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Technical Aspects of Shiploading Coal Slurries

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Summary

The loading of coal slurries direct into ships has many important economical advantages but the technical problems involved have not all satisfactorily been solved. The present article reviews the advantages and technical difficulties involved with this procedure and comes to the conclusion that the method will be increasingly used in future.

1. Introduction

In the last few years the following coal-shipping studies have been carried out chronologically:

a) 1978—80: The Boeing Pacific (BPAC) Bulk Commodity Transportation System was studied for the Maritime Administration to evaluate the slurry pipelining of Utah coal to California for export to the Orient. Dual 40-in. diameter pipelines, would extend 3 miles offshore with a 36-in. diameter water-return pipe, would load 6000 t/h into a 350,000 DWT ship with a 75 ft draft lying in 177-ft deep water.

b) 1980—81: New York City has contracted for engineering and environmental studies for two 30-in. diameter coarse coal slurry pipelines across North-east Staten Island to dry-load coal ships for European trade at a rate of 4000 t/h ($20 \cdot 10^6$ t/year).

c) 1982: A conference was held in Hawaii in January to examine Pacific Rim coal markets such as The Electric Power Development Corporation in Tokyo, Hong Kong, Korean, and Taiwanese utilities and industries. The suppliers are expected to be Canada (met. coal), Australia (met. and steam coal), and the US (steam coal).

d) 1982: Italy, the Netherlands, and France are scheduled to have deep draft ports of 75 ft for 350,000 DWT ships by 1985. All of Europe except the UK is expected to import coal in the 80s.

Recent port congestion on the US eastern coast has highlighted the limitations of coal exports from the eastern seaboard. The ports suffer from aged facilities, shallow drafts, built-up neighborhoods restricting expansion, labor strikes, and they are governed by authorities with conflicting and narrow interests. Despite these shortcomings, the US has considerable incentives to develop overseas trade from all coasts. Her coal is generally higher quality, cheaper to mine and transport, and more recently, due to the Staggers Act, now able to be shipped under long-term contracts.

The greatest limitation is the shallow draft of the US ports. An interim suggestion has been to use barges to top-off colliers berthed in deeper water thus alleviating the shallow draft and port congestion problems. Two longer-term and probably superior solutions are to dredge deeper channels or to load ships from single-point mooring buoys (SPM) fed by submarine pipeline. The first method is extremely expensive and time-consuming. Furthermore, Mother Nature has a bad reputation for total disrespect of dredging projects and continuously fills the holes that man digs. Also, there are conflicting authorities and environmental concerns involved with dredging projects.

The second method involving SPM buoys does not have these disadvantages. Offshore ship loading by submarine slurry pipeline is flexible in that the pipeline can be extended to depths accommodating deep-draft coal ships. However, on the shallow eastern seaboard, the pipelines become excessively long to reach carriers with drafts greater than 65 to 70 ft. The greatest drawback to the SPM buoy is that it is a new technique for coal hydrotransport and suffers from the fears of the unknown. This paper challenges those fears.

2. Technical Difficulties

In the shiploading of coal slurries approximately ten areas of technical difficulty have been identified. These are discussed in order of increasing difficulty.

2.1 Submarine Pipeline

The difficulty lies not so much with the technical difficulty in laying pipe on the ocean bed but the expense associated with such an endeavor. Slurry pipelines pose no additional problems other than being thicker-walled and carrying a heavier flow than conventional fluid hydrocarbon pipelines.

2.2 Vertical Riser

The vertical risers or under buoy hoses connect the submarine pipeline to the buoy from which the ship is loaded. The risers are projected to be as high as 30 meters (100 ft). Slurry flows in vertical risers are not as difficult to handle as horizontal flows. The total headloss is equal to the static lift plus a few percent of additional head to overcome wall fric-

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tion. For a given flowrate in a constant diameter pipe, a horizontal pipe will develop a plug before a vertical pipe plugs. The major concern is whether an emergency shutdown causes the solids to fall to the bottom of the riser in a compacted state making startup difficult or impossible. Fine particulate slurries can be fluidized by low startup flows and then worked loose as pump speeds are increased to develop higher flows and pressures. Coarse slurries present a more difficult problem.

