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THE PROCEDURE FOR CALCULATION OF THE OPTIMAL CARRYING CAPACITY OF PUSHED CONVOY BASED ON PARAMETERS OBTAINED BY EXPERIMENTS IN ACTUAL NAVIGATING CONDITIONS

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Summary

Exploitation and technical parameters of a ship are very important qualitative characteristics which determine the efficiency of the use of any kind of transportation vessels both for pushboats and for pushed convoys as a whole. Some of the most important exploitation and technical parameters are: parameter of transport efficiency, tonnage quality parameter, and thrust output of propeller. The complexity of these parameters can be seen from the fact that they present the values of achieved payload-distance during transportation of cargo in the unit of time per unit of installed (or effective) power of propelling engines of ships.

The most reliable means for determining the transport efficiency is the method of testing in actual navigating conditions, which is conducted in order to determine exact technical characteristics of propelling engines of pushboats, and to determine drawbacks in their work and to increase their thrust and speed characteristics. This paper will present the process of choosing the size, shape, and number of barges in the convoy based on experiments conducted on a pushboat whose propelling engines have installed power 3×809.6 kW (3×1,100 HP). Obtained results are based on presumption that the total resistance of a pushed convoy is equal to the total thrust achieved by the ship's propelling complex.

Keywords: *pushboat; parameter of transport efficiency; thrust; thrust output of propeller; pushed convoy; convoy; optimal speed of navigation*

1. Introduction

As an objective criterion of accuracy of the theoretical calculations during determination of navigational characteristics of ships-pushboats, experiments are conducted in actual navigating conditions, especially dynamometric and torque measurements together with measurements of speed of navigation.

These experimental measurements are conducted for the highest draught of barges for different working regimes of propelling engines and different shapes of pushed convoys, as well as for stationary measurements. In order to conduct the measurements of already built ships in actual conditions it is necessary to choose a measuring track (measuring mile) of substantial length which needs to meet the following conditions [7]:

1. that the speed of river flow is negligible;

2. that the depth in the measuring track (H) is chosen from the simultaneous fulfilment of the following equations $\frac{H}{T} \leq 7$ and $\frac{v}{\sqrt{g \cdot H}} \leq 0.5$ where H is the depth of water in measuring track (m), T, draught of vessels-barges during experiments (m);

3. length of measuring track needs to be long enough for measurements to take place and it also needs to have approaching sections on both ends of the track.

The basis for this paper is the presumption that the force needed to overcome the produced resistance of a pushed convoy, called thrust (F_t), is equal to the total measured resistance (R_{tot}) shown in Figure 1.

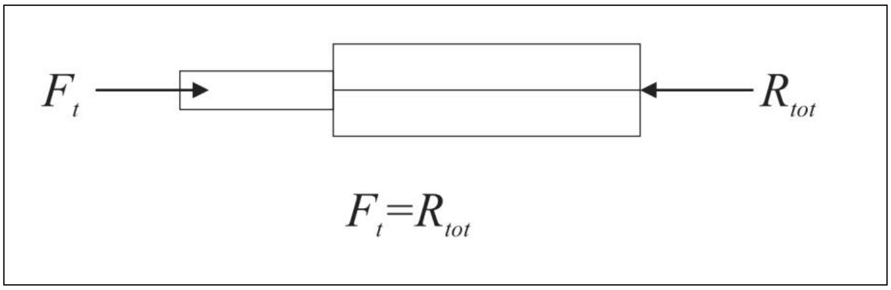

Figure 1 Schematic presentation of relation between thrust and total resistance of pushed convoy

The previously mentioned measurements are performed for the highest possible number of different pushed convoys, for example, a pushboat and one barge (P+1), or a pushboat and two barges (P+1+1), a pushboat and four barges (P+2+2), etc. The experiment ends in such manner that the pushboat works “stationary“, or when the speed of navigation is v=0, pushing against a river bank. In this case it encounters resistance equal to infinity R_∞, which is equal to navigation with a convoy of endless number of barges.

