THE ARCHIVE OF MECHANICAL ENGINEERING

VOL. LV 2008 Number 2

DOI: 10.24425/ame.2008.131620

Key words: product tankers, chemical tankers, hydraulics, flow control, drive, liquid cargo properties

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THE INFLUENCE OF LIQUID CARGO PROPERTIES ON THE DISCHARGE RATE OF SUBMERGED CARGO PUMPS WITH HYDRAULIC DRIVE ON MODERN PRODUCT AND CHEMICAL TANKERS

The paper presents the influence of different liquid cargo properties on discharge rate of hydraulic submerged cargo pumps on modern product and chemical tankers is presented in the paper. Main parts of submerged cargo pumps and hydraulic drive system are described. Some examples of technical solutions of the described systems installed on board of the newly building constructed ship m/t 'Helix' are presented. The formula of use application of flow and drive characteristics of cargo pumps is given. These characteristics were made derived for a basic cargo (fresh water) for the case of the service of a real cargo of different viscosity and density.

1. Introduction

In the 20^{th} century, the majority of petroleum-based liquid cargoes and chemicals are transported by sea. This is the result of large distances between the locations of refineries, petroleum terminals, and the industrial centers in the USA, Europe or in the Far East. Moreover, there are specialized ships, called the product and chemical tankers, which are used for transporting these liquid cargoes. The structure of the above mentioned vessels is characterized by partition of the loading- part into many separate, smaller cargo tanks. Additionally, each cargo tank is equipped with a separate submerged cargo pump, designed for liquid cargo service. Such an idea of cargo system allows for simultaneous transport of diverse liquid cargoes during one sea voyage. The described cargo installation, with many different segregations on board, is very flexible in operation. It permits better use of cargo tanks capacity and

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better adjustment to individual requirements of customers and brokers. It is worth noticing that in a typical harbor, there are many different liquid cargoes that are transported by the sea, however, the quantities of these products are small. It results from growing diversification and strong competition on the freight market of liquid cargoes transported by the sea. On the other hand, transport of special cargoes (e.g. toxic, dangerous, aggressive ones) brings high profits to the shipowner, although such cargoes usually appear in small quantities in standard harbours. Therefore, the above-mentioned cargo system solution enlarges the competitiveness of such a product and chemical cargoes, and increases its profitability in exploitation. The example of such type tanker is the product tanker of B578-I/1 class, m/t 'Helix', built in the Szczecinska Shipyard S.A. (Szczecin, Poland) for the well-known ship-owner 'SHELL' from Australia (see Fig.1). The above mentioned tanker is equipped with 20 separate cargo tanks of various capacity (from 1534.4 – to 4719 [m3]) and two slop tanks (with a capacity of 253 – 471.9 [m3]). Cargo tank system is served by 20 separate FRAMO/Norway submerged cargo pumps. 16 of them have nominal discharge flow of 500 [m3/h] with load of 135 [mlc] – sp.g. 0.85 and kinematic viscosity of 1.0 [cSt], and 4 pumps – 300 [m3/h] each. Additionally, two slop tanks are served by 2 cargo pumps of discharge flow 200 [m3/h] each. However, the a/m cargo pumps are mounted inside the cargo tanks in a dangerous environment due to the possibility of explosion [3],[4],[5]. Therefore, a hydraulic drive system is commonly used there, as it is safer than the alternative solution with electric motors. Because the distance between cargo pumps and other hydraulic receivers mounted on the

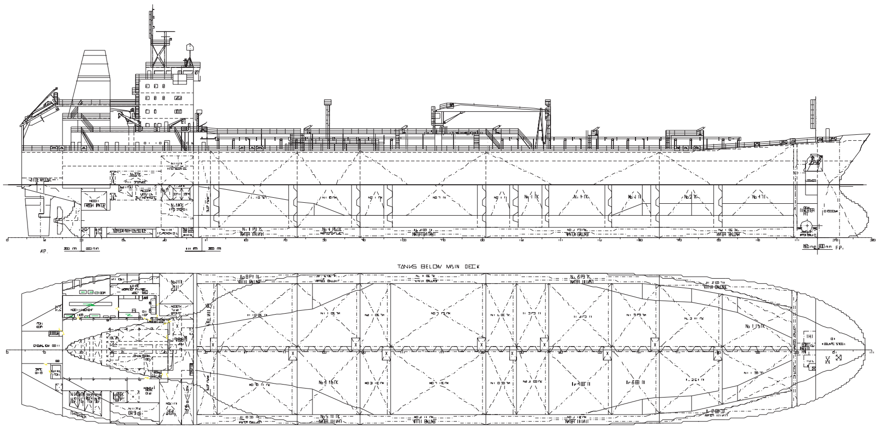

Fig. 1. View on the product tanker B578-class m/t "Helix" built in Szczecinska Shipyard /Poland for the Owner SHELL – Australia

deck is not too long, individual hydraulic feeding systems are, in this case, too expensive [6] and are not applied in the shipbuilding practice. As a more convenient one, the hydraulic central loading system is installed.

