New high capacity discharge system for self-unloading ships

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Summary

A new type of pneumatic unloading system for self-unloading ships is being introduced and compared with existing systems. The new unloading system uses a large-volume pressure vessel in each cargo hold which is filled via a screw arranged in the vessel itself and which conveys out of the cargo hold directly to the storage silo located ashore, without transfer points. Several of these senders are connected with each other in such manner that a quasi-continuous unloading takes place: One sender is filled while another conveys. The new system is suitable for fine-grained bulk solids, such as cement. Compared with other conventional systems, it is operated with two-stage compressors and is characterised by a clearly lower specific energy consumption at simultaneously higher unloading mass flows and considerably lower numbers of switching cycles of the discharge vessels. The structure of the new system will be described and discussed in detail.

Introduction

The main requirements of unloading systems for self-unloading ships transporting bulk solids are:

- High discharge flow rate
- Low specific power consumption
- High availability, i.e. long lifetime of valves, wear parts, etc.
- Matching different port setups
- Easy to maintain
- Simple design, easy to operate
- Low space requirement

In the case of unloading systems for fine-grained/dust-like solids, these requirements have to be supplemented by appropriate measures in order to prevent dust nuisance. Here, closed systems are required with a minimum of transfer points ashore as well as on the ship. In particular, the latter requirement has led to an increased use of pneumatic conveying systems for unloading of fine-grained bulk solids, though their specific energy consumption is generally higher than that of mechanical systems.

This article will provide a description and discussion of three exemplarily chosen unloading systems for fine-grained solids available on the market, followed by a comparative analysis of the newly developed system. Cement is assumed as the unloaded material in all cases.

Existing unloading systems

The systems used for comparison are shown schematically and strongly simplified in Figures 1-3. Transport to the storage silos ashore is realised pneumatically. The connection with the systems on board the ship is realised by means of flexible hoses. Usually two parallel conveying lines on shore are used. The cargo holds of the ships are equipped with a gas-permeable aeration bottom, which is inclined by approx. 10° to a central discharge point and is aerated section-wise in such manner that at all times a continuous flow channel forms to the discharge point. The aeration dissolves the friction lock inside the bulk solid close to the bottom and on the bottom itself so that the material flows to the outlet due to the load of the material column. Only during residual discharge is the bulk solid/cement fully fluidized [1].

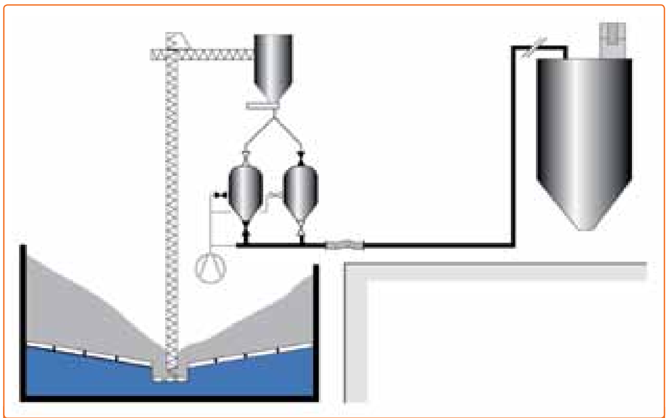

Figure 1. Unloading system 1: Vertical/horizontal screws + twin-pressure vessel conveyance.

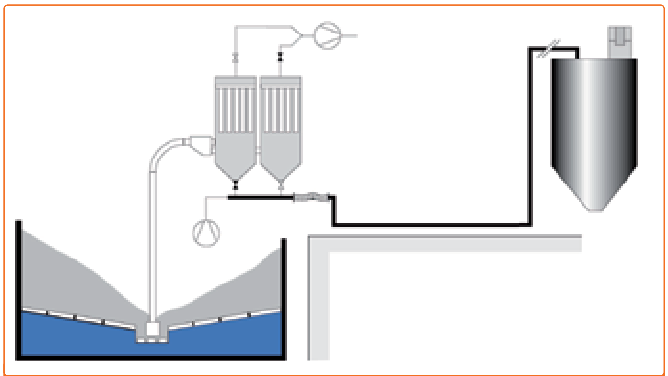

Figure 2. Unloading system 2: Combined suction/positive pressure conveyance.