The thrust created by each of the propellers as a function of power on propeller shafts, the number of rotations of propeller shafts and the speed of navigation in calm water $F_t=f(P_D; N_p; v)$ are determined while the pushboat is working with each of convoys and for each working regime of the propelling engines. The total thrust achieved by the pushboat ΣF_t is equal to the sum of thrusts created by all pushboat’s propellers. Based on achieved values of the total thrust it is possible to construct a diagram which shows the change $\Sigma F_t=f(v)$ in a matching coordinate system. It is understood that during the process of thrust calculation, besides the main dimensions of the pushboat, it is necessary to know the constructive characteristics of the propeller and the nozzle and it is necessary to use corresponding propeller diagrams.

Product of multiplication of pushboat’s propeller thrust ΣF_t and the measured speed of navigation in relation to water (v) for each of the convoys and for all the different working regimes of the propelling engines gives thrust output, A_t. Based on the calculated values a diagram of change of thrust output $A_t=f(F_t; v)$ can be constructed in a corresponding coordinate system (Figure 2). The purpose of constructing such a diagram of the thrust output A_t is to create a curve which for one, the optimal speed, for the current technical condition of the pushboat achieves its maximal value and can be described with a mathematical function. The diagram of thrust output starts at the coordinate system origin – since it is the speed of navigation v=0, and $A_t(v)$=0, it ends in the point where the speed of the pushboat is at its maximum ($v=v_{max}$) while the pushboat is navigating without a convoy, when thrust of a convoy is $\Sigma F_t(v)$=0, because of which $A_t(v)$=0.

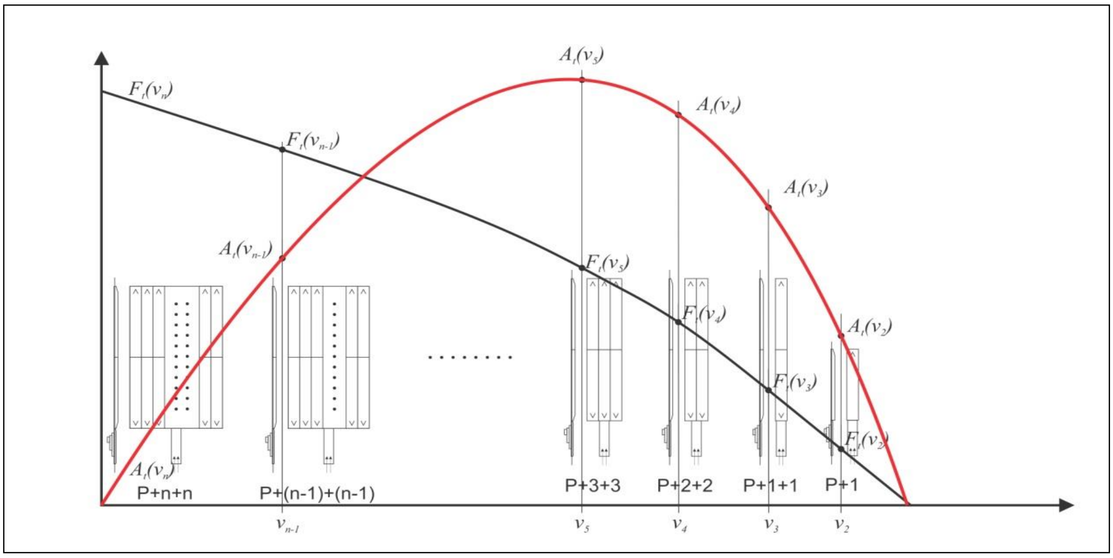

Figure 2 Construction of the curve of the change in thrust and thrust output in relation to speed of navigation

2. Exploitation and technical parameters of ship's work

Ships have the main productive role in the process of cargo transportation in the system of water transport. Exploitation of a ship is a term used when refering to the work (use, utilization) of a ship in order to achieve maximal effects. This is the reason why it is necessary to direct the organization of work in transport process towards efficient use of water transportation units and to improve the methods of transport processes management. One of the ways to determine the use of ships in the transport fleet and to analyze their work is to calculate the actual values of exploitation and technical parameters of each individual vessel, where these parameters include technical and economic characteristics of the use of the vessel in the unit of time.

The technical parameters of ship's work that are being determined in actual navigating conditions for pushboats include: number of rotations per minute and power on coupling of propelling engines, pressures and temperatures in each cylinder for each propelling engine, total and specific fuel consumption, number of rotations and power measured on the propeller shaft. These data on propelling engines, during analysis of the results, are compared to the results obtained by the measurements on the engine test stand performed by the manufacturer.

