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Sea Transportation of Coal Liable to Liquefaction

M. Popek
Gdynia Maritime University, Gdynia, Poland

ABSTRACT: The marine industry is a vital link in the international trade, with vessels representing the most efficient, and often the only method of transporting large volumes of raw materials. Coal is a major cargo with hundreds of millions of tons being shipped every year for power consumption and industrial uses. The vast majority of coal traded is delivered by sea. The IMSBC Code specifies requirements related to the safe stowage and shipment of coal that may give rise to relevant on-board risks, for example structural damage due to improper coal distribution, chemical reaction leading to spontaneous combustion, emission of explosive gases and liquefaction. As coal is liable to liquefaction, several precautions should be taken before accepting the cargo for shipment and procedures for safe loading and carriage should be respected. According to the analysis of the data, the proportion of fines in the cargoes shipped worldwide has been accepted as an appropriate criterion to identify the potential of a coal cargo for liquefaction.
The main purpose of this paper is to investigate the impact of coal properties on the ability to liquefy. The relation between the degree of fragmentation and the value of the TML was analyzed. In addition, the possibility of using different method for determination of the TML was discussed.

1 INTRODUCTION

1.1 *Economic aspects of coal transportation*

Shipping is the safest and most environmentally benign form of commercial transport. Throughout the last four decades, the shipping industry has experienced a trend of increase in total trade volume.

Supported by the world economic recovery in 2017, total volumes of the global seaborne trade expanded at 4 % and reached 10.7 billion tons. Nearly half of the volume increase comprised of dry bulk commodities. A dry bulk cargo (solid bulk cargo) is a commodity which is shipped in large, unpackaged amount.

These dry bulk commodities are usually divided into two categories: major bulks and minor bulks. Some examples of major dry bulk commodities include coal, ore and grain. Minor bulks include steels, sugars and cements. Coal is the second largest dry bulk commodity in terms of trade volume (behind iron ore) that transported by sea, accounting for about the 25 % of the world dry bulk trade.

Coal is a mineralized fossil fuel, mined extensively throughout the world and widely utilized as a source of domestic and industrial power. Coal which is used for power generation accounts for more than 75 % of the total coal transported by sea. Coal is linked to the energy market and its transport is affected by seasonal demand fluctuations. Coking coal, which is used for metallurgical purpose, amounts to about 25%

of the total annual volume of coal. The increase in seaborne transportation of coking coal has been primarily driven by an increase in steel production.

As a seaborne commodity, it is nearly always carried in bulk and is of considerable importance, being shipped in large quantities from Indonesia, United States' East and Gulf Coasts, Canada's West Coast, Australia, South Africa and Russia. Most of the seaborne trade of coal is confined to large bulk carriers (e.g. Panamax-size and above) hence the industry is relying on economies of scale on certain well-established trade routes. Coal markets today are very dynamic and large variety of qualities are traded. Higher import demand in China, Republic of Koreas and number of South-East Asian countries contributed to the volume increase [UNCTAD 2017].

The statistic in Figure 1 represents the volume of coal that was transported via seaborne trade between 2010 and 2017 [UNCTAD 2018].

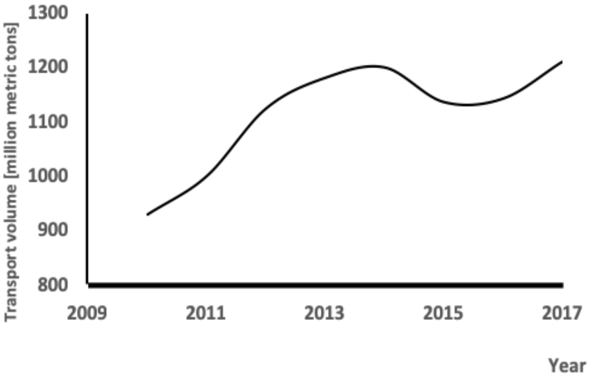

Figure 1. The volume of coal sea transportation 2010÷2017

Globally, 1.12 billion metric tons of coal were transported by sea in 2012 which showed significant increase from the 930 million tons of coal transported in 2010. Global coal trade resumed growth in 2017, increasing by 5.8% following a limited expansion in 2016 after a significant decline between 2014 and 2015.

Coal is an emission-heavy fuel and it is the target of several environmental regulations which are going into effect nowadays. Furthermore, there is a worldwide shift to renewable energy. A decrease in the consumption of coal will definitely be a big hit to the dry bulk shipping. Despite the looming environmental changes, coal still remains one of the two major dry bulk commodities and there are no signs of slowdown in its current trade volumes or its short-term prospects.