Cargo pumps are usually of centrifugal 1-stage type. They are designed for direct installation inside the cargo tanks. The structure of a/m pumps with hydraulic drive is shown in Fig.2. The main elements of the pumps are: the head of pump, the concentric hydraulic lines with cargo discharge pipe and the deck trunk with a hydraulic control block and connection ports to the cargo deck installation, and other (e.g. hydraulic) service installations. In the head, situated in the lower part of the pump, there is an impeller driven by the hydraulic motor. As the rule, in this type of cargo pumps, a high speed axial piston, hydraulic motors of constant displacement are mounted. Usually, due to the required high service reliability and extremely difficult working conditions inside the cargo tanks, there are used motors of A2FM type made by Bosch Rexroth/Germany. The power of standard cargo pumps reaches the level of approx. 200 [kW]. The hydraulic motor is powered by means of a concentric pipe system, in which hydraulic oil flows from the control block

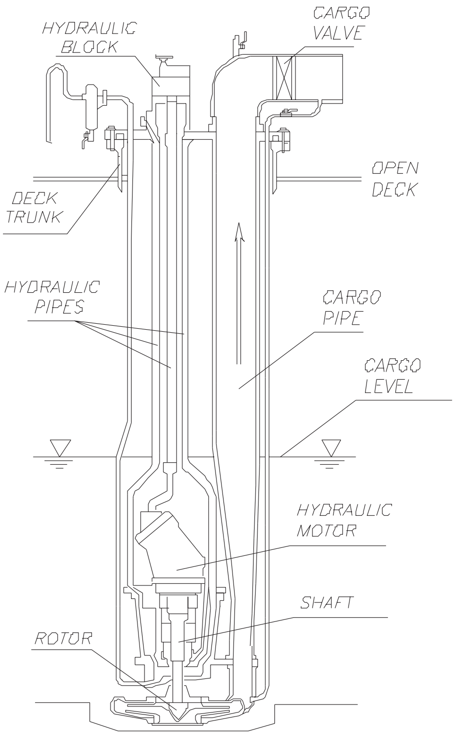

Fig. 2. View of typical hydraulically-driven submerged cargo pump

mounted on the deck trunk. Such a construction, with the hydraulic drive motor localized in the lower part of the cargo pump, makes it possible to avoid an excessive noise and vibrations of the impeller drive shaft by reducing its length to a minimum. Usually, a/m vibrations in classical long-shaft cargo pumps with electric drive are caused by a bad state of the shaft bearings and an unbalanced long-drive shaft. The liquid cargo, pumped by the impeller, flows through the separate cargo pipe mounted in the pump structure to the deck trunk connection port. At the end of the cargo installation, near the pump, there is an installed cargo stop valve. It is used to cut the pump off from the rest of the cargo system in the case of a pump damage. This valve allows for executinge the stripping operation – removing the liquid cargo remainders from the pump suction well and the pump interior cargo area.

The simultaneous drive of several cargo pumps requires the power reaching up to 3000 [kW] and more. The hydraulic central loading system makes it possible simultaneous and intependend feeding of many hydraulic receivers with such a great total power. Therefore, the hydraulic central loading systems mounted on board of modern product and chemical tankers, are counted among the greatest hydraulic systems not only in the ocean technology, but in the whole area of hydraulics, as well. A detailed description of this type of hydraulic central loading systems was given in other papers by the author [4],[5],[6].

There are many factors that influence the discharge flow of the cargo system. The hydraulic drive and control adjustments are as important as the physical properties of the transported liquid cargoes, especially their density and kinematic viscosity. This is the major problem for the designers of cargo installations and their users, because the producers of cargo pumps give in the catalogues only the flow performance characteristics pertaining to the case of pumping a standard, basic liquid cargo, which, typically, is the fresh or sea water. In the world literature there aren't any mathematical algorithms for calculation of drive and flow characteristics in the case of real liquid cargoes. Referring to the influence of viscosity, many authors [7],[9] use the results of Hydraulic Institute New York [10], which are published in the nomogram form. Such an approach is impractical, because it requires that the deck officers and fuel terminal staff supervising the unloading operations of tankers should introduce manual corrections of drive and flow parameters, and make necessary calculations. This situation can lead to errors in the staff service, which could be extremely dangerous.

In this paper, the author presents a computing algorithm for determining the influence of the liquid cargo density and kinematic viscosity on the change of flow of cargo pumps and drive characteristics. The resulting change of flow of the cargo system, in the case of shipment of some different liquid cargoes, has also been shown. The presented computing algorithm can be also helpful in more effective planning of works in harbour fuel terminals.