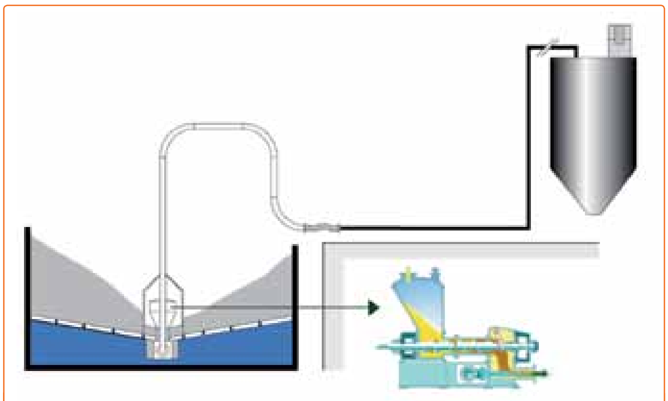

Figure 3. Unloading system 3: Conveyance with screw feeders.

In system 1, shown in Figure 1, the cement is removed from the respective cargo hold by a stationary vertical screw, handed over to horizontal screws and fed to the pre-bin of a twin pressure vessel system. While one vessel conveys, the other one is filled. One-stage compressors are used so that a conveying pressure of max. p_V = 3.5 bar(g) can be realised. The number of revolutions of the vertical screw, required for an economic operation, lies above $n_{VS} \cong 300\ min^{-1}$ due to the functional principle. The relatively high available conveying pressure in combination with the pressure vessel feeding enables the system to react flexibly to the requirements of the transport facilities on shore, for example with regard to different distances and/or pipe diameters. A further advantage is the reduced overall energy consumption due to the mechanical conveying equipment on board the ship. Due to the limited space available along with the required pre-bin, the single pressure vessels are realised with effective volumes of approx. 10 m³ and less. From this a relatively high number of cycles results which causes considerable strain on the valves switching in contact with the bulk solid. Example: 300 m³ cement/h / (2 vessels · 10 m³/vessel) = 15 cycles/(vessel · h).

The discharge of bulk solid from the different cargo holds in system 2 (Figure 2) is realised by stationary pneumatic suction conveyance, ending directly in the vessels of a twin-pressure vessel system, both equipped with an integrated filter systems. While the bulk solid is drawn into one of the vessels, using a max. underpressure of approx. 0.8 bar = 0.2 bar(abs.), the contents of the second vessel are conveyed to the storage silo. For this purpose one-stage compressors, $p_V \leq 3.5$ bar(g), are used. The suction/pressure conveying line forms a closed pipe system with only one transfer point. Since the number of pressure vessel cycles/time is similarly high as in system 1, the valves are activated with a similar frequency but at the higher pressure difference (4.5 – 0.2) bar = 4.3 bar. The outlet valves into the positive pressure conveying line have shown to be extremely sensitive. The energy consumption of a pneumatic suction conveyance is clearly higher than that of a positive pressure conveyance. All in all this is a system with a very complicated structure.

In system 3 (Figure 3), the bulk solid is fed laterally to a screw

	ADVANTAGES	DISADVANTAGES
SYSTEM 1	• High flexibility of twin pressure vessel system and positive pressure conveyance • Reduced power consumption due to mechanical screw transport on ship	• Maintenance intensive due to small vessel sizes and high cycle numbers • Different transfer points • Pre-bin necessary
SYSTEM 2	• Closed pneumatic conveying system from cargo hold feed point to silo; only one transfer point	• Higher specific power consumption due to suction conveyance • Maintenance intensive complicated system, especially due to discharge valves
SYSTEM 3	• Closed positive pressure conveying system from cargo hold feed point silo	• Limited conveying pressure of screw pumps ≤ 2bar (g) • Bigger pipes are necessary for a given solid mass flow • High power consumption of screw pump
Conclusions/Consequences: • Positive pressure conveying system • Closed conveying pipe from cargo hold to silo without transfer points • Pressure vessel feeder with a low number of cycles / of a bigger size		

Figure 4. Advantages and disadvantages of existing unloading systems.

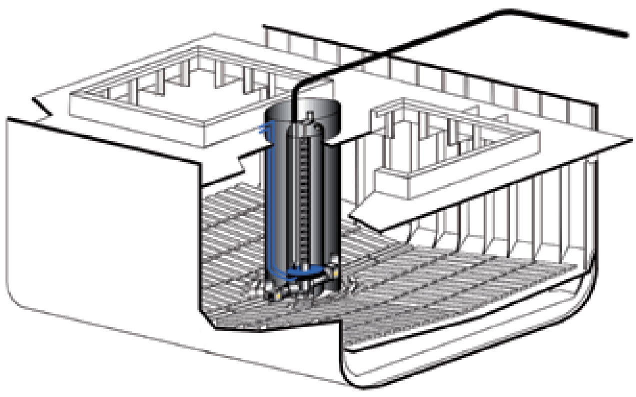

Figure 5. New unloading system: arrangement in the cargo hold.