1.2 *Coal as a hazardous cargo*

Despite the carriage of coal in bulk being a long-established trade provided with a wealth of experience, it remains a difficult and dangerous cargo to transport with several major safety considerations: chemical reactions of cargo such as emission toxic gases, spontaneous combustion, cargo shifting at sea – loss or reduction of stability during a voyage, liquefaction and corrosions of ship's holds.

The International Maritime Solid Bulk Cargo Code specifies the requirements related to the safe shipment of coal that may give rise to relevant on-board risks. The current IMSBC Code includes regulations for the shipment of coal as Group B "materials hazardous only in bulk" (MHB) [IMO 2017].

Coal emits methane which when mixed with air is liable to explosions if in contact with a naked light. In certain conditions, an explosion might be augmented by a following coal-dust explosion.

Coals are subjected to heat which may lead to a spontaneous combustion. This possibility will depend on factors such as methods of handling of the coal, length of time on the ship, the ventilation provided, weather conditions and ambient temperature. If coal undergoes a spontaneous oxidation it can result in secondary hazard, which includes the production of carbon monoxide as well as other toxic and flammable gases. Carbon monoxide has no smell and is a "silent killer" because it binds to hemoglobin in blood leading effectively to suffocation. In addition, the care should be taken when dealing with coal as it is an oxygen-depleting cargo as combustion consumes oxygen. If the carbon monoxide level increases yet the oxygen does not decrease, then this indicates that the holds are not sealed effectively.

Although, the cargo surface should be ventilated to reduce the risk of gas explosion, such ventilation may encourage spontaneous combustion. Consequently, ventilation of coal must be very carefully supervised and directed at the surface area only, in order to avoid air reaching deep into the cargo.

The provision in the IMSBC Code states that "*This cargo shall only be accepted for loading when the temperature of the cargo is not higher than 55°C.*" The reason for having a maximum coal temperature limit is the fact that the self-heating reactions are like any chemical reaction hence the rate of reaction doubles for every ten degree rise in temperature. Even when the cargo was loaded with temperature below 55°C, the monitoring of the cargo during the voyage is important because the issues with self-heating may occur during the voyage.

The shipment of coal should be monitored for gas variations during the voyage. Changes in the gas concentrations will indicate whether self-heating or methane emissions are taking place.

Coals with a high Sulphur content (especially when loaded wet) are liable to create a situation whereby chemical action can corrode steel hold sides and bulkheads. These problems may be worsened if the coal temperature rises and the longer the cargo remains on the ship.

Coal is liable to shifting at sea thereby endangering the safety of the ship concerned. Cargoes with an angle of repose greater than 35 degrees are less prone to surface shift, but nevertheless need trimming to sufficiently cover the entire tank top area out to the ship's side.

2 LIQUEFACTION OF COAL CARGO

2.1 *Liquefaction in maritime transport*

Solid bulk cargoes can be categorized with regard to their hazards during shipping. Liquefaction is one of the greatest safety risks in solid bulk shipping. The most significant consequences for vessel resulting from liquefaction include cargo shift which progressively leads to a loss of stability. The consequence of the loss of stability can be such that the vessel and the lives of those onboard are lost [Andrei & Pazara 2013].

Cargo liquefaction has become one of the greatest concerns for safe carriage of dry bulk over the past ten years. Nine bulk carriers transporting ore concentrates over 10,000 dwt have been lost from 2008 to 2017. 101 crew members have lost their lives as a consequence of ships capsizing [Intercargo 2018]. Fatality numbers are speculative, as it is usually difficult to establish if the liquefaction was the cause of capsizing.

Another significant problem due to a loss of ship's stability is the pollution created by harmful properties of cargo discharged into the sea due to ship's capsizing [Cristian et. al 2015]. Cargoes at risk of liquefaction include concentrates and other fine-grain material such as coal. These cargoes usually contain a portion of fine particles that are exhibiting low permeability when compacted [Rose 2014].

During the loading, these cargoes are usually partially saturated. Forces applied by ship's motion and engine vibration cause particle rearrangement and further compaction. In addition, moisture migration leads to an increase in moisture content in part of the cargo.

The main regulation for solid bulk cargo that was developed by the International Maritime Organization is the IMSBC Code which is key instrument in mitigating the risks of cargo liquefaction. The Code is mandatory under the International Convention for Safety of Life at Sea (SOLAS). The IMDG Code categorizes solid bulk cargoes based on hazards involved. Group A are the cargoes which may liquefy.

Two important parameters, which should be determined are the Flow Moisture Point (FMP) and the Transportable Moisture Limit (TML). FMP is the moisture content at which a sample of cargo will begin to lose shear strength. The moisture content of a cargo beyond the FMP may liquefy [P&I Association 2012]. TML is defined as 90 % of the TMP.