Special problem presents determination of thrust F_t,(N) which is achieved by the pushboat's propellers by indirect measurements in actual navigating conditions. This is the reason why in this paper the thrust of the propeller is calculated according to the methods suggested in the literature.

In order to determine ***optimal carryingcapacity*** and ***optimal speed*** of navigation of convoys the thrust output A_t, ($kN \cdot \frac{km}{h}$) achieved by all the propellers of a pushboat is used and it is calculated according to the following expression [4], [5]:

$$A_t = \sum F_t \cdot v \tag{1}$$

whereΣF_t is total thrust of all the propellers of one pushboat, (N).

The optimal speed of convoy is considered to be the one which achieves the highest thrust output of the pushboat. Based on this claim the following can be stated: $v_{opt}=f(F_t)$, or $v_{opt}=f(A_t)$.

The highest thrust output is achieved in the point when the derivative of the function that presents the thrust output (A_t) per speed (v) is equalized to zero, or $\frac{dA_t}{dv} = 0$

3. Basic characteristics of the K series pushboats

The pushboats of the K series include the *Kumanovo*, *Kragujevac* and *Kadinjača* pushboats. Their basic characteristics are shown in Table 1.

Table 1 Basic characteristics of K series pushboats [18]

Characteristic	Abbreviation	Unit	Value
Length over all	L_{oa}	m	34.32
Length at the constructive water line	L_{CWL}	m	33.20
Beam	B	m	11.00
Maximal drought	T_{max}	m	1.80
Displacement	D	t	505.50
Block coefficient	δ	-	0.76898
Total power of propelling engines	P	kW	3×809.6

The characteristics of the propelling engines of the K series pushboats are the following: manufacturer: MAK; type of the engine: 8 M 281 AK – four stroke; number of cylinders: 8; total displacement of the cylinders: 101.4 l; permanent power of the engine: 809.6 kW (1,100 HP) at 750 rpm; reduction rate 2.526:1.

The characteristics of the propeller-nozzle complex of the K series pushboats: propeller diameter D=1800 mm; number of propeller blades: z=3; expanded blade area ratio: a_E=0.661; diameter at the entrance of the nozzle: D_u=2030 mm; diameter at the exit of the nozzle: D_i=1900 mm; length of the nozzle: l_H=1200 mm; shape coefficient of the nozzle: α_H=1.244; expansion coefficient of the nozzle: β_H=1.089; relative length of the nozzle: $\bar{l}_H = 0.66$.

Names and symbols of variables, where possible, have been matched to the ITTC 2008 recommendations [15].

The pushboats of the K series, shown in Figure 3, have been designed to work with homogenous pushed convoys made of 12 barges in formation P+4+4+4 of total carrying capacity 19,200 t at a navigation sped of v=12 km/h in calm water [13].