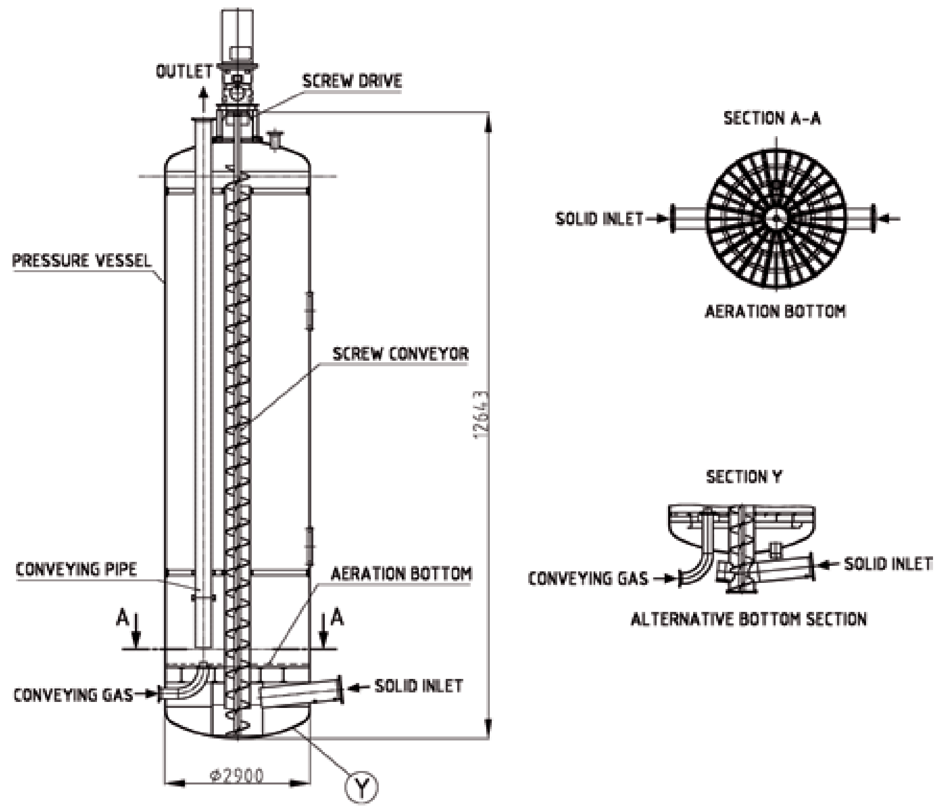

Figure 6. Simplified illustration of the unloading vessel.

feeder allocated to each cargo hold and installed in an accessible duct. This feeder, which is colloquially called a 'screw pump', is a compression screw system with a high number of revolutions, $n_P \cong (500 - 1{,}500)\ \mathrm{min}^{-1}$, whose screw duct is completely filled with bulk solid. The sealing of the conveying pressure is realised by the moved bulk solid in the screw. Conveying line = feeder pressure differences of up to approx. $\Delta p_R \cong 2.0$ bar are possible. During start and shutdown a check flap seals off the screw duct. Details on the functional principle are given in [2]. The bulk solid is conveyed to the storage silo directly from the cargo hold. The plant structure is extremely simple and the material is conveyed continuously. The main disadvantage is the limited conveying pressure, which results in a bulk solid throughput $\dot{M}_S$ clearly lower than that of systems 1 and 2 at a given conveyor pipe diameter D_R and necessitates a bigger D_R for a given $\dot{M}_S$. Since the screw feeder requires its own drive motor, the energy consumption of the plant rises.

Figure 4 shows the main advantages and disadvantages of systems 1-3 and the resulting consequences for future developments. The latter are, inter alia: the execution of the unloading system as a positive pressure conveying system with a continuous conveyor pipe from the unloading point to the storage silo, no bulk solid transfer points, solids feeding with pressure vessels, reduction of cycle times by large-volume senders.

New unloading system

The transport system described below is a result of the above mentioned analysis of the unloading process of fine-grained bulk solids from self-unloading ships and the unloading systems available for this, supplemented by the respective economic calculations.

Plant structure

Figure 5 shows the arrangement of the system inside the cargo hold; Figure 6 shows the principle structure of an unloading pressure vessel.

