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Review paper

Review of Cargo Operations on Crude Oil Tankers and Methods/Models Used for Optimisation and Improvement of Safety*

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Abstract: Very Large Crude Carriers (VLCCs) are special ships because of their length, breadth, draft, stability stresses and manoeuvrability. Cargo handling is one of the most sensitive operations in terms of safety and oil pollution, as oil is a dangerous cargo to transport. Of particular concern is the potential marine pollution from accidental oil spills. Operational oil spills on crude oil tankers are caused by operations such as loading and unloading, tank cleaning, crude oil washing, ballasting and discharge of oily water overboard. Over the years, advanced equipment, numerous procedures and checklists have made cargo operations safer, but unfortunately have also made ship crews and officers less attentive. Strict control must be maintained throughout the loading, unloading and all other cargo related operations. The main objective of this article is to review the methods and models used to improve the safety of cargo handling operations.

Keywords: Tanker, Cargo operations, Safety, Oil spill, Cargo pumps, Cargo planning.

1. Introduction

Cargo handling operation on Crude oil tankers is a very sensitive operation in terms of safety and oil pollution and must be carried out with great care. Tanker operations such as loading, unloading, crude oil washing (COW), inerting, purging, tank cleaning, and degassing (gas free) pose a great risk to marine pollution and to the ship itself, as there is a risk of fire and explosion. An operations plan must be prepared for each operation, including permits and checklists, accompanied by a risk assessment. The plan must be strictly followed when carrying out each operation. Any deviation from the plan must be discussed with all persons involved and the risk assessment reviewed. A safety meeting must be held with all persons involved before

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work commences and all crew must be aware of their duties and responsibilities. Oil spill equipment must be in place in accordance with the plan to prevent possible pollution from cargo and to prevent oil spill overboard. All natural vents must be closed and the air conditioning system set to recirculation mode in the event that hazardous gases are spread.

Loading and discharging operations on very large crude carriers are very demanding and require full commitment in cargo planning. Particular care must be taken in stability calculations, especially when more than one parcel of crude oil is loaded. When more than one parcel of crude oil is loaded, the stability calculation must take into account that any loaded parcel of crude oil may be discharged first. Therefore, proper distribution of cargo is very important. Oil tankers are designed to withstand the loads (stresses) on the ship's structure, but cargo plan must be prepared in order to minimise the loads. The bending moment of the ship (BM) and the shear factor (SF) must always be within their safety limits. During the discharge process on crude oil tankers, a crude oil wash (COW) is carried out. During the crude oil wash, the cargo tanks are washed with the existing cargo to remove the remaining sediments of crude oil in the cargo tanks. If tank cleaning is required after COW, the removal of the remaining residues in the cargo tanks will be significantly reduced. To control oil residues, at least 25 percent of cargo tanks must be washed with crude oil before each ballast voyage and each cargo tank must be washed with crude oil at least every fourth time crude oil is discharged from the cargo tank.

On crude oil tankers, inerting cargo tanks is a procedure that is carried out by an experienced crew due to the high risk of fire and explosion. The procedure is carried out before loading to prevent an unsafe (explosive) atmosphere in the cargo tanks. At this time, the lower explosive limit (LFL) in the cargo tanks can be lowered by inerting the cargo tanks. Therefore, the gas mixtures in the cargo tanks are not in the flammable zone because the oxygen concentration is below 8% or less. Although this process is critical to the safe operation of tankers, harmful consequences of particular operation could represent potential harm to human life (oxygen deficiency), the environment (hazardous gas emissions) and the cargo on board (explosion). Therefore, it is of utmost importance for ship operators and marine engineers to assess the risk of human error during the inerting process to avoid unexpected consequences [1].