To control the risk of liquefaction, Group A cargoes are tested at a minimum of semi-annual intervals to determine their TML.

The mandatory provision requires that if a cargo prone to liquefaction has a moisture content that exceeds the Transportable Moisture Limit it should not be loaded.

Three methods of testing for the FMP and TML are listed in Appendix 2 of the Code: Flow table test, Penetration Test and Proctor-Fagerberg test. As each method has its advantages, the selection of the test method depends on the type of cargo being tested.

The flow table is generally suitable for mineral concentrates and other materials with a maximum grain size of 1 mm. Penetration test is an alternative to the Flow table test. It is generally suitable for mineral concentrates up to a size of 25 mm and coarse cargoes such as coal.

Proctor-Fagerberg test is suitable for fine and relatively coarse –grained materials up to a top size of 5 mm.

2.2 *Risk of coal cargo*

One of difficulties with transporting large quantities of coal in bulk is that it is a cargo capable of liquefaction. Coal that is at risk of liquefaction is the one containing at least some fine particles and some moisture content. Although coal often looks dry in appearance at the time of loading, the cargo may contain moisture in between the particles. According to IMSBC Code regulation, coal is defined as a dangerous good in solid form in bulk Group B (and A) meaning that an individual coal product may exhibit either Group B properties only, or both Group A and B properties. Shipping this cargo safely is a key concern for the dry bulk industry.

At the time of loading, the coal is in solid state, where the particles are in direct contact with each other and there is physical strength of resistance to shear strains. During the sea transportation, coal is exposed to engine vibration, ship's motions and wave impact, resulting in compaction of the cargo. This leads to a reduction of spaces between the particles. If compaction is such that there is more water inside the cargo than there are spaces between particles, the water pressure inside the cargo can rise sharply and press the particles apart. This suddenly reduces the friction between particles, and thus the shear strength of the cargo [Jones & Bell 2010].

The applicable provisions of the IMSBC in the previous years included a criterion for a cargo being declared as Group A in the Hazard section as "*Can liquefy if predominantly fine 75 % less than 5 mm coal*". Furthermore, the requirement in soil mechanics literature is usually expressed as $0.003 \text{ mm} < D_{10} < 0.3 \text{ mm}$, where D_{10} represents the particle size for which only 10% of mass of the material is finer. When expressed in a form that would be more usual in the coal industry, the requirement is that approximately 15% or more of the material is finer than 0.50 mm (D_{15}) for liquefaction to be likely [Eckersley 1997]. The proportion of fines in the cargoes shipped worldwide has to date been accepted as an appropriate criterion for estimation of the potential for liquefaction of a coal cargo.

Australian coal producers and exporters have been safely shipping millions of tonnes of coal from Australia for many decades using the appropriate schedule contained in BC Code and IMSBC Code.

A few years ago, Australian industry has initiated research to study what other factors, if any, may affect coal's liability to liquefaction [IMO 2014]. The research has been designed to develop understanding of coal's stability during shipping, including the potential for cargo liquefaction.

The TML methods in the IMSBC code provide techniques to determine the TML for a range of bulk cargoes. The size distribution of the material being tested is considered an important parameter when selecting a TML test.

The project has investigated the behaviour of minus 50 mm coal cargoes because this is the material size of a typical Australian black coals but current TML tests are intended for products with smaller particle sizes. The research was focused on determination whether any coal is likely to liquefy under shipping condition and identification of a safe method to determine the TML for minus 50 mm coals.

In 2015, Australia introduced the procedure for the laboratory determination of TML for coals up to a nominal top size of 50 mm. The procedure is based on the modification of Proctor/ Fagerber test for bulk materials [IMO 2015].

Currently, the Proctor/Fagerber test described in IMSBC Code has been modified to allow application to coal with a top size of 50 mm. The research has confirmed that there are some coal types that need be declared as Group A and B products, and there are some coals that may be declared as Group B only. Criteria based on particle size distribution have been established to identify Group B only coals. Coal shall be classified as Group B only by a test determined by the appropriate authority or where it has the following particle size distribution:

– no more than 10% by weight of particles less than 1 mm ($D_{10} > 1$mm),
– no more than 50% by weight of particles less than 10 mm ($D_{50} > 10$ mm).

The main purpose of this paper is to investigate the impact of coal properties on the ability to liquefy. The relation between the degree of fragmentation and the value of the TML was analysed. In addition, the possibility of using different method for determination of the TML was discussed.

3 EXPERIMENTAL

3.1 *Materials*

The following coal cargos that came from Polish coal mines were used in the test:

– sample A: an energetic coal (particle size dimension 0÷20 mm);
– sample B: coking coal (particle size dimension 0÷20mm);
– sample C: an energetic coal (particle size dimension 0÷1 mm);
– sample D: coking coal (particle size dimension 0÷1 mm).
– sample E: an energetic coal (blend: 20% of sample A and 80 % of sample C),
– sample F: coking coal (blend: 20% of sample B and 80 % of sample D).