Experimental data are extremely scarce for determining the particle size distributions of coal that are amenable to hydraulic hoisting from a shutdown condition. In practice, additional techniques would have to be available such as auxiliary ports for air or water, interconnected piping and remotely controlled valves. Since no discharge of blackwater to the sea is likely to be permitted, triple pipes in parallel will probably be standard: one for slurry, one for return blackwater, and a standby. Interconnections would provide additional flexibility of operation in the event of plugs.

2.3 Single-Point Mooring (SPM) System

The single point mooring industry spans 20 years with the last ten tears involving slurry products. Imodco designed, constructed, and brought into service in June 1971 the first SPM system for the ship loading of iron sand concentrates in slurry form at Waipipi, New Zealand for the Marcona Corporation. The SPM buoy has been sufficiently tested on iron concentrates that only minor questions arise about its service with coarse coal. These include the larger sizes required and the design of the bearing and seals of the product distribution unit for coal slurry service.

2.4 Flexible Hose System

Flexible hoses are used to connect the SPM buoy to the loading vessel for the following reasons:

a) to meet the requirement of following the ship as it orients itself in a position of minimum drag from the winds and currents.
b) they float thus allowing easy pickup by the rigging of the mooring ship for connection to the ship's manifold.
c) the hoses must take considerable abuse from the elements and frequent contact from both the buoy and the ship.

Aside from the issue of expense, the major concern with flexible hoses is their availability in larger sizes. It is difficult to purchase hoses in excess of 0.5 m (20 in) diameter. Of even more importance are the pressure forces present in a curved coal- slurry hose. From linear momentum principles, the force in a horizontal 90-degree bend carrying coal slurry at a velocity of 4.5 m/s (15 ft/s) under a pressure of 170 kPa (25 psi) is about 8 tonnes (9 short tons). Thus the breakage or accidental disconnection of flexible hoses can create dangerous conditions. For these various reasons, the loading of large vessels with loading rates up to 2,500 t/h may best be handled by two smaller pipelines rather than one large one.

2.5 Loading Sequence on Ship

The chief concern is not to overstress the ship during loading. Structural analysts have already studied the effects of shiploading ironsands. The major differences with coal slurry is its reduced density which means high volumes are required per tonne of coal with an attendant higher dewatering time. This means that in addition to proper sequencing of loading the holds, at least one, if not several, toppings have to be made before the final trimming of the cargo. Also, a special delay in dewatering time is required in the last hold to prevent overloading of the vessel from the extra weight of unwatered coal slurry.

For example, a small vessel of 100,000 DWT can be loaded in just under 100 hours at an average rate of 1,000 t/h of coal. Such a vessel is about 250 m long, has a 35-m beam, and requires about 20 m of draft when fully loaded. Its nine holds can be loaded in under 50 hours for the first loading, allowing time for dewatering. A second loading sequence then follows and finally, the holds are topped up.

2.6 Ship Modifications

A standard bulk carrier would require the following modifications for slurry loading:

a) a fitting on the bow for mooring to the SPM
b) a hoisting rig for pulling the flexible hoses on board ship near the bow
c) a piping manifold on deck for discharging the slurry to each hold in the proper sequence
d) screens in each hold for dewatering
e) piping in the hold from the dewatering screens leading to a central pump. Since offshore discharge of what could be black water, will not be legal, sufficient on-ship pumping capacity will be necessary to discharge the water back to shore.

Item (d) needs experimental work to determine the optimum sizing and spacing of the grills. Item (e) in conjunction with item (d) should not be a problem with smaller vessels but modifications of 250,000 DWT ships might be expensive enough that dedicated ships would be required. The Japanese have been the most active with designs for coal-oil slurry dedicated ships.

2.7 Energy Requirements

Heterogeneous slurries have not been as prolific as homogeneous slurries in the minerals industries. However, with the decades of success that slurry pipelines have enjoyed, there is a natural tendency to extend the art to coarser slurries. Consequently, more headloss equations are appearing for such slurries, especially coarse coal in water or a heavy medium consisting of finer coal fractions. Where mixed slurries are encountered the design approach becomes complicated.