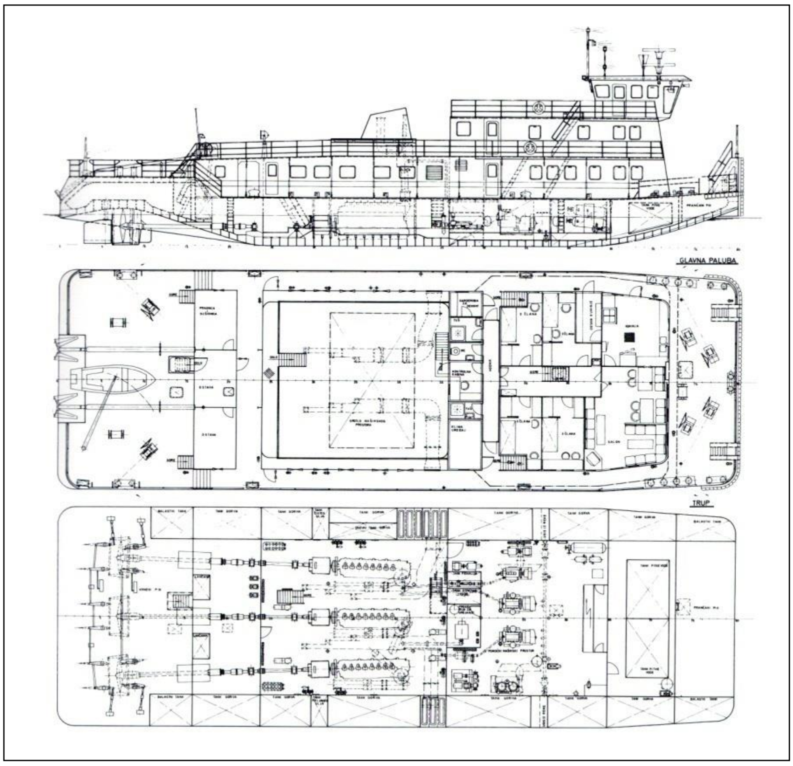

Figure 3 Pushboat of the K series

4. Basic characteristics of the barges

For determination of the thrust of the K series pushboats propellers, the barges and towed units presented in Table 2 were used.

Table 2 Basic characteristics of barges and towed units [14] [18]

Basic dimensions		L_{oa} (m)	L_{CWL} (m)	B (m)	T_{max} (m)	D (t)	δ	Q_r (t)
Barge type	JRB71300	66.95	65.65	10.2	2.3	1497.56	0.972	1267.56
	JRB81200	67.03	65.65	10.2	2.3	1454	0.944	1224
	JRB81500	77.02	75.4	11	2.56	1991.22	0.9378	1707.89
Towed units	01008	75.12	71.90	10.01	1.95	1184.00	0.843	949.11
	01009	75.12	71.90	10.01	1.95	1184.00	0.843	955.95
	19702	72.90	69.15	9.04	2.20	1165	0.847	915.32
	26773	59.62	58	8.07	2.10	822.76	0.837	676.89
	26808	57.90	56	8.20	2.15	805.2	0.815	664.75

The barges used in the experiments with the pushboats of the K series are asymmetrical and they are presented in Figures 4 and 5. The JRB71300 barges are used for dry bulk cargo without a lid, while the JRB81200 and JBR81500 barges are intended for transport of crude oil and its derivates.