Degassing (gas free) operation is described as one of the most dangerous operations on crude oil tankers. The aim of degassing process is to remove explosive or toxic gases from cargo tanks and to increase oxygen content to atmospheric conditions. The atmosphere in the cargo tank must contain sufficient oxygen to be entered. The procedure is performed after tank cleaning to prepare the tank atmosphere for entry so that it is available for inspection and maintenance. A typical degassing (gas free) operation begins by inerting the cargo tanks to reduce the oxygen content to 8% or less. Then tank cleaning operation is done in order to remove sediments of previous cargo. This increases the volatile organic compound content (VOC). Then the cargo tanks are purged before gas free operation. There are two methods of degassing widely used on tankers: Degassing by displacement and degassing by dilution. Degassing (gas free) operation starts with fixed or portable fans through an open manhole. In this way, toxic and flammable gases (inert gas and residues from VOC) are removed from the cargo tanks and fresh air is introduced into the cargo tanks. The cargo tanks are ˝gas-free˝ when the oxygen concentration is 20.9% and no traces of toxic gases are present. As the process is harmful to the crew and the maritime environment due to the toxic gases release during ventilation, all personnel are required to wear personal gas detectors and respirators as required [2].

2. Crude oil carriers

The size of tanker depends on the amount of cargo to be carried, the size and limits of the port, and draft restrictions. Ultra Large Crude Carriers (ULCC) with a capacity of 300-500,000 dwt are the largest crude oil tankers. Due to their size, most ports and terminals cannot accommodate these huge tankers, so they have to transfer their cargo to smaller tankers which then proceed to the terminals. Such "smaller" tankers are called Aframax tankers with a capacity of 79,999 dwt.

Very Large Crude Carriers (VLCC) have a very large cargo capacity of 160-300,000 dwt and can call at many ports, giving them an advantage in the amount of crude oil they can transport. They can carry several types of crude oil (usually four) and have a simple loading system. Larger ships, lower transportation costs and the ability to call at numerous ports around the world make VLCC's unique vessels in the tanker business.

Product tankers range in size from 26-40,000 dwt and are used to transport clean and dirty products as well as crude oil.

Handy- sized tankers (coasters) have a carrying capacity of 16-25,000 dwt and are used to transport clean and dirty products and crude oil along the coast, usually between the same locations [3].

3. Important parameters of crude oil for cargo operations

Crude oil is a liquid that comes directly from deposits beneath the earth's surface. It is called crude oil because this liquid must be processed (refined) into usable products such as gasoline. There are different types of crude oil around the world. Important characteristics (properties) of crude oil related to cargo operations are density (API), vapour pressure, flash point, pour point, wax content, cloud point, viscosity, sediment and water, sulphur content, benzene content. Density is the ratio of mass to volume. API (American Petroleum Institute) gravity is an inverse measure of the density of an oil liquid relative to the density of water. Vapour pressure indicates the tendency of a liquid to change into a gaseous or vapour state. Flash point is the lowest temperature at which a liquid gives off enough gas to form a flammable gas mixture near the surface of the liquid. Pour point is the lowest temperature at which a liquid remains in the liquid state. Crude oils with a high pour point must be heated to reduce viscosity so they can be discharged by cargo pumps. Only crude oil tankers with a heating system for cargo can carry such crude oil. Wax content is the percentage of paraffinic wax by volume. Cloud point is the temperature at which a liquid hydrocarbon begins to solidify and take on a cloudy appearance. Viscosity is the ability of a liquid to resist flow. Crude oil with high viscosity is unsuitable for crude oil washing (COW). Basic sediment and water (BS &W) are a percentage of free water, sediment and emulsion. This value is added to the total amount of crude oil volume loaded. Sulphur content is the amount of hydrogen sulphide (H2S) present in the crude oil. This is a dangerous gas that smells like rotten eggs and can cause instant death in large quantities. When transporting crude oil with high H2S content, warnings must be posted and special precautions taken during transportation and loading.

Benzene is found in aromatic hydrocarbons and is carcinogenic. Physical contact, ingestion or inhalation must be avoided.

Because of these properties, there are different procedures for transport, loading, unloading, COW (crude oil washing), purging, tank cleaning and degassing [4], [5].

4. Cargo equipment

Fig. 1 shows the most common cargo pumps on crude oil tankers are centrifugal pumps located in the pump room. There are three centrifugal pumps in the pump room, each connected to a separate cargo line that can be connected by crossover valve when the same crude oil is being loaded. They are used for bulk transfer of crude oil. There are also two centrifugal ballast pumps in the pump room for ballast transfer. Centrifugal pumps consist of two main components: the impeller and shaft as rotating elements and the casing, mechanical seals and bearings as stationary elements. Before starting the pump, liquid must enter the pump (priming) and pressure must be released from the pump (purging). The pump must never be started without liquid, as this may cause severe damage to the cargo pump. During discharge, when the cargo tanks are full, the pumps operate at high capacity and are called bulk discharge. When the liquid in the cargo tanks drops to the stripping level, the capacity of the cargo pumps drops to low suction and the discharge must be completed with the stripping system.