2. Density and viscosity range of the standard liquid cargoes in sea transportation

The cargo pumps, destined for the service of liquid cargoes on modern product and chemical tankers are, as it was mentioned above, of submerged, centrifugal type, designed to direct montage inside cargo tanks. Physical properties of the transported liquid cargoes have an influence on discharge flow and drive loading value reached during the unloading operation. The most important technical parameters characterizing the pumped liquid cargo are its density, and the coefficient of kinematic viscosity. A cargo installation on board of product and chemical tankers must be appropriate for serving a dozen of different cargoes during one sea voyage. The values of density and kinematic viscosity of standard liquid cargoes in the sea transportation market are presented in Table 1. It is important to remember that the value of kinematic viscosity coefficient depends on temperature of the liquid. Therefore, in Table 1 there are the values of cargo viscosity in specific, standard temperatures. As it is shown in Table 1, standard liquid cargoes in sea transport are characterized by a large variability of density and the value of kinematic viscosity coefficient. Most of petroleum-based liquid cargoes have a density smaller than fresh water, commonly treated as the basic cargo in maritime area comparisons. However, the majority of chemical liquid cargoes, especially acids, are characterized by much higher density. An example: the density of sulphuric acid (98% liquid at temperature 20 [°C]) reaches 1830 [kg/m3]. The values of kinematic viscosity coefficient of standard liquid cargoes are also quite diverse.

Table 1.

Density and kinematic viscosity coefficient of standard liquid cargoes on sea transport market [8],[12],[13]

Name of liquid cargo		Density [kg/m3] / 15[$^\circ C$]	Temperature [$^\circ C$]	Viscosity [cSt]
Crude Oil, Arabian Heavy, Ras Tannura, Saudi Arabia		887	37.8	8.5
Crude Oil, Wilmington, Long Beach, California USA		933	37.8	72.2
Crude Oil, Quiri, Carpito, Wenezuela		959	37.8	164.0
SOR Heavy Fuel Oil (HFO)		940	15	40.0-70.0
SOR Light Fuel Oil (LFO)		830	15	1.0-2.0
Gasoline, Vehicle		710	15.6	0.7
Vegetable Oil (Oliva)		910	25	89.0
Hydraulic Oil	Mobil VI = 146 DTE11M	859	40	15.0
			100	3.7
	MobilVI=141 DTE15M	879	40	46.0
			100	7.9
Gear Oil, Delvac 1MX2T	Mobil VI=140 75W90	859	40	120.0
			100	15.9
	Mobil VI=139 80W140	870	40	310.0
			100	31.2
Engine Oil, Vehicle Mobil 1 10W-30 VI = 147		860	40	62.0
			100	10.0
Glicerine		1136	0	10.6
			20	5.4
Residual Fuel Oil Sorbo 110		970	40	120.0
			100	12.0
Methanol		790	0	1.1
			60	0.4
Toluene		870	20	0.67
			70	0.41
Benzen		900	20	0.72
			50	0.49
Hydrochloric Acid (Liquid) 30 %		1161	0	2.7
			20	1.8
Sulphuric Acid (Liquid) 98%		1830	0	26.6
			20	13.9

Generally, liquid cargoes transported by sea usually have higher viscosity than fresh water (1.0 [cSt]). Particular cargoes, like gear oils, mazut or bitumens, reach so great values of kinematic viscosity that it is necessary to use intensive heating for their transport and shipment in [12]. In the case of bitumen transport, the required minimum temperature reaches 135 degree of Celsius. The deck officer, supervising the shipment operation in a harbour, or ship cargo installation designers must take into account the value of liquid cargo density and kinematic viscosity. Technical parameters of cargoes may have an important influence on the shipment operation strategy. The value of viscosity value of the transported cargo may decide about the start of additional cargo heating, which is extremely expensive.

3. Flow and drive characteristics of typical submerged cargo pumps with hydraulic drive

As it was mentioned in the introduction, the popular way of drive in cargo pumps working in an area threatened with explosion, is the use of hydraulic drive. Considering economical conditions, one realizes power supply of the hydraulic equipment in the from of hydraulic central loading system [2][3]. The important technical parameters of the supply process in cargo pump discharge flow control are:

p_G – working pressure value in hydraulic supply system

Δp_S – drop pressure in cargo pump hydraulic motor.

The first parameter- working pressure in hydraulic system is defined as the output pressure of the hydraulic main power pack unit. Its value can be adjusted by means of p=const common main pump controller, installed directly on the power pack in the power pack room [2]. The value of p_G should not be lower than the total pressure drop in hydraulic motor (most loaded hydraulic receiver in the hydraulic system) Δp_S and hydraulic installation with control valves on way of hydraulic oil flow. The next parameter Δp_S can be adjusted by means of the constant torque controller, located on the top of each cargo pump. The values of both parameters, can be remotely adjusted by deck officer using the control panel mounted in Cargo Office Room, or by the managing computer. The flow and drive characteristics of a typical submerged cargo pump, powered from hydraulic central loading system, are presented in Fig.3. They were determined for cargo pump of FRAMO SD125 type, at fresh water as basic liquid cargo with a density of 1000 [kg/m3] and kinematic viscosity coefficient $\nu = 1$ [cSt]. The presented characteristics are very important in practice, because the deck officer on board, who is responsible for unloading operation, has at his disposal in ship's office only flow and drive characteristics determined for basic liquid cargo (i.e. fresh water). The real cargo transported at sea by tanker has usually different density and viscosity than those of basic cargo. As it was mentioned in the previous papers by the author [1][2], the density and the viscosity have an essential