The field of coarse coal hydrotransport is still too new to offer a sound, long-proven headloss equation. One of the more recent equations comes from Russian data and is given by:

$$i_m = i_w \left[(1 + C_v \frac{(\varrho_s - \varrho_l)}{\varrho_l} \right] + \left[\sqrt{gD} / (k C_d V) \times (\varrho_s - \varrho_{hm}) C_{vc} / \varrho_l \right] \quad (1)$$

where

i_m = hydraulic gradient of slurry
i_w = hydraulic gradient of clear water

C_v = total solids volumetric concentration
C_{vc} = coarse solids volumetric concentration
ϱ_s = solids density
ϱ_l = liquid density
ϱ_{hm} = density of heavy medium produced by fines
g = gravitational acceleration
D = inside pipe diameter
k = constant for coarse coal = 1.9
C_d = drag coefficient for coarse coal fraction = 0.75
V = mean slurry velocity

Example:

Assume a coarse coal distribution having 20 % passing 100 mesh (150 microns) is delivered as a slurry in a 0.5 m (20 in.) diameter steel pipe at a velocity of 4.2 m/s (13.8 ft/s) with a total solids concentration of 50 % by weight. The density of the dry coal is 1.35 g/cm³. What is the hydraulic gradient due to wall friction?

Solution:

Density of clear water, $\varrho_s = 1.0$ g/cm³

Density of dry coal, $\varrho_w = 1.35$ g/cm³

Total solids concentration by weight, $C_w = 0.50$

Fines concentration by weight, $C_{wf} = 0.20 \times 0.50 = 0.10$

Coarse solids concentration by weight, $C_{wc} = C_w - C_{wf}$
$= 0.50 - 0.10 = 0.40$

Density of slurry $\varrho_m = \varrho_s \cdot \varrho_l / (\varrho_s - C_w [\varrho_s - \varrho_l])$
$= 1.35 \times 1.0/(1.35 - 0.50 [1.35 - 1.0]) = 1.148$ g/cm³

Total solids concentration by volume, $C_v = \varrho_m \cdot C_w / \varrho_s$
$= 1.148 \times 0.50/1.35 = 0.4255$

The fines contribute to the heavy medium carrier which has density, $\varrho_{hm} = \varrho_s \cdot \varrho_l / (\varrho_s - C_{wf} [\varrho_s - \varrho_l])$
$= 1.35 \times 1.0/(1.35 - 0.10 [1.35 - 1.0]) = 1.0266$ g/cm³

Fines volumetric metric concentration,
$C_{vf} = \varrho_{hm} \cdot C_{wf} / \varrho_s$
$= 1.0266 \times 0.10/1.35 = 0.076$

Coarse volumetric concentration, $C_{vc} = C_v - C_{vf}$
$= 0.426 - 0.076 = 0.350$

Headloss due to water:

Reynolds Number, $Re = VD/\nu$
$= 4.2 \times 0.5 \times 10^6 = 2.1 \times 10^6$

Relative roughness, $\epsilon/D = 9 \times 10^{-5}$

Darcy-Weisbach friction factor from Stanton-Moody diagram gives $f_w = 0.0126$

Water hydraulic gradient, $i_w = fV2/2gD$
$= 0.0126 \times 4.2^2/(2 \times 9.81 \times 0.5) = 0.0227$ or 2.27 %

Headloss due to slurry from Eq. (1):

$i_m = 0.0227\,(1 + 0.426\,[1.35 - 1.0]) + \sqrt{(9.81 \times 0.5)/}$
$(1.9 \times 0.75 \times 4.2) \times (1.35 - 1.0266) \times 0.35$
$= (0.0227 \times 1.1491) + 0.04189 = 0.0680$ or 6.8 %

The slurry headloss is about three times the clear water headloss.