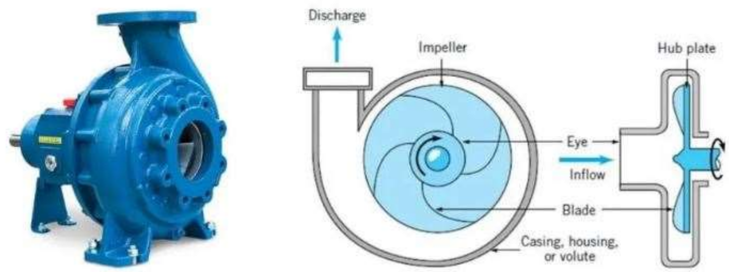

Fig. 1 – *Centrifugal pump [4].*

Fig. 2 shows fluid driven educator which are used for the final stripping of the cargo tanks. The eductor requires a constant and adequate flow rate to create suction, which must remove the remaining cargo from the cargo tanks.

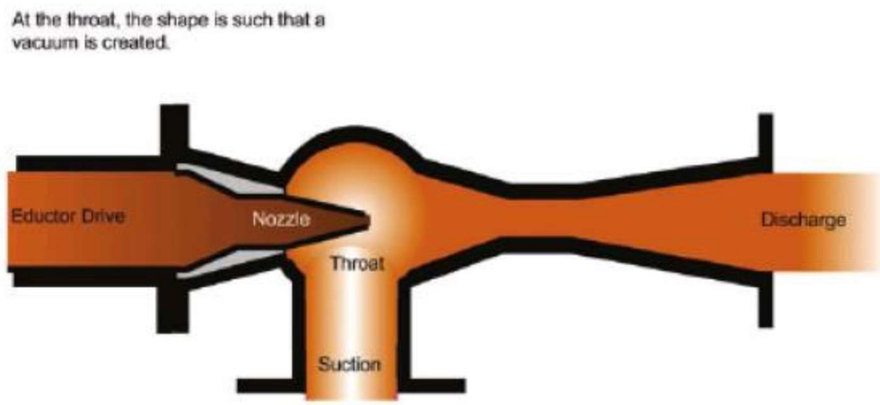

Fig. 2 – *Eductor [4].*

Fig.3 shows a stripping pump which is used to complete the discharge and final stripping of the cargo lines and tanks. Stripping pumps shall be steam driven duplex piston pumps.