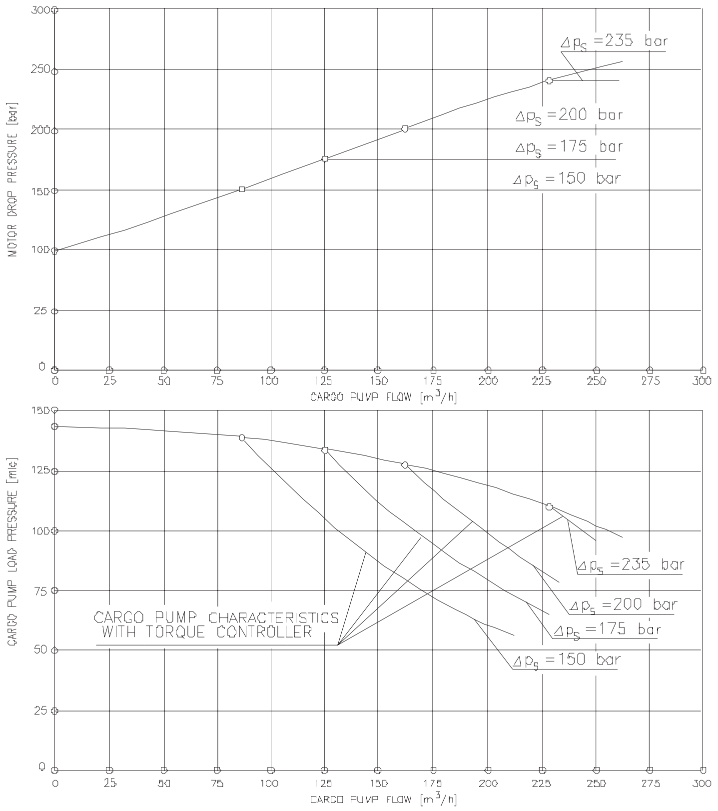

Fig. 3. Flow and drive characteristics of submerged cargo pump FRAMO SD125 type with hydraulic drive for basic cargo – fresh water sp.g=1.0, viscosity $\nu = 1$ [cSt].

influence on the value of the load torque on the cargo pump impeller. This is the result of the occurrence of viscosity friction between the liquid cargo layers and the impeller blades and the pump body.

The weight and inertia of cargo has also some influence on the shaft drive torque. This influences has a strongly non-linear character. Therefore, drive and flow characteristics presented in Fig.3, prepared for basic cargo, are not valid in the case of pumping other liquid cargoes. In shipping practice, deck officer relays on nomograms nomographs established according to the requirements of the Hydraulic Institute New York (HINY). The officer prepares suitable proof-corrections for flow characteristics determined for basic cargo. All the corrections are introduced manually by deck officer based on traditional nomographs from the literature (Troskolanski, Łazarkiewicz [7], Jędral [9]). This is an important disadvantage of this approach.

4. Calculation of pump flow and drive characteristics in the case of real liquid cargo pumping with different density and kinematic viscosity

4.1. Mathematical model

The analyzed cargo system contains submerged cargo pumps with hydraulic drive, mounted directly in the cargo tanks. The hydraulic drive is powered from the hydraulic central loading system. This supply system is of constant pressure type with main power pack unit equipped with the controller of p=const. [3][5]. Each pump is connected in parallel to the main line of supply system. To control the operation of pumps, the constant torque controller is mounted on the inlet of hydraulic oil flow to the cargo pump. The hydraulic diagram of the analyzed hydraulic system is presented in Fig.4. It illustrates the pressure losses at the hydraulic oil flow from the main power pack unit to the hydraulic motor of the cargo pump.

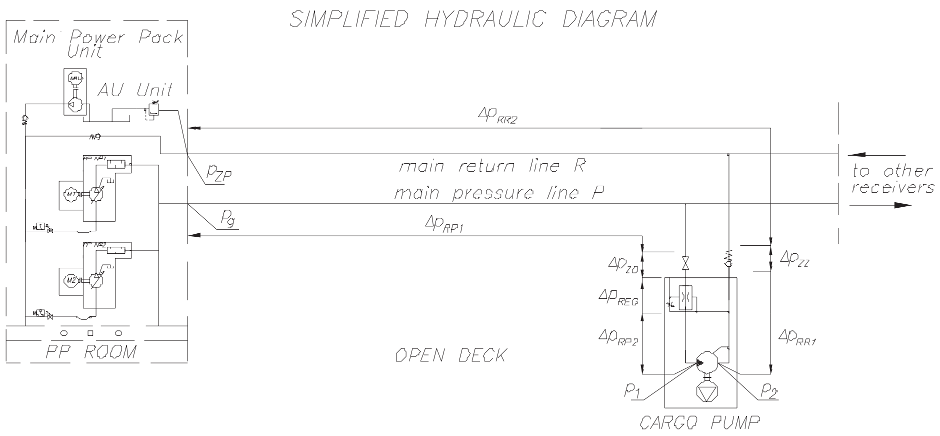

Fig. 4. Hydraulic oil pressure drops in supply process of cargo pumps hydraulic motor