A single pressure vessel is allocated to each cargo hold, equipped with an aeration bottom/system. This vessel is installed inside an accessible vertical duct and is filled with bulk solid by a vertical screw integrated in the vessel. The solid is fed to the screw from two sides via aeroslides either directly or via a pre-chamber, which lifts the material into the discharge area of the vessel. This discharge area is closed at the bottom

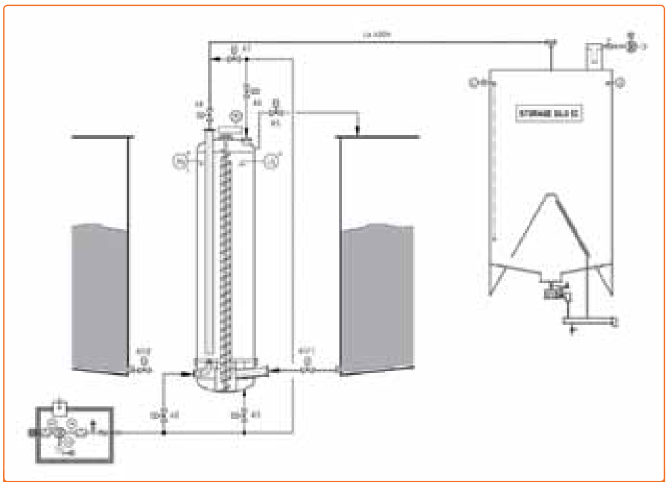

Figure 7. New unloading system: flow sheet of single vessel.

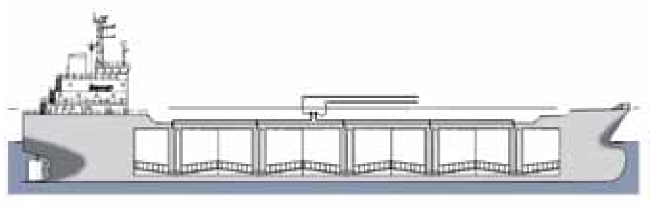

Figure 8. New unloading system: arrangement in the ship.

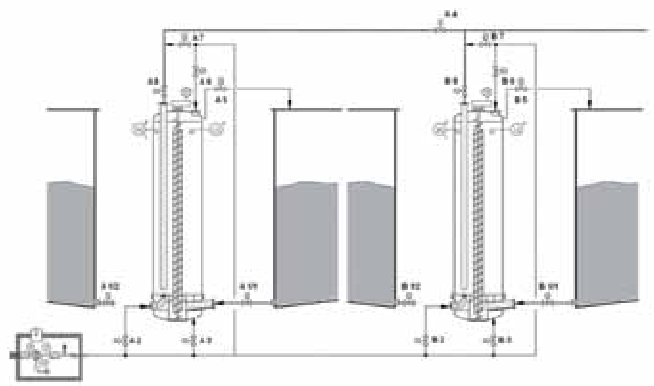

Figure 9. New unloading system: flow sheet of a twin vessel arrangement.

Figure 10. Test installation vertical screw.

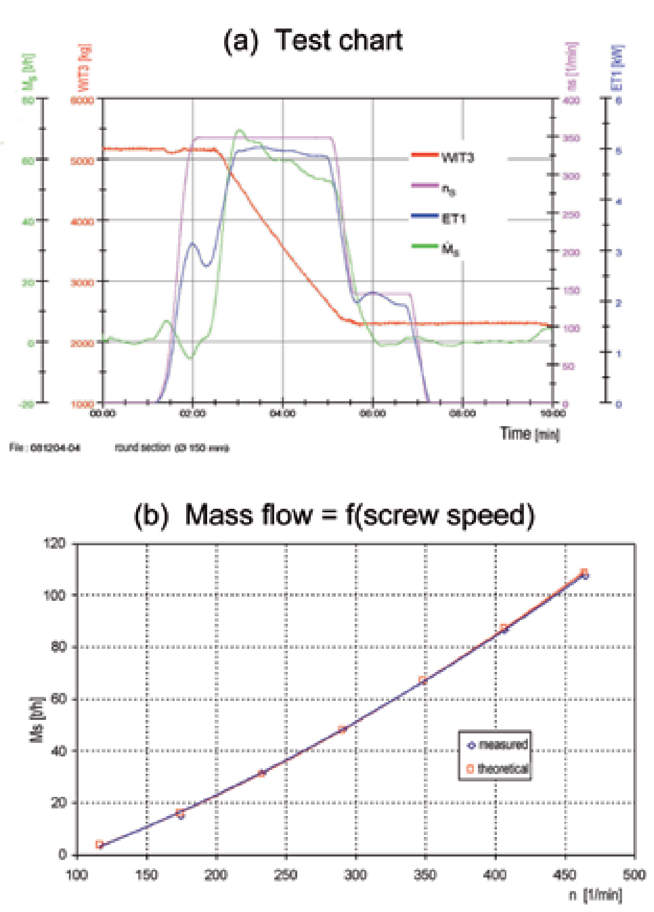

Figure 11. Test results vertical screw: 11a) Test chart. 11b) Mass flow = f(screw speed).