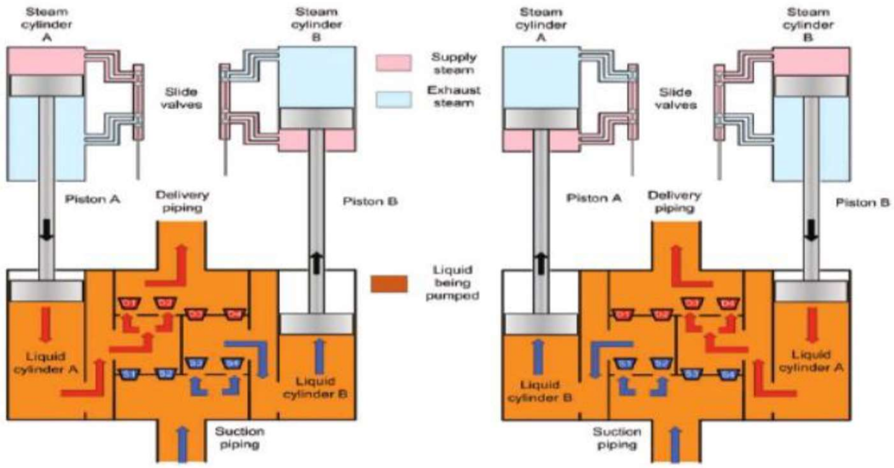

Fig. 3 – Stripping pump *[4].*

The operation of cargo pumps must only be carried out by an authorized person such as the Chief Officer or a Deck Officer under the supervision of the Chief Officer. A sudden change in flow velocity when the line valve on the discharge side is closed rapidly or partially may cause water hammer. This may cause structural damage, pollution, or injury. Water hammer must be avoided by opening and closing valves slowly or gradually. When handling with cargo pumps rapid change in flow rate must be avoided by increasing and decreasing cargo pumps revolutions gradually [3], [4], [6]. The amendments to SOLAS regulations II-2/4.5.5 and II 2/16.3.3 require an inert gas system to be fitted on all new oil and chemical tankers of 8,000 dwt and above, (when transporting low-flash point cargoes of < 60°C). Oil tankers above 20,000 dwt were already required to install such systems. For tankers fitted with exhaust gas inerting systems, the application of inert gas must be carried out during loading, on passage, unloading, tank cleaning and purging prior to gas freeing. The oxygen limit (all tankers) for inert gas supplied to cargo tanks has also been lowered from 8% to 5% for new systems [7]. The importance of inert gas system on tankers is that the atmosphere in cargo tanks is always kept below 5% of oxygen and decreases risk of fire and explosion to minimum. Crude oil washing was made mandatory for new tankers by the 1978 Protocol to the MARPOL Convention. Regulation 33 of MARPOL Annex I requires every new crude oil tanker of 20,000 tons deadweight and above to be fitted with a cargo tank cleaning system using crude oil washing [8]. Crude oil washing was introduced to reduce cargo residues (sludge) to minimum after discharge operation. The outcome is less oil aboard after discharging operation and substantial reduction in air pollution.

5. Cargo planning

Cargo planning can begin as soon as the ship receives the complete voyage order. The voyage order must include the amount of cargo to be loaded, the API value or density, and the temperature of the crude oil for cargo calculation. The name of the port of loading must also be included. The first step is to create a loading plan using the information contained in the voyage order as shown on Fig. 4.

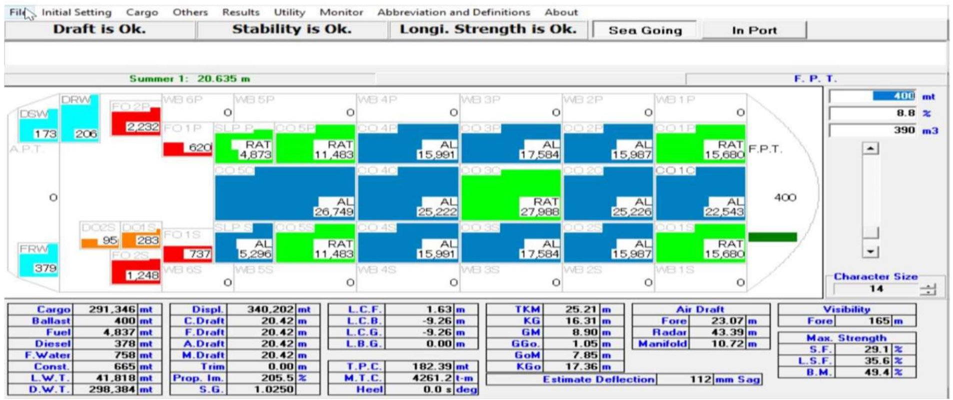

Fig. 4 –*Cargo plan VLCC MT "Pacific Voyager" [4].*

If the vessel is to load more than one grade of crude oil (usually up to four grades for VLCC), the loading plan should be prepared so that each grade loaded can be discharged first at the discharge port. Normally, the vessel does not know which grade will be discharged first until it reaches the discharge port. This loading plan is not easy and sometimes impossible to achieve due to the large load (stresses) of VLCC tankers. The plan must include the details of how cargo handling and ballasting will be carried out. A good cargo plan must include procedures for the safe operation of cargo equipment, standing instructions detailing the stages of cargo operation, and emergency procedures in the event of a fire, explosion or oil spill. Information about the cargo should be clearly stated in the plan, as should the arrangements for pipelines, pumps and the venting arrangements for each type of crude oil. Segregation arrangements must be indicated for each grade and the valves that must not be opened. Cargo plan must be clearly understood by all parties, contain sufficient detail and be easy to understand. The cargo plan must include qualified personnel capable of performing the task, personnel performing critical operations, and rest periods for all personnel involved in the cargo operation. The terminal at berth must provide a Material Safety Data Sheet (MSDS) for all cargo to be loaded, which should be included in the cargo plan [5].