3.2 *Methods*

Based on these rules, the ability of coal cargoes to liquefy was assessed on the basis of determination of essential parameters: grain size distribution and the TML of tested coals.

The samples have been tested in original state as delivered. The sieve analysis has been performed and effective D_{10} and D_{50} have been determined. For all samples, the Transportable Moisture Limit has been estimated by performing the Proctor/Fagerberg test and the Flow Table test. As each of these procedures has a particular field of application, the TML of the samples of coal has been tested in the original state and after division by the sieving process.

3.3 *Results*

Grain size distribution was measured for each sample. Coal A is a coarser coal with less than 30 % particles smaller than 1mm. Coal B is relatively fine coal with more than 40 % particles smaller then 1mm.

The values of effective size D_{10} and D_{50} are presented in Table1.

Table 1. Value of effective size D_{10} and D_{50} of tested sample

Kind of material	Effective size D_{10} [mm]	Effective size D_{50} [mm]
Sample A	0,43	2,00
Sample B	0,25	1,50
Sample C	<0,06	0,088
Sample D	<0,06	0,088

Table 2. Estimation of TML

Type of concentrate	TML [weight %]	
	Proctor/Fagerberg Test	Flow Table Test
Sample A	15,1	Attempts of determination unsuccessful
Sample B	15,5	Attempts of determination unsuccessful
Sample C	16,2	23,1
Sample D	16,3	20,6
Sample E	16,1	17,5
Sample F	16,2	16,9

Criteria based on particle size distribution can identify Group A coals.

Based on the particle size criteria, coking and energetics coal coming from polish coal mines would be considered liquefiable since there are generally more than 50 % of particles of the coal finer than 10 mm and D_{10} is generally less than 1 mm.

The results of estimation of coal's TML determined by the method recommended by the IMSBC Code are presented in Table 2.

The conducted research has confirmed that tested types of coal need to be declared as Group A products. The result confirms that successful estimation of the TML by the Flow Table test is not possible when D_{10} value is larger than 0.20 mm and the maximum grain size is greater than 1mm (samples

A and B). It may be concluded that the Flow Table Test is not suitable for materials of the size representing coal cargo. Flow table test is applicable to finer materials such as coal with particle size below 1 mm represented by samples C and D.

Both the TML test results and particle size distribution confirm the functional relationship between ability to liquefy and their inherent particle size distribution. Considering the results of estimation of the TML for tested coals, it can be said that the increase of TML values is connected with increasing degree of concentrates grinding. Research confirms the impact on the TML levels when different component coals were mixed to form a blended cargo.

Significant differences between the TML values obtained by the Flow Table test and the Proctor/Fagerberg test show that the methods cannot be used alternatively. Each of the TML tests has been designed with the intension of determining the moisture content at which cargo strength is likely to be lost due to liquefaction. However, the assumption of when this occurs is different for each TML test and they each give different results. For the Flow Table test, it corresponds to the moisture content when cone strength is lost, and plastic deformation is first observed on the flow table. For the Proctor/Fagerber test, it corresponds to the moisture content at 70 % saturation.

The results of investigation confirm the need for evaluation of the modified test for estimation of the TML including repeatability, reproducibility, performance of blends of coals and relationship between test outcomes to coal particle distribution.

The findings of the Australian research confirmed that the modified Proctor/Fagerberg method is applicable for use on coal where particle sizes are up to 50mm. The test was adopted for application to coal cargoes transported in accordance with the Coal Schedule in Appendix 1 of the IMSBC Code.

4 CONCLUSION

Liquefaction is an aspect of solid bulk cargoes behaviour that occurs during sea transportation and is of considerable importance from both safety and financial standpoints. It is clear that prevention of the risks linked to transportation of solid bulk cargoes that may liquefy depend on correct measurement of the TML and moisture content of the cargo.

Inaccurate declarations and certificates from shippers appear to be a major problem with the transport of coal liable to liquefaction, though it is recognized that there are numerous complications.

The familiarity with the IMSBC Code remains essential as well as the awareness of contents of the regulations by all parties involved in coal transportation.

For all coals that do not meet criteria determined only for Group B, the Transportable Moisture Limit testing using the modified Proctor/Fagerberg method should be undertaken. It is recommended that prior to utilization of this method, coals should be firstly assessed for particle size distribution.

The adoption of the Modified Proctor/Fagerberg test to determine the TML and include screening criteria test based on particle size distribution guarantees the safety shipment of coals cargo.

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