side by an aeration bottom and contains the conveying pipe, whose inlet is arranged above the bottom and is supplied separately with conveying gas. Filling of the sender with bulk solid is accomplished in a non-pressurized condition. After full level indication the screw is stopped, the shaft passage to the surroundings is sealed with an inflatable sealing and the vessel is pressurized from the bottom and the top to a pre-selected conveying pressure. By opening the bulk solid outlet valve and the gas supply to the conveyor pipe, the pneumatic transport is initiated. During transport, the aeration bottom is continuously fed with gas. Complete emptying of the vessel is detected by a pressure sensor, which initiates a residual pressure release. Afterwards the next filling process starts. A single vessel plant flow sheet is shown in Figure 7. The net filling volume of the single sender amounts to $V_{PV} \cong 60$ m^3, the screw diameter is $D_S \cong 500$ mm, the screw speed runs at $n_S \geq 350$ min^{-1}.

The single vessel described conveys discontinuously: Filling and discharge processes alternate. Through parallel connection of two or more vessels to a common conveyor pipe, a quasi-continuous operation can be adjusted. Figure 8 shows the arrangement of the single senders on the ship, while Figure 9 illustrates the connection of two of theses pressure vessels to a twin vessel arrangement: One of the vessels is being filled while the second one conveys. For this type of arrangement the number of conveying cycles/time runs at 300 m³ cement/h/(2 vessels · 60 m^3/vessel) = 2.5 cycles/(vessel · h), i.e. it is far lower than in the compared systems 1 and 2. It can be flexibly decided which vessels can be connected with each other and to which conveying pipe, depending on the requirements of the unloading/ship operation.

Examination of vertical screw

The pressure vessel conveyance of fine-grained bulk solids, such as cement, is a typical task performed by Claudius Peters (CP),

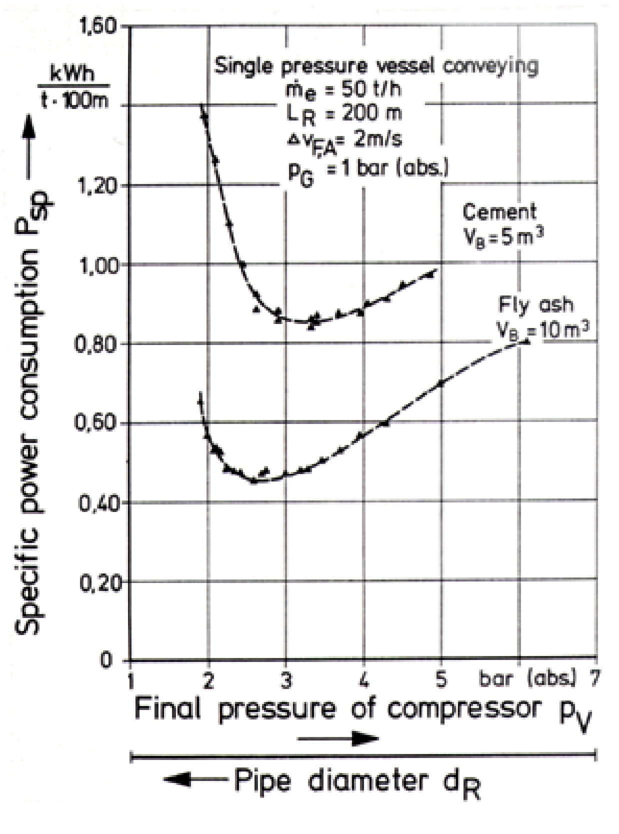

Figure 12. Example of optimisation of a pneumatic conveying system.