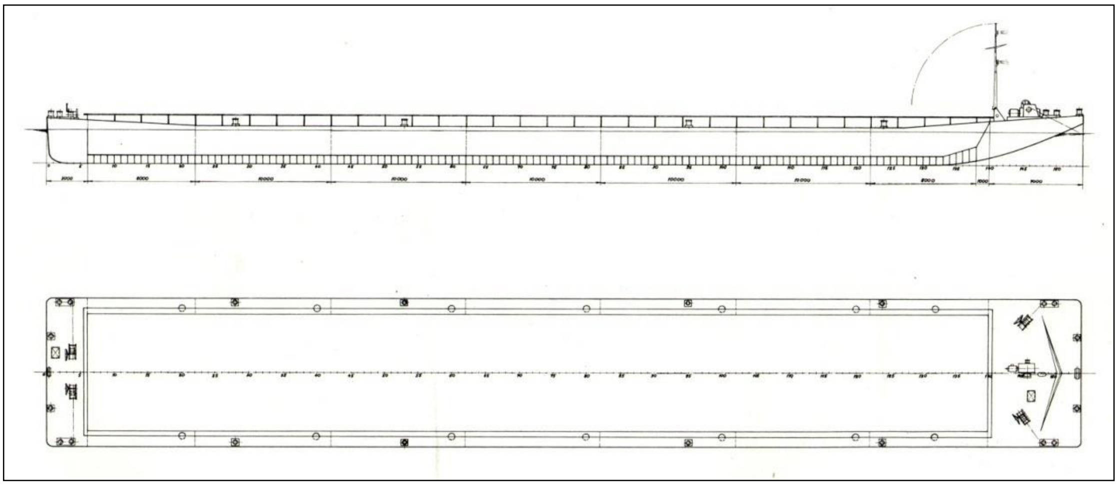

Figure 4 Barge type JRB71300

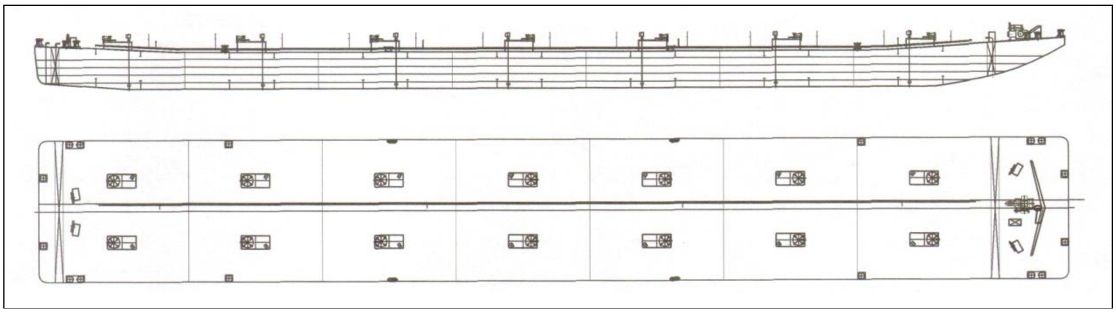

Figure 5 Barges type JRB81200, JRB81500

For better understanding of the problem, it is necessary to make difference between the terms ‘convoy’ and ‘pushed convoy’. A convoy is made up only of barges of the same or different types, while a pushed convoy is made up of a convoy of barges together with a pushboat. This is shown in Figure 6.

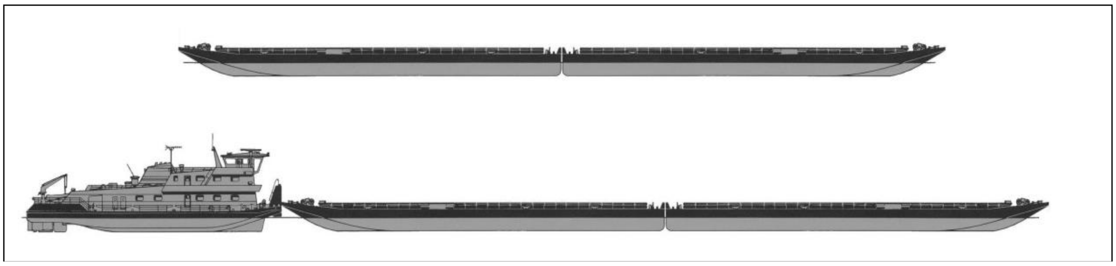

Figure 6 Difference between convoy and pushed convoy

5. Procedure of determination of technical and exploitation parameters of the K series pushboat

Determination of technical and exploitation parameters of the K series pushboat is conducted under the condition of the full use of the power of propelling engines and gaining the highest value of the thrust known for the characteristics of the propeller-nozzle complex. Torsion meters (devices for measuring torque, Maihak type) and electric contact counters are placed on all three propeller shafts just in front of the propeller shaft post. Determination of thrust characteristics of pushboats is based on precise determination of the power delivered to the propeller (P_D) and the number of rotations per minute (N_p) for each propeller shaft for work with different barge convoys, together with simultaneous measurement of the speed of navigation for such pushed convoys in calm water.

The assumption is made that the torque (used to calculate power) and the number of rotations in front of the propeller shaft post is equal to the power and number of rotations given to the propeller. It is considered that the losses in the propeller shaft post are negligible.

The measuring procedure consists of measuring the characteristics of the working regime of propelling engines for the highest number of rotations of engine shafts which achieve approximately 100% of nominal power.

Measurement of speed in relation to water is done by hydrometric wing which is positioned at approximately 5 meters in front of the front row of barges at a depth of 0.8 to 1.0 meters.

During the testing of the K series pushboat in each case the barges that formed the convoy were loaded to the maximum draught so their coefficient of the use of carrying capacity was $\varepsilon = \dfrac{Q_e}{Q_r} \approx 1.0$, where Q_e is the really loaded amount of cargo in a barge and Q_r is the registered (maximal) carrying capacity of the barge. The shapes of pushed convoys for which the measurements of thrust characteristics were done are marked with letters A, B, C, D, E, F, G and H and are shown in Figure 7. Experiments with all pushed convoys were done on Djerdap lake (reservoir) where the depth of water during measurements was between 15 and 16 meters. This fact leads to the conclusion that there had not been any negative influences on the results of measurements.