The value of pressure drop in the hydraulic motor Δp_S is defined as :

$$\Delta p_S = p_1 - p_2 \quad [\text{bar}] \tag{1}$$

where : p_1 – inlet pressure to the hydraulic motor,

$$p_1 = p_G - \Delta p_{RP} - \Delta p_{ZO} - \Delta [_{REG} \quad [\text{bar}] \tag{2}$$

p_G [bar] – working pressure of main hydraulic power pack unit
Δp_{ZO} [bar] – pressure drop in ball valve (we can neglect this value as small in comparison to other components $\Delta p_{ZO} \approx$ [13])

Δp_{REG} [bar] – adjusted value of pressure drop in constant-torque controller
Δp_{RP} – pressure drop in hydraulic main pressure line- we can calculate this value, according to [15], from the following equation:

$$\Delta p_{RP} = \sum_{i=1}^{n} \lambda_i \cdot \frac{l_i}{d_i} \cdot \rho_h \cdot \frac{v_i^2}{2} + \sum_{j=1}^{m} \zeta_{-}j \cdot \rho_h \cdot \frac{v_j^2}{2} \quad ; \quad v_{i,j} = \frac{4Q_{i,j}}{\pi \cdot d_{i,j}^2} \tag{3}$$

where:

i – number of hydraulic resistance element of linear type in hydraulic pressure line,
j – number of hydraulic resistance element of local type in hydraulic pressure line,
n – total number of hydraulic resistance elements of linear type in hydraulic pressure line,
m – total number of hydraulic resistance elements of linear type in hydraulic pressure line,
λ_i [–] – coefficient of pressure losses in i*th* resistance element of linear type in pressure line
l_i, d_i [m] – length and diameter of i*th* – resistance element of linear type (hydraulic pipe) in pressure line
ρ_h $[kg/m^3]$ – density of hydraulic oil
$v_{i,j}$ [m/s] – hydraulic oil velocity in i*th*- or j*th*- resistant element in pressure line
$Q_{i,j}$ $[m^3/s]$ – hydraulic oil flow in i*th*- or j*th*- resistant element in pressure line
ζ_j [–] – coefficient of pressure losses in jth- resistance element of local type in pressure line

We can determinate the outlet pressure in the hydraulic motor from the following formula:

$$p_2 = p_{ZP} + \Delta p_{ZZ} + \Delta p_{RR} \quad \text{[bar]} \tag{4}$$

where:
- Δp_{RR} [bar] – pressure drop in hydraulic main return line

$$\Delta p_{RR} = \sum_{i1=1}^{n1} \lambda_{i1} \cdot \frac{l_{i1}}{d_{i1}} \cdot \rho \cdot \frac{v_{i1}^2}{2} + \sum_{j1=1}^{m1} \zeta_{-}j1 \cdot \rho \cdot \frac{v_{j1}^2}{2} \quad ; \quad v_{i1,j1} = \frac{4Q_{i1,j1}}{\pi \cdot d_{i1,j1}^2} \tag{5}$$

where:

il – number of hydraulic resistance element of linear type in hydraulic return line,
jl – number of hydraulic resistance element of local type in hydraulic return line,
n1 – total number of hydraulic resistance elements of linear type in hydraulic return line,
m1 – total number of hydraulic resistance elements of linear type in hydraulic return line,
λ_i [–] – coefficient of pressure losses in ith resistance element of linear type in return line
l_{il}, d_{IL} [m] – length and diameter of il- resistance element of linear type (hydraulic pipe) in return line
$v_{il,jl}$ [m/s] – hydraulic oil velocity in il- or jl- resistant element in return line
$Q_{il,jl}$ [m/s] – hydraulic oil flow in il- or jl- resistant element in return line
ζ_{ij} [–] – coefficient of pressure losses in jl- resistance element of local type in return line
-Δp_{ZZ} [bar] – pressure drop in non-return valve

(practice proves that [14],[15],[16] we can assume the pressure drop value on standard spring valve of this type as:

$$\Delta p_{ZZ} \approx const. = 0.5 \quad \text{[bar]}$$

- p_{ZP} [bar] – pressure value in support relief valve in filling -up system of main hydraulic power pack unit

In the case of the above described product tanker m/t ‘Helix’, the value of support valve pressure amounted to:

$$p_{ZP} = 4 \quad \text{[bar]}$$

Constant-torque controller establishing hydraulic oil flow to hydraulic motor of cargo pump works in 2 ranges:.
In the first range, the pressure drop value in hydraulic motor is as follows:

$$p_1 - p_2 < \Delta p_{SN} \quad \text{[bar]} \tag{6}$$

where:

Δp_{SN} [bar] – adjustment pressure in the constant-torque controller of a the nominal hydraulic oil pressure drop in the motor

then the controller acts as the flow regulator maintaining the constant flow of hydraulic flowing to the hydraulic energy receivers. In this case, ignoring volumetric losses in hydraulic motor, we can assume that the rotation speed of cargo pump impeller is constant, independent of the load of drive.
In the next performance range of the constant-torque controller, the following formula is valid:

$$p_1 - p_2 = \Delta p_{SN} \tag{7}$$

In this case, the controller adjusts the pressure drop Δp_{REG} so that the pressure drop in a hydraulic motor is maintained on the same level:

$$\Delta p_S = \Delta p_{SN} \tag{8}$$

In the classical approach, the deck officer should use the pump flow and drive characteristics, determined for basic cargo, and the kinematic viscosity coefficient of current liquid cargo for manual calculations to set the value of the following correction factors from nomographs given by the Hydraulic Institute New York [10] (see Troskolanski-Łazarkiewicz [6], Jędral [8], Kutyrkin-Postnikow [17]):
f_Q – cargo pump flow correction coefficient [-]

$$f_Q = \frac{Q}{Q_0}[--] \tag{9}$$

where:

Q $[m^3/h]$ – cargo pump flow at current liquid pumping
Q_0 $[jm^3/h]$ – cargo pump flow at fresh water (basic cargo) pumping

f_H – pumping pressure (lifting height) correction coefficient of cargo pump

$$f_H = \frac{H}{H_0}[--] \tag{10}$$

where:

H [mlc] – pumping pressure (lifting height) of cargo pump at viscous liquid pumping
H_0 [mlc] – pumping pressure (lifting height) of cargo pump at fresh water (basic cargo) pumping
(mlc – meters of liquid cargo - unit of pumping pressure, popular in liquid cargoes sea transport technology)

f_η – efficiency correction coefficient of cargo pump

$$f_\eta = \frac{\eta}{\eta_0}[--] \tag{11}$$

where:

η [–] – total efficiency of cargo pump at current liquid cargo pumping
η_0 [–] – total efficiency of cargo pump at fresh water (basic cargo) pumping

The driving power correction coefficient of cargo pump f_P can be determined, based on the dependencies (9),(10) and (11), in the following form:

$$f_P = \frac{P}{P_0} = \frac{f_Q f_H}{f_\eta} \cdot \frac{\rho}{\rho_0}\ [--] \tag{12}$$

where:

P [kW] – driving power of cargo pump at current liquid pumping
P_0 [kW] – driving power of cargo pump at fresh water (basic cargo) pumping
ρ $[kg/m^3]$ – current liquid cargo density
ρ_0 $[kg/m^3]$ – basic cargo (fresh water) density

In classical approach, the deck officer is forced to manually execute the necessary calculations for every performance point of cargo pump separately. It is troublesome. Additionally, this can result in many mistakes, which is dangerous. Therefore, in order to automatize and accelerate calculations in managing computer system in the deck office, it is better to use the algorithm presented below.

In a modificated way, we can, according to vector record rules [11], define correction coefficients vector **f** :

$$\mathbf{f} = \left\{ \begin{matrix} f_Q \\ f_H \\ f_\eta \end{matrix} \right\} = \left\{ \begin{matrix} f_Q(Q_0, H_0, \nu) \\ f_H(Q_0, H_0, \nu) \\ f_\eta(Q_0, H_0, \nu) \end{matrix} \right\} \tag{13}$$

The value of vector components can be calculated from the following formula:

$$f_i = \begin{cases} 1 & \\ \dfrac{a_i}{1 + b_i \cdot e^{-c_j \cdot x_k}} & \text{for} \quad \begin{matrix} x_k \geq \overline{x}_{ki} \\ x_k > \overline{x}_{ki} \end{matrix} \end{cases} \tag{14}$$

where:

i = Q, H, η

a_i, b_i, c_i – proportional coefficients of characteristics for the given cargo pump type

$x_k = x_k\ (\nu, Q_0, H_0)$ – influence function

$\overline{x}_{ki}$ – critical value of influence function

The basic state vector in logarithmic co-ordinates **S** is :

$$\mathbf{S} = \begin{Bmatrix} \ln(\nu) \\ \ln(Q_0) \\ \text{lm}(H_0) \\ l \end{Bmatrix} \tag{15}$$

wherein:

ν [cSt] – liquid cargo kinematic viscosity coefficient

Q_0 [m^3/h] – cargo pump flow at fresh water (basic cargo) pumping

H_0 [mlc] – pumping pressure (lifting height) of cargo pump at fresh water (basic cargo) pumping

In the result, the basic state vector **S** can be use for calculation of particular values of influence function from the equation:

$$x_k = x_k(\nu, Q_0, H_0) = \mathbf{K} * \mathbf{S} \tag{16}$$

where:

K – constant values vector.