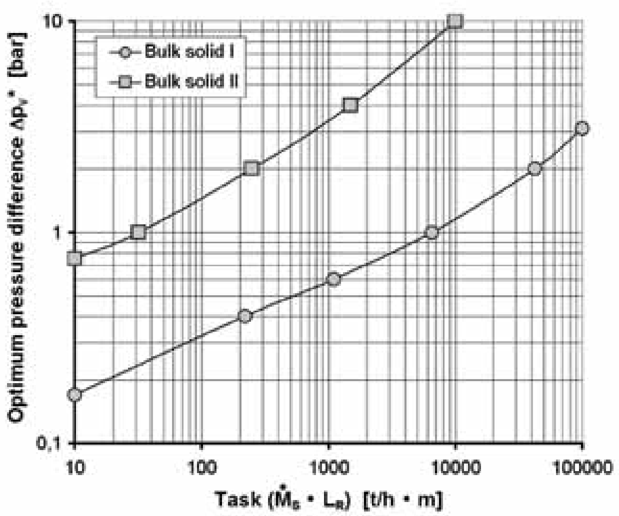

Figure 13. Dependency of the minimum energy conveying pressure p^*_V on the task ($\dot{M}_S \cdot L_R$).

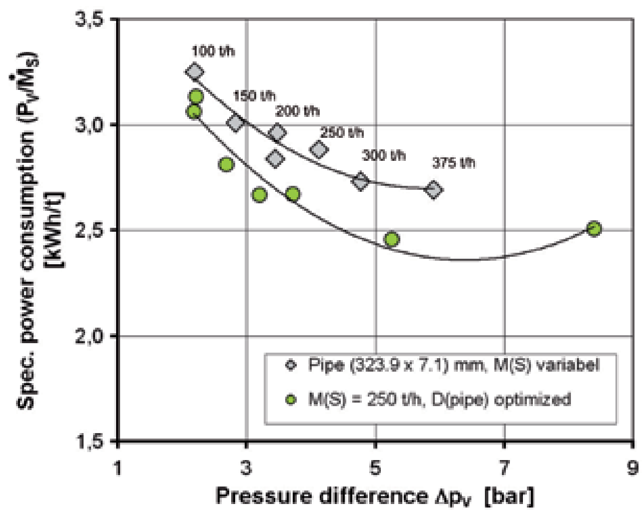

Figure 14. Optimisation of the new unloading system.

and they possess a wide range of experience and references at their disposal in regards to this. Thus, only examinations with regards to vertical screw conveying behaviour under operating conditions were required. For this purpose, a test plant designed to technical scale was installed in the CP Test Centre and systematic measurements were carried out [3]. The vertical screw dimensions used were:

Screw diameter D_S	: 250 mm
Conveying height H	: 6,716 mm
Shaft diameter D_i	: 60 mm
Screw speed n_S	: 50-500 1/min
Installed power P_S	: 11 kW

Figure 10 shows the supply of the bulk solid to the screw inlet/screw base. The solid (cement), is taken from an aerated silo and fed via an aeroslide directly to the screw. This corresponds to the situation in the real unloading plant. By variation of the fluidizing gas velocity of the aeroslide, different inlet densities ρ_b to the screw can be adjusted and examined with regard to their effects, for example on the intake behaviour. Since the vertical screws are volume conveyors, this also influences the mass throughput $\dot{M}_S$.

Figure 11a shows an example of a measuring strip chart. For pre-defined boundary conditions, such as: the type of bulk solid, inlet density ρ_b, screw speed n_S, and height of bulk solid level inside the silo, the following, amongst other things, has been recorded: the changes of the weight WIT3 of the pre-bin over time, calculated from this the current mass flow $\dot{M}_S$, the speed of the screw n_S and its power consumption ET1. Figure 11b shows the dependency $\dot{M}_S$;= $\dot{M}_S$ (n_S) measured with the bulk solid (cement) for a defined operation setting. Below a critical speed $n_{S,crit} \cong 100$ min^{-1},the screw does not take on any more bulk solid. The cause for this is that the axial transport in vertical screws can only start when the bulk solid forms a sufficient friction lock with the wall of the surrounding pipe, i.e. the solid first needs to be moved towards the wall by the centrifugal force acting on the solid. To this end, a minimum speed of $n_{S,crit}$ is required. Up to $\dot{M}_S \cong 110$ t/h at $n_S \cong 460$ min^{-1} have been conveyed with the DN 250 screw examined in this test series.