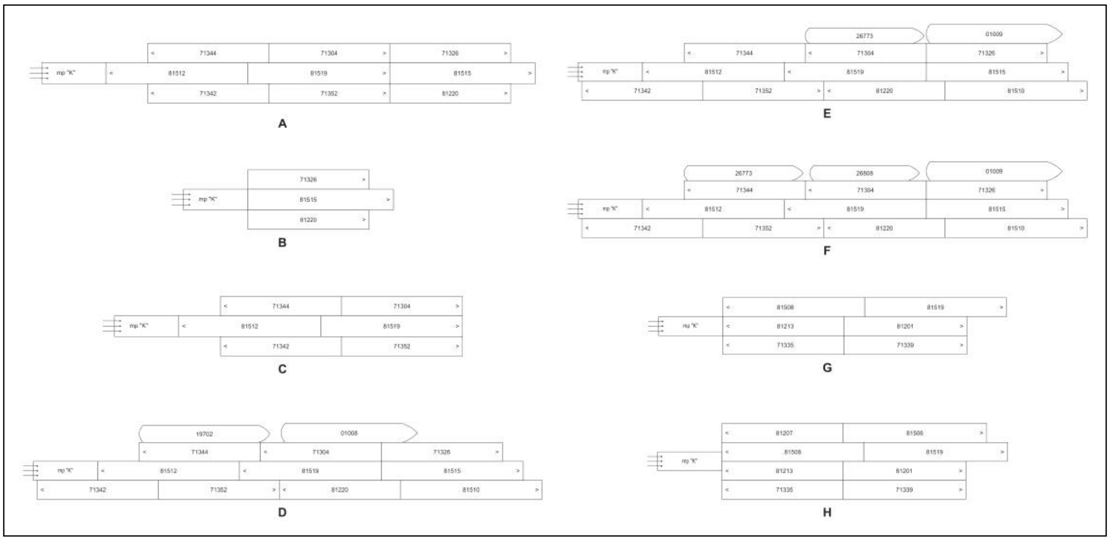

Figure 7 Shapes of pushed convoys while testing the K series

Technical parameters referring to the pushed convoys A, B, C, D, E and F were determined by the Laboratory for Testing of Ships and Waterways of the Faculty of Transport and Transport Engineering, University of Belgrade, Serbia while the parameters referring to the pushed convoys G and H were obtained by research conducted by Brodarski Institute from Zagreb, Croatia.

6. Parameters measured during testing of pushed convoys

During testing of the considered pushed convoys, the number of rotations of propeller shafts (N_P) and power on propeller shafts (P_D) were measured and the values obtained are shown in Table 3.

Simultaneously with the measurements of the number of rotations and torques on propeller shafts, the speed of navigation in relation to water was measured and the obtained values are presented in Table 4.

Table 3 Measured numbers of rotations and power on propeller shafts [1], [6]

Shape of pushed convoy	Measured number of rotations N_p (rpm)			Measured power P_D (HP)		
	LS	MS	RS	LS	MS	RS
A	294	293	297	864.9	997.0	968.1
B	295	300	297	878.6	1013.9	954.5
C	288	289	291	857.9	970.1	921.9
D	298	294	298	915.4	1007.1	971.4
E	293	297	296	893.2	1037.7	964.8
F	295	299	298	933.7	1058.5	991.8
G	283.5	294.7	285	895	978	944
H	280.7	291.3	281	901	993	940

Notice:

1. During calculations the power on propeller shafts given in HP was converted and presented in kW
2. LS – left shaft; MS – middle shaft; RS – right shaft

Table 4 Measured speeds of navigation in relation to water (v)

Speed v	Shape of pushed convoy							
	A	B	C	D	E	F	G	H
km/h	14.20	24.078	16.90	12.14	12.02	11.95	18.08	15.75
m/s	3.9444	6.6883	4.6944	3.3722	3.3388	3.3194	5.0222	4.375

In the procedure of measuring the pushboat parameters, the convoys whose total carrying capacity ΣQ_e is presented in Table 5 were used [1], [6].

Table 5 Total carrying capacities (ΣQ_e) of convoys of barges

ΣQ_e	Shape of pushed convoy							
	A	B	C	D	E	F	G	H
tons	12,685	4,198	8,482	16,251	15,990	16,654	8,396	11,327

7. Presentation of working parameters of the K series pushboat

As mentioned, the thrust of each propeller built into the K series pushboat is calculated according to the methods given in the literature [3], [7], [8], [9], [10] in actual navigating conditions (v), (N_p) and (P_D), while taking into account characteristics conditioned by different shapes of pushed convoys. The graph of the change of total achieved thrust ΣF_t is best presented by a curve shaped according to the following expression:

$$F_t = f(v) = -0.0655 \cdot v^3 + 1.4852 \cdot v^2 - 10.604 \cdot v + 384.6,\ (r^2=0.9939). \tag{2}$$