One can determine the values of particular constants and vector components on the basis of experimental flow characteristics and their simplified forms of regression graphs (complying with basic state vector **S**), for a given type of cargo pump.

For example, for the cargo pump FRAMO SD type, assuming that the basic cargo is fresh water with density equal $\rho = 1000$[kg/ m^3] and kinematic viscosity $\nu = 1.0$ [cSt], one can evaluate these values as:

$$\{a_i \quad b_i \quad c_i\} = \left\{\begin{array}{ccc} a_Q & b_Q & c_Q \\ a_H & b_H & c_H \\ a_{eta} & b_\eta & c_\eta \end{array}\right\} = \left\{\begin{array}{ccc} 1.040 & 1.232\cdot 10^{-3} & -5.233 \\ 1.023 & 1.214\cdot 10^{-3} & -4.343 \\ 1.000 & 2.775\cdot 10^{-3} & -5.551 \end{array}\right\} \tag{17}$$

$$\begin{aligned} \mathbf{K} &= \{0.158 \quad -0.040 \quad -0.076 \quad 0.541\} \\ \{\overline{x}_{kQ} \quad \overline{x}_{kH} \quad \overline{x}_{k\eta}\} &= \{0.652 \quad 0.652 \quad 0.295\} \end{aligned} \tag{18}$$

On the basis of the cargo parameters presented above (17)(18), the corrected drive characteristics of cargo pump can be determined from the following dependence:

$$\Delta p_S = \frac{\Delta p_{S0}\cdot f_Q \cdot f_H}{f_\eta}\cdot\frac{\rho}{\rho_0} \tag{19}$$

where:

Δp_S [bar]	–	pressure drop in hydraulic motor of cargo pump at current liquid cargo pumping;
Δp_{S0} [bar]	–	pressure drop in hydraulic motor of cargo pump at basic cargo (fresh water) pumping.

When the value Δp_S exceeds the adjustment range of constant-torque controller, the system will limit hydraulic the magnitude of oil flow affecting the hydraulic motor of cargo pump in such a way that the dependence (8) i.e. $\Delta p_S = \Delta p_{SN}$ will be fulfilled. The minimum value of performance pressure of main power pack unit controller, i.e. adjustment of p=const. regulator should be not less than :

$$p_{G\min} \geq \Delta p_s + \Delta p_{RP} + \Delta p_{ZO} + \Delta_{REG} + p_{ZP} + \Delta p_{ZZ} + \Delta p_{RR} \tag{20}$$

In order to avoiding the problems with stability of the controller, in shipping practice, the value of regulator adjustment p_G is fixed on the level of:

$$p_G = \Delta p_s + \Delta p_{RP} + \Delta p_{ZO} + \Delta_{REG} + p_{ZP} + \Delta p_{ZZ} + \Delta p_{RR} + 10[bar] \tag{21}$$

4.2. Numerical calculations of corrected pump flow and drive characteristics

For numerical calculations, we used the set of 5 different liquid cargoes, among those three petroleum based cargoes and two acids as liquid chemicals (see table 2.). All cargoes are often met in maritime transportation. These liquids are transported with the use of the described product and chemical tankers. Special attention must be paid to the fact that petroleum-based cargoes (cargo No 1,2,3) are characterized by density lower than fresh water, at the same time having much higher values of kinematic viscosity. The properties of the chemicals are just quite opposite. In the analyzed case, acids (cargo No 4 and 5) have kinematic viscosity almost the same, relative to the basic value 1.0 [cSt], but with much higher density. The appreciation of such a difference in technical properties- of liquid cargoes makes it possible to properly evaluate the influence the density and viscosity have on the performance characteristics of the analyzed cargo pumps. As basic flow and drive characteristic, we accepted the results of research on the cargo pump FRAMO 125-5, performed for the basic cargo – fresh water with density $\rho_w = 1000[kg/m^3]$ and kinematic viscosity coefficient value $\nu_w = 1.0[cSt]$.

Table 2.

Technical properties of liquid cargoes used in the analysis

No of Cargo	Name of liquid cargo	Densitykg/m3¿kg/m3	ViscositycSt¿cSt
1	SOR Heavy Fuel Oil (HFO)	940	70.0
2	Crude Oil, Quiri, Carpito, Wenezuela	959	164.0
3	Gear Oil, Delvac 1MX2T Mobil 80W140 VI = 139	870	310.0
4	Nitric Acid (Liquid)	1513	0.8
5	Sulphuric Acid (Liquid) 98%	1830	13.9
6	Basic cargo – fresh water	1000	1.0