A calculation programme was developed [3] at the same time as the tests, based on the available theory [i.a. 4, 5], which describes the transport process in vertical screw conveyors. This programme calculates the dependencies $\dot{M}_S = \dot{M}_S(n_S)$ and $P_S = P_S(n_S)$, i.e. solids throughput and the respective screw drive power, for the task at hand. The programme can be adjusted to any bulk solid by means of a set of reference measurements. Figure 11b shows that $\dot{M}_S$ (n_S) measurement consistency and calculation for cement is excellent, while that of $P_S(n_S)$ is comparatively good.

Optimisation of pneumatic conveyance

Pneumatic conveying systems can be optimised energetically; this also applies for dense-phase conveyance. The generally high-energy consumption of pneumatic conveyances was the reason for analysis and optimisation of the system planned for the above-described application with regard to possible energetic savings.

A given task (bulk solid, solids mass flow $\dot{M}_S$, conveying distance L_R) can be fulfilled by different combinations of pipe diameter D_R, and conveying pressure p_V . A large D_R leads to a small p_V and vice versa. A defined conveying gas flow and thus

System		1	2	3	New I	New II
Consisting of		Screw conveyors, twin pressure vessel conveyors	Combined suction and positive pressure systems	Screw pump conveyors	Pressure vessel conveyors with internal filling screw	
Total conveying length	m	-	-	430	440	440
Total height	m	-	-	40	55	55
Length on shore	m	350	350	350	350	350
Height on shore	m	40	40	40	40	40
Inner pipe diameter	mm	309.7	309.7	339.6	309.7	309.7
Capacity/pipe	t/h	200	200	160	200	300
No. of discharge pipes		2	2	2	2	2
Total capacity	t/h	400	400	320	400	600
Necessary air pressure	bar(g)	3.5	3.5 / 80% vacuum	2.5	3.5	5.0
Discharge power consumption	kW	1465	1680	1352	1390	1896
Specific power consumption	kWh/t	3.66	4.20	4.23	3.47	3.16

Figure 15. Energetic comparison of different unloading systems.

- **Reduced power consumption / power costs**
  Example: Comparison of system „1" and system „New II" gives = 0.50 kWh/t
  Cost savings/year = 15,000 t/ship • 50 ships/a • 0.50 kWh/t • 0.1 EURO/kWh = **37,500 EURO/a**
  ⟹ **Further benefits in case of optimum selected pipe diameter**
- **Time savings for unloading**
  Example: time savings/year = (15,000/400 - 15,000/600) t/ship/t/h • 50 ships/a = **625 h/a**
  ⟹ **12.5 h/ship**
- **Reduced maintenance**

Basic data: 15,000 t Cement/ship ; 50 journeys/a ; 0.1 EURO/kWh ;
$\dot{M}_s(1)$ = 400 t/h ; $\dot{M}_s$(New II) = 600 t/h ; 12" pipe

Figure 16. Main advantages of the new unloading system.

a defined power consumption P_V of the pressure generator are allocated to each (D_R, p_V) combination. The function $P_V = P_V(D_R, p_V)$ passes a minimum at an energetically optimal conveying pressure p_V^* or an energy-minimised combination (D_R, p_V^*), as shown in Figure 12 on the basis of a specific application. The value of p_V^* is not a constant specific to the bulk solid, but depends on the specific task ($\dot{M}_S \cdot L_R$). With increasing product ($\dot{M}_S \cdot L_R$), p_V^* also increases [6]. Figure 13 shows this correlation.

For different variants of the task at hand, optimisation calculations were carried out. The specific boundary conditions for the calculations are:

Bulk solid	: Cement
Ship size	: 12,000 dwt – 16,000 dwt 4 cargo holds Aeration bottom with 10° inclination
Pneumatic conveying lines	: 2 pipes on shore
Length on shore	: 390 m including 40 m height
Total length	: 440 m including 55 m height and 6 x 90° bends
Conveying pipe diameter	: D_r = 309.7 mm (pipe 323.9 mm x 7.1 mm / 12")

The material conveyed is cement. First the case of a landside existing conveying line D_R = 309.7 mm = 12" is discussed before the case of building a new conveyor pipe for a mass flow of $\dot{M}_S$ = 250 t/h will be considered. Figure 14 shows the dependency of the specific energy consumption ($\dot{P}_V$ / $\dot{M}_S$) on the compressor pressure difference Δp_V for both cases. The top curve describes the case D_R = 309.7 mm = constant: The bulk solid mass flow increases along this curve from the left, $\dot{M}_S$ = 100 t/h, to the right to $\dot{M}_S$ = 375 t/h. With increasing conveying pressure p_V or throughput $\dot{M}_S$, the energy required for the transport of a mass unit bulk solid decreases. Energy-optimal operating points lie within the range of $p_V = \dot{P}_V \cong (5 - 6)$ bar(g), i.e. two-stage compressors are required. The max. throughput which can be reached with a one-stage compressor, $p_V \leq 3.5$ bar(g), amounts to $\dot{M}_S \cong 200$ t/h for the defined pipeline. This is confirmed through practical experiences. At a conveying pressure of $p_V \cong 5$ bar(g), a solids throughput of $\dot{M}_S \cong 300$ t/h is possible with simultaneously lower specific energy consumption. Higher throughputs are not realistic due to the transport velocities at the end of the pipeline, which would be excessively high.