While the thrust output from Equation 1 for the same shapes of convoys is presented by a curve:

$$A_t = f(v) = -1.9208 \cdot v^3 + 45.052 \cdot v^2 + 88.765 \cdot v + 256.91,\ (r^2=0.9918). \tag{3}$$

The first derivative of the function of the thrust output by speed $\frac{dA_t}{dv} = 0$ determines the optimal speed of navigation in calm water, for the given technical state of the propelling engines and propulsion complex of the pushboat, which (in this case) equals *v*=16.72 km/h. Graphs of the change of total thrust ΣF_t and the thrust output of K series pushboat are obtained based on experiments with pushed convoys having shapes marked as A, B, C, D, E, F, G and H are shown in Figure 8.

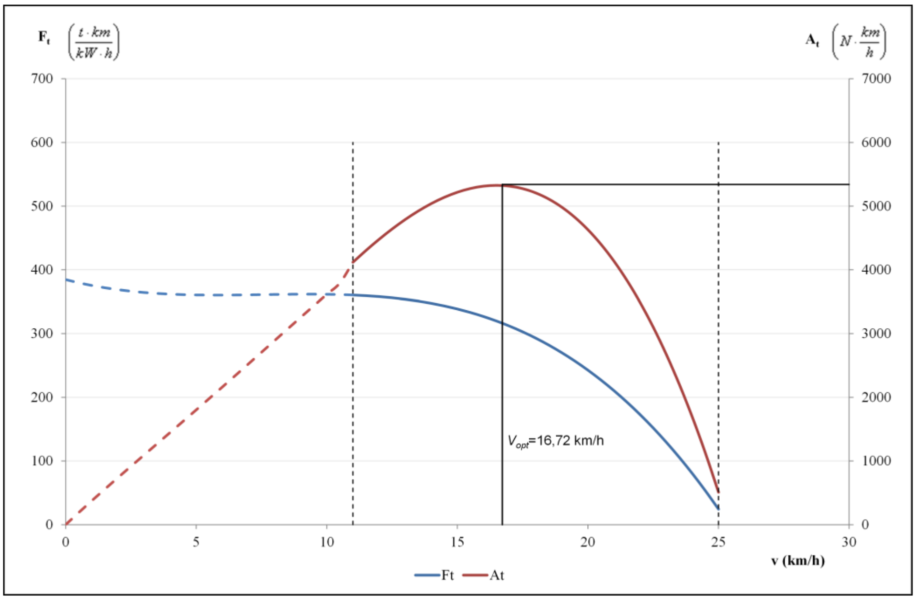

Figure 8 Graph of the change in thrust and thrust output of the K series pushboat

It is known that thrust F_t during constant movement of pushed convoys can be equalized to the total resistance of pushed convoy R_S, or in other words $\Sigma F_t = R_S$. Based on this assumption, the curve of the change of resistance of the pushed convoys shown in Figure 7 (R_S, kN) for the range of measured speeds (*v*, km/h) has the following shape:

$$R_S = f(v) = 0.160 \cdot v^3 - 8.562 \cdot v^2 + 136.3 \cdot v - 321.8, \; (r^2=0.998). \tag{4}$$

When solving tasks which relate to the choice of the pushboat and pushed convoy it is often useful to use the method of reduced resistances [7], [8], [9], according to the following equation:

$$\overline{R}_S = \frac{R_S}{v^2} \tag{5}$$

Reduced resistance can be described by the following equation:

$$\overline{R}_S = f(v) = -0.01 \cdot v^3 + 0.736 \cdot v^2 - 18.65 \cdot v + 167.3, \; (r^2=0.999). \tag{6}$$

The total resistance of the pushed convoy is usually lower than the sum of all individual resistances of all the barges within the convoy and the resistance of the pushboat, which is especially characteristic when barges form a shape which has a favourable *L/B* ratio. Calculation of the resistance of the pushed convoy is done according to the following equation (7) [7], [8], [9]:

$$R_S = k_S \cdot \left(\sum_{i=1}^{n} R_i + R_T \right) \tag{7}$$

where:

k_S, shape coefficient of the pushed convoy;

$\sum_{i=1}^{n} R_i$, total resistance of all the barges that make the pushed convoy, N;

n, number of barges in the pushed convoy;

R_i, individual resistance of each individual barge that make the convoy, N;

R_T, resistance of the ship (pushboat) in the pushed convoy, N.

