätning i förvaringstanken. 16 metoder hittades för flödesmätning men detta begränsades till endast fyra tänkbara flödesmätningar. Dessa jämförs i resultatet för att se vilken metod som är bäst anpassad för övervakning.

Dokumenteringen av de nya metoderna som hittades är viktiga att ha inför framtiden. De kan finnas tillgängliga inom en snar framtid och då är det viktigt att veta att man har sett metoderna tidigare. Metoderna kan vara billigare, ha enklare konstruktion och installationsmetod, större driftområde eller presentera bättre resultat med en stor noggrannhet. En av de nya metoder som hittades är Fiber Bragg Grating, som använder sig av optisk teknologi. Denna metod har utvecklats specifikt för temperatur- och nivåövervakning av LNG i förvaringstankar. Den är av intresse för att den eliminerar säkerhetsrisker som finns med nuvarande mätinstrument som används i förvaringstankar.

De tillgängliga mätinstrument som undersökts i denna avhandling och som anses vara bäst lämpade för övervakningen av LNG-processer är sådana som används inom industrin i dagsläget. För tryckmätning är piezoresistiva tryckgivare den bästa lösningen. De har högst noggrannhet, brett driftområde och är kostnadseffektiva. För temperaturmätning står valet mellan en resistent temperaturdetektor eller termoelement. Båda används inom branschen i en bred utsträckning, har liknande användningsområden och kan bytas ut sinsemellan. Skillnaderna är att en resistent temperaturdetektor är lite mer noggrannare och har stabilare drift medan ett termoelement är billigare. Termoelement används oftare i laboratorier.

För nivåmätning står valet mellan en differentialtrycksensor eller en guidad nivåradar. Differentialtrycksensorer har länge varit ett naturligt val för nivåmätning och är piezoresistiva tryckgivare. En differentialtrycksensor använder sig av trycket för att kunna beräkna nivån i tanken medan guidad nivåradar innehåller en kabel som placeras inne i tanken och känner av vätskan och gasen. Användningen av guidad nivåradar har ökat under de senaste åren och blir allt vanligare. Båda har stor noggrannhet och ett brett driftområde. Båda har dessvärre brister inom olika delområden. Om mätningen ska vara oberoende av densitet ska guidad nivåradar användas. Valet mellan dessa avgörs av den totala kostnaden och förvaringstankens konstruktion.

För flödesmätning används olika typer av flödesmätare. Den första är en Coriolis-mätare som använder sig av Corioliseffekten för att mäta massflödet. Nästa är en volymflödesmätare som använder sig av en turbin. Följande är en akustisk flödesmätare som använder sig av ultraljud för att mäta volymen. Slutligen används en strypfläns med en differenstryckmätare för att beräkna massflödet. För överföring av LNG kan de tre fösta användas. Strypflänsen är inte tillåten på grund av för liten noggrannhet. Coriolis-mätaren är det bästa alternativet för överföring av LNG. Den mäter massflödet med en stor noggrannhet och är billigare än de två andra flödesmätarna. Volymflödesmätarna kan också användas men har större krav för att bli godkända för överföring av LNG. Volymflödesmätaren med en turbin innehåller rörliga delar vilket man helst undviker. Coriolis-mätaren har den bästa noggrannheten och mäter direkt massflödet medan strypflänsen är minst noggrann. De två övriga flödesinstrumenten mäter volymflödet i processen med lite sämre noggrannhet än Coriolis-mätaren. Trots att strypflänsen är minst noggrann är den ändå ett starkt alternativ till Coriolis-mätaren då det kommer till flödesmätningen. Den är betydligt billigare och då kraven för överföring av LNG inte behöver följas, är det en flödesmätare som hellre används för att spara på utgifterna.

Det är viktigt att känna till standarder och veta var man hittar information om mätinstrumenten och design på LNG-processerna. Det finns dock ingen standard som är specifikt skriven för en LNG-satellitterminal. Detta beror på många olika saker men framför allt är en LNG-satellitterminal ett nytt koncept inom LNG-industrin. En standard återspeglar god praxis inom branschen och kräver konsensus mellan medlemsländerna i internationella standardiseringsorganisationen. Med tiden kommer förhoppningsvis en standard för LNG-satelitterminal att kunna upprättas.

De metoder som presenteras i avhandlingen är alla lämpade för användning i alla LNG-processer och inte bara för en satellitterminal. Målen med denna avhandling uppnåddes i stort. När det gäller kontrollsystemet och mätinstrumenten kunde vidare undersökningar göras med avseende på säkerhet, tillförlitlighet och ekonomiska perspektiv. Då man valt ett instrument kunde pålitlighetsberäkningar göras utgående från teknisk information från tillverkaren. Jämförandet av mätinstrumenten kan förbättras genom att få teknisk information från tillverkaren. Då får man information om det mätinstrument man vill ha istället för att utgå från generell information och kan utföra en noggrannare jämförelse. Med att ta kontakt med tillverkaren får man också information som till exempel noggrannhet, installationsanvisningar och totala kostnader.

Nya mätmetoder utvecklas inom LNG-industrin vilket visas i denna avhandling. Det har dock inte högsta prioritet då det kommer till utvecklingen. Fokuset inom LNG-industrin ligger mera på processerna i sin helhet och utrustningen än på kontrollsystemet och mätinstrumenten. Det finns etablerade övervakningssystem inom branschen. Flera undersökningar om nya mätinstrument går att finna där driftmiljön är mera krävande som till exempel i rymden. Det vore även viktigt att utveckla nya övervakningsmetoder eftersom en säker drift av en LNG-process är det viktigaste kravet inom LNG-industrin.

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