2.8 Deposition Velocity

The deposition velocity is high for coarse coal and increases approximately as the square root of the pipe diameter. Hence for large tonnage throughputs the deposition velocity in large diameter pipes will be quite high resulting in high operation velocities for hydrotransport. Since pumping power is proportional to the cube of the operating velocity, it is readily seen how the trade-off between dewatering costs and power costs must be balanced. In other words, particle size distribution is the key to the hydraulic transportation of solids in pipelines.

Again, as with headloss equations there is no universally accepted equation for deposition velocity. One of the more recent equations, again coming from Russian data, is given by

$$V_d = \sqrt{gD} \times \sqrt[3]{(\varrho_c - \varrho_{hm})/\varrho_c k C_d f_w} \qquad (2)$$

where

V_d = deposition velocity
ϱ_c = density of coarse coal portion of the slurry and all the other variables have been defined previously.

$\varrho_c = \varrho_s \cdot \varrho_{hm} / (\varrho_s - C_{wc}\,(\varrho_s - \varrho_{hm}))$
$= 1.35 \times 1.0/(1.35 - 0.40\,[1.35 - 1.0266]) = 1.1354$ g/cm³
$V_d = \sqrt{9.81 \times 0.5} \times \sqrt[3]{(1.1343 - 1.0266)/(1.1354 \times 1.9 \times 0.75 \times 0.0126)}$
$V_d = 3.87$ m/s or 12.7 ft/s

Allowing a suitable safety factor for a minimum operating velocity to protect against fluctuations in coal feed rates and size increases as control screens wear, a velocity of 4.2 m/s (13.8 ft/s) is picked. Notice that the top particle size is not particularly important, either for headloss or deposition velocity calculations. This is because the drag coefficient of large particles approaches a constant minimum value.

2.9 Dewatering

Dewatering is probably the second most important concern in that it affects the economics of the slurry shiploading concept. The ironsands aboard ship contain only 8 to 10 % moisture because of their high density and rapid dewatering rate. Coal is expected to exceed 10 % moisture aboard ship under gravity settling unless special dewatering schemes are used such as vibrating screens and sieve bends. Vacuum filtration is too complicated and is not considered to be cost-effective at this time.

Some limited work has been done on measuring the dewatering rates of coals, but these data can serve only as rough guidelines. Dewatering rates are usually measured with small coal-slurry samples in tall, narrow cylinders that bear little resemblance to a ship's hold.

Table 1 gives the results of drainage tests using a Colorado coal of specific gravity of 1.51 and slurry sample sizes of 4 kg at 50 % solids by weight.

With just plain gravity settling, it appears that a moisture level of less than 10 % will be idealistic. Values up to 15 % should be considered acceptable providing the coal has been washed and/or beneficiated to upgrade its properties. The moisture levels in all cases are based on a total slurry

Table 1: Coal moisture (%) after 1-hour drainage tests
(M = Tyler mesh)

Size	50 mm × 100 M	50 mm × 200 M	50 mm × 270 M	50 mm × 325 M	50 mm × 0
%	15.2	18.8	18.3	14.8	17.8

Table 2 gives the results of drainage tests using a foreign coking coal. Final moisture levels are reached essentially after two hours.

Table 2: Coal moisture (%) after 2-hour drainage tests

Size	1.0 mm × 0	1.32 mm × 0	1—50 mm	1.32—50 mm
%	32	29	7	7

weight. The 1.32 mm × 0 coal size in Table 2 approximates the size distribution of the Black Mesa coal slurry. The 1—50 mm and 1.32—50 mm coal sizes in Table 2 were subjected to a half-hour recirculation of the drainage water which changed the void structure of the coal resulting in a cleaner effluent. Whether or not this is characteristic of most coals in not known, so further work would be necessary to verify this phenomenon.

2.10 Emergency Shutdown/Startup

Coarse slurries are more difficult to pump than fine slurries, a well known, almost incontestable statement. High transport velocities are required for coarse slurries with their attendant pressure transients and high power consumption. These difficulties can be designed for, but the most serious problem is the startup of a coarse slurry after an unplanned shutdown.