Along the lower curve in Figure 14, the cement mass flow $\dot{M}_S = 250$ t/h is conveyed with different conveying pressures p_V through pipelines with different diameters D_R. Stepped as well as non-stepped pipelines have been considered. It is obvious that conveyances with minimum specific energy consumption require a high conveying pressure, in this case $p_V^* \cong 6$ bar(g). The conveyor pipe diameters in this case are correspondingly small. For example: At a conveying pressure of $p_V \cong 5.3$ bar(g) a two times stepped pipeline D_R = 260.4 mm / 309.7 mm (pipes (273.0 x 6.6) mm / (323.9 x 7.1) mm) is required. Comparative calculations with changed/increased bulk solid mass flows $\dot{M}_S$ and other conveying distances L_R also show, as a result, that the task at hand is solved with lower energy input when the conveying pressures are higher than those used up to now. Figure 14 also shows that in case of new installations on shore, the energy consumption can be additionally reduced by an optimised adjustment of the pipeline diameters to the current operating data of the ship. The previous analysis has considered the compressor systems of different manufacturers. All calculations have been made possible with the CP calculation program for pneumatic conveying systems.

The consequence of the above examinations is that the new CP unloading system will be equipped as standard with a two-stage compressor and conveying vessels with 6 bar(g) admissible operating pressure.

Comparison of systems

Figure 15 shows the energetic comparison of systems 1-3, discussed earlier, and the new system for the defined task already illustrated in Figure 14. The new system is equipped with a one-stage compressor – "New I" and a two-stage compressor – "New II". The total power consumption during the unloading process is indicated, for which have been considered: the power consumption of the individual cargo hold aeration systems, the pressure generator for the pneumatic conveyances, the drives of the mechanical transports, the filter systems on board of the ships, as well as the required auxiliary aggregates. Data for systems 1-3 are based on the operating values of executed plants.

The comparison of systems 1, 2 and "New I" shows that max. $\dot{M}_S \cong 200$ t/h cement/pipe can be unloaded with a 3.5 bar(g) compressor through a conveyor pipe of 309.7 mm. In system 3, equipped with screw pumps, a throughput of only $\dot{M}_S \cong 160$ t/h cement/pipe is possible due to the restricted conveying pressure for screw pumps, despite that pipeline diameter is increased to D_R = 339.6 mm. The lowest specific energy consumption for the use of a one-stage compressor is required by the system "New I" with ($P_V / \dot{M}_S$) = 3.47 kWh/t, followed by system 1 with ($P_V / \dot{M}_S$) = 3.66 kWh/t. Systems 2 and 3 lie within the range of 4.2 kWh/t.

By use of a two-stage compressor and operation with $p_V \cong 5$ bar(g) system "New II", the throughput can be increased to $\dot{M}_S \cong 300$ t/h cement/pipe and the specific energy consumption can be reduced to ($P_V / \dot{M}_S$) = 3.16 kWh/t. Compared to system 1, an energy amount of 0.50 kWh per tonne of unloaded cement is saved this way and the unloading times of the ships can be reduced to approximately two thirds of the previous unloading times. Calculations with other conveying lengths show similar results.

Figure 16 summarises the main advantages of the new system and tries to evaluate these in figures. In particular, the energy costs could still be reduced considerably by optimising the conveyor pipe diameter on shore. A dimensioning of these pipes to even higher bulk solid throughputs is possible. The low number of pressure vessel cycles/time allows such an increase. For example: conveying distance and boundary conditions such as in Figure 15; pipe twice stepped: D_R = 309.7 mm / 339.6 mm inner diameter; solids mass flow/pipe: 350 t/h, total capacity: 700 t/h; final pressure of compressor: $p_V \cong 5$ bar(g). These data result in a specific power consumption of ($P_V / \dot{M}_S$) = 2.85 kWh/t and a reduction of unloading times to 57 per cent of the 400 t/h case.

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