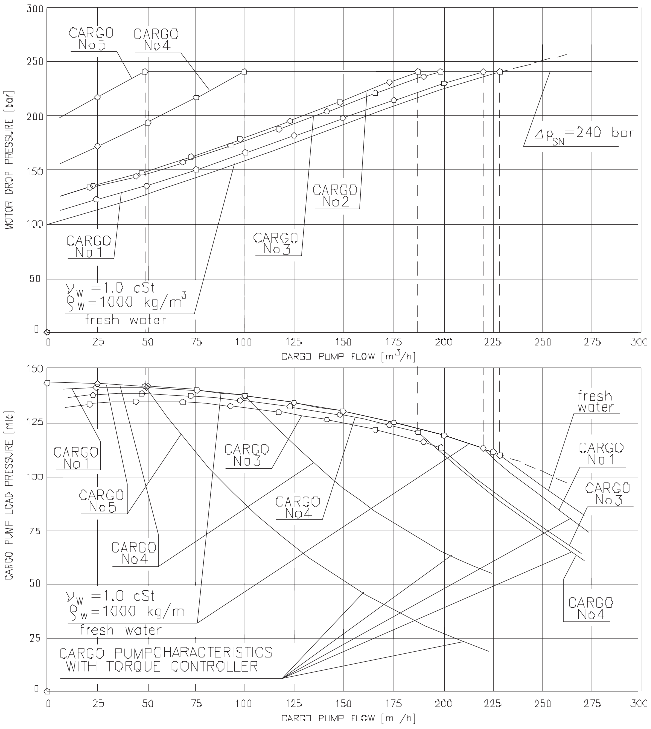

Fig. 5. Corrected flow and drive characteristics of cargo pump FRAMO SD 125 the in case of pumping the following liquid cargoes:
Cargo No 1- Heavy fuel oil HFO $\rho = 940\_[kg/m^3]$, $\nu = 70.0[cSt]$
Cargo No 2- Crude oil Quiri/Wenezuela $\rho = 959\_[kg/m^3]$, $\nu = 164.0[cSt]$
Cargo No 3- Gear oil 80W140 $\rho = 870\_[kg/m^3]$, $\nu = 310.0[cSt]$
Cargo No 4- Nitric acid $\rho = 1513\_[kg/m^3]$, $\nu = 0.8[cSt]$
Cargo No 5- Sulphuric acid $\rho = 1830\_[kg/m^3]$, $\nu = 13.9[cSt]$

We assumed the hydraulic controller adjustment value of nominal drop pressure on hydraulic motor on the level of $\Delta p_{SN} = 240[bar]$ and a nominal speed of cargo pump $n_0 = 2480$ [rpm]. The results of calculations are shown in Fig. 5.

5. Summary

The cargo system, designed for servicing liquid cargoes on modern product and chemical tankers, is based on submerged cargo pumps. These are of centrifugal type with hydraulic drive. As they are installed in a dangerous areas, threatened with explosion, the pumps are often powered from hydraulic central loading system. This powering system is most effective and popular in shipbuilding practice. Cargo pumps drive – and its flow characteristics with technical parameters, are provided by the producers only for basic liquid cargo. Usually, it is fresh water with density equal to 1000 [kg/m^3] and kinematic viscosity coefficient of 1 [cSt]. Performance characteristics determined in such a way are not applicable in the case of pumping liquid cargoes with density and viscosity different than those of basic cargo. Therefore, the deck officer or terminal operator supervising unloading operation should estimate the corrected discharge rate value of cargo pump and cargo system. In order to do it, is important to take into account liquid cargo properties especially including its density and viscosity. The algorithm for calculation of the corrected flow and drive characteristics has been presented in the paper. The most important conclusions from the presented analysis are as follows:

► The properties of pumped liquid cargoes, including density and kinematic viscosity, must be into account in calculations of the corrected cargo pump flow and drive characteristics,

► The increased value of density of the pumped liquid cargo has an essential influence on the load of the cargo pump in hydraulic drive, with almost invariable cargo pump flow,

► The increased value of the pumped liquid cargo viscosity has a lower influence on the cargo pump drive load than that of liquid density, and deteriorates the performance flow characteristics of the pumps.

Manuscript received by Editorial Board, May 15, 2008

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Wpływ własności ładunku płynnego na wydajność zanurzeniowych pomp ładunkowych z napędem hydraulicznym na współczesnych produktowcach i chemikaliowcach

Streszczenie

W referacie przedstawiono wpływ własności różnych ładunków płynnych na wielkość wynikowej raty wyładowczej zanurzeniowych pomp ładunkowych z napędem hydraulicznym stosowanych na współczesnych produktowcach i chemikaliowcach. Opisano budowę głównych elementów zanurzeniowych pomp ładunkowych oraz strukturę napędowego układu hydraulicznego. Zaprezentowano przykładowe rozwiązania omawianych systemów na nowo wybudowanym statku m/t ‘Helix’. Podano formułę wykorzystania charakterystyk przepływowych i napędowych pomp, sporządzonych dla ładunku wzorcowego (wody słodkiej), dla przypadku obsługi rzeczywistego ładunku o różnej lepkości oraz gęstości.