Shutdowns can occur from power failures and mechanical failures on pumps and drives or pipeline components. Also the ship's captain has the prerogative to shut down the slurry flow if the loading technique is overstressing the vessel. If the pipeline cannot be flushed with clear water prior to shutdown, then flow cessation results in a slurry-filled pipe. A velocity of 4 m/s requires over an hour to travel 16 km (10 mi). Consequently, proper clear water shutdowns are not a swift procedure.

The major problem in coarse coal shiploading is the necessity to design a particle size distribution that can be started up from a stationary bedload in a pipe. The coarser the coal and the longer the pipeline, the more difficult it is to restart the flow. Pump startups have to be slow to develop low flows and low pressures by variable speed drives so that the bedload is not pushed along (the snowplow effect) but is sheared across the upper layers by progressively faster velocities. A minimum amount of coal fines is required to increase the viscosity and density of the liquid carrier to enable it to pick up and support coarser particles. Coarse coal particles are angular and plate-like in shape and can develop a certain degree of mechanical interlocking thereby requiring a larger shear stress to dislodge them. Thus, a fairly wide size distribution is required to permit this pickup by shearing. Yet excess fines slow the dewatering rate on board ship. Therefore, a compromise is required in sizing the coal to allow good slurry restart capabilities, acceptable dewatering rates, and if lucky, good filtering characteristics aboard ship so that much of the fines are retained and do not return with the black water pumped back to shore.

Unfortunately, there has been extremely little test work performed in this area. Some limited test work on coarse coal hydrotransport is being carried out or planned in the US (by the US Dept of Energy, Bruceton, PA), Japan, Holland, New Zealand, and Australia.

3. Some Not-So-Wild Ideas

In the preceding list, two items were not discussed; degradation of the coal, and slurry unloading of the coal. Slurry unloading has not received the same attention as slurry loading for the obvious reason that it is a secondary event chronologically in the concept. It will not be discussed here. Likewise, degradation is put aside in the belief that the use of large centrifugal pumps, the short distance of transport, and the wide size distribution of the coal will not produce significant degradation. This question may still be open for debate, but based on some limited experience, the author does not anticipate a significant degradation of the coal.

In the ten areas, some ideas have surfaced recently which may ameliorate some of the technical difficulties.

a) Recognizing that start-up of a coarse coal slurry may be extremely difficult, the obvious solution is to moderate the coarseness by extending the size distribution to finer sizes and accepting the increased penalty for dewatering. Additional dewatering stages can be implemented to speed up the process. For example, two-stage screening involving vibrating screen decks and sieve bends could be placed on board the ship.

b) Extending this idea further, an even finer coal slurry could be pumped aboard ship, dewatered by the two-stage screening and gravity settling system as mentioned above. The black water could be returned for on-shore thickening and then added back to the main slurry stream for topping off the holds. However these extra steps require experimental work to determine their effectiveness.

c) The reduced coal size suggests that additional water will have to be accepted for shipping. In that case, this should give impetus to shipping a higher grade coal, either washed, or beneficiated to reduce sulfur and ash. This would upgrade the calorific content per unit mass and make more tolerable the higher moisture content. There appears to be sufficient evidence that foreign buyers are more interested in the reliability of coal shipments than the quality of the coal. Therefore, higher moisture contents presumably will be tolerated, if shipments become more reliable.

d) Along with beneficiation come the thoughts of black magic, i.e., the use of chemical additives, and/or air to reduce hydrophobicity, flocculate fines, thin out slurry viscosity, stabilize the slurry, and so forth. Some of these concoctions include: coal-oil-water emulsions; highly concentrated, specially pulverized coal-in-water mixtures; enlightened coal slurries; and coal-water-oil mixtures wherein the oil causes the coal fines to ball up for easier dewatering. The first three slurries need no dewatering, the latter one only limited dewatering.

e) At this point, there is such a marvelous product on-board ship that it can be readily slurried off-ship and burned directly in slurry form. If it cannot be slurry unloaded, it can still be bulk-unloaded in a conventional manner.

Most of these ideas are receiving serious consideration and in some cases, substantial amounts of money and effort have been expended on preliminary studies. It appears to be only a matter of time before some of these ideas will reach fruition and increase the economic and technical feasibility of coal-slurry shiploading.