6. Methods/models for optimisation and improvement to safety

Over the years, computerised (automated) systems have been introduced on tankers to improve safety and make it easier for officers. An automated system detects anomalies much faster than the officers on watch and alerts them, giving the officers enough time to correct the anomalies in a timely manner. The officers on watch must be familiar with computerised or automated systems to recognise certain alarms and respond accordingly. The emergency shutdown system (ESD) on tankers in the event of an oil spill can be remotely controlled from the ship as well as from shore. Automated systems can interrupt certain operations on tankers, for example, the cargo pump automatically shuts down if it overheats, preventing damage to the pumps. Over the years, computerised and automated systems, checklists, routines and procedures have minimised human error. Computer programmes and automated systems cannot replace the officer on watch, but they can make the job easier and assist to complete cargo operation in a much safer way for the ship and the environment. Automated systems and computer programs are welcome on tankers but must be under the strict control of trained personnel. Therefore, seafarers are required to be familiar with automated systems on board and to continuously educate throughout their sailing life. Every new automated system introduce on board must be accompanied by a trained crew who will have to take the appropriate course for a particular automatic system installed on board. Automated systems are good as long as there is good supervision over them by trained personnel [9].

Human factor is one of the major causes of accidents and breakdown in the shipping sector. A cognitive reliability and error analysis method has been developed (CREAM) to provide estimates of human error probability (HEP) in tanker operational safety [10].

Over the last decade, the regulatory framework in the shipping industry has put enormous pressure on ship designers, owners and operators to improve on-board safety and drastically reduce the environmental footprint of shipping. Holistic methodology was developed for the systematic variation and optimization of new tanker designs based on the principles of simulation-based driven design in the Friendship Framework [11].

Collision and grounding data registered in GISIS (Global Integrated Shipping Information System) were studied for oil tankers. Risk assessments were carried out using the Fault Tree Analysis (FTA) programme for incidents resulting in collisions and groundings for oil tankers [12].

Advanced computer methods were used to model and simulate gas freeing processes to determine the progress of gas freeing in terms of studying the concentration and distribution of vapours in the cargo tank during the gas freeing process. The simulation also includes the study of the decrease in vapour concentration in terms of forming a quality model to predict the time required for degassing, given the initial conditions [13].

In order to improve the safety and operational reliability in the maritime industry for the tank cleaning process on board chemical tankers, ship methodology is extended by integrating the Analytic Hierarchy Process (AHP) technique into the approach HEART. It is a methodological development in the field of decision making and human factors to weight the share of impact in the calculation of error-causing conditions by operations [14].

7. Conclusions

Although safety on tankers has improved considerably in recent years, accidents still occur, a high percentage of which are attributable to the human factor. Modern tankers have integrated systems and are equipped with all the alarms foreseen for each operation. Ship safety is closely related to ship procedures and depends on the ability of the crew to follow the required procedures. With the advent of technology on ships, shipping companies have attempted to solve the problem of managing automated systems with a series of checklists and work permits. In recent years, there has been a significant increase in administration on ships and a decrease in the number of crew members on board, which has affected the work of the crew. Due to the overload of paperwork, officers no longer read permits and checklists thoroughly, which poses a danger to the ship and the environment. Permits and checklists have contributed to safety on board, but their number should be limited or we will have the opposite effect. Reducing the number of crew on board leads to an increase in the volume of work and therefore fatigue. This significantly increases the risk of human error.

Tankers will be even more modern in the near future in terms of safety for the crew and the environment, but the crew must be trained to operate such vessels and monitor new systems for cargo operations. To maintain safety on board, shipping companies must find a way to keep a certain number of crew members on board who are able to thoroughly monitor automated systems without compromising the safety of the ship. The crew must also be constantly trained (educated) in various courses for certain new automated systems on board.

Cargo handling on super tankers is complicated and challenging due to a variety of factors that affect the process. Contributing to this are the different types of crude oil that are transported to the port of discharge. Each type of crude oil needs to be unloaded separately, so a good handling plan is very important.

Due to the large volume and different types of cargo (grades), it is important to have a quality cargo plan in place to reduce stress on the ship's structure and avoid damage to the handling equipment. A quality cargo handling plan increases safety in general and reduces the possibility of pollution of the marine environment.

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