Based on the above stated it follows that the shape coefficient of the pushed convoy (k_S) is calculated according to the expression:

$$k_S = \frac{R_S}{\sum_{i=1}^{n} R_i + R_T} \tag{8}$$

By using the described procedure for each pushed convoy A, B, C, D, E, F, G and H the coefficient of the shape was calculated. The curve of the change of the coefficient of shape of the pushed convoy as a function of speed of navigation has the following shape:

$$k_S = f(v) = -0.0207 \cdot v^2 - 0.0825 \cdot v + 1.9493, \ (r^2=0.9996) \tag{9}$$

and can be presented by a graph, as shown in Figure 9.

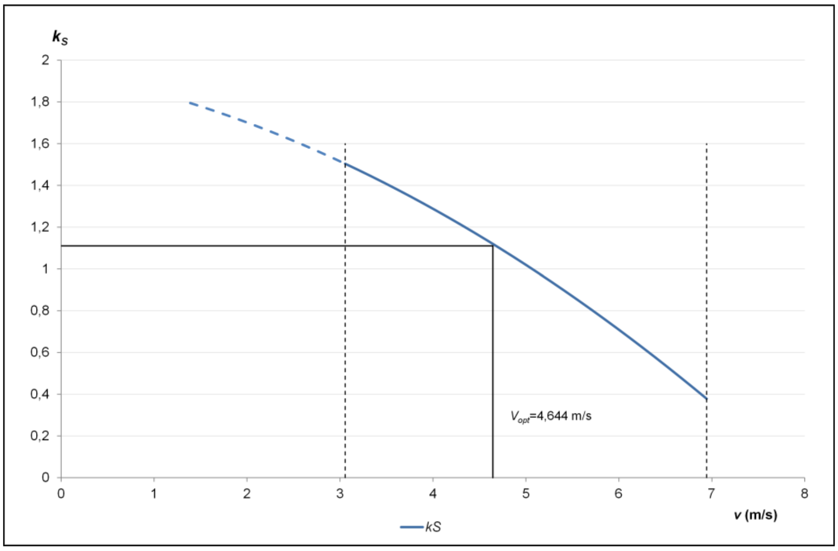

Figure 9 Graph of the change of shape coefficient of pushed convoy

Presented results are valid for the range of speeds between 11 km/h and 25 km/h, which is presented by vertical dashed lines in Figures 8 and 9.

Since there are no measurements of resistance for barges within the series JRB71300, JRB81200 and JRB81500 in actual navigating conditions, to calculate the value of coefficient of shape of the tested pushed convoys (k_S), the resistance of each barge was determined according to the ITTC-57 method as stated in [2], [3], [4], [7], [8], [9], [10]. In this way, the curve of change of total resistance (R_i) was determined for each of the stated barge types for speeds of navigation in calm water up to 6.0 m/s, together with the curve of change of their reduced resistance ($\overline{R}$) for the same speeds, Table 6.

Table 6 Shapes of the change of curve of resistance (R_i) and reduced resistance ($\overline{R}$) for barges JRB71300, JRB81200 and JRB81500

Barge type	Curve of change of barge resistance R_i(N) and curve of change of reduced resistance $\overline{R}$ (N·s²/m²)
JRB71300	$R_{71300} = f(v) = 1.7901 \cdot v^2 + 0.0823 \cdot v - 0.0759$, ($r^2$=0.9997) $\overline{R}_{71300} = f(v) = -2.22 \cdot v^4 + 27.04 \cdot v^3 - 111.4 \cdot v^2 + 175.2 \cdot v + 1723$, ($r^2$=1,0)
JRB81200	$R_{81200} = f(v) = 1.9835 \cdot v^2 - 1.5969 \cdot v + 0.5592$, ($r^2$=0.9995) $\overline{R}_{81200} = f(v) = -7.87 \cdot v^3 + 101.9 \cdot v^2 - 371.3 \cdot v + 1980$, ($r^2$=0.997)
JRB81500	$R_{81500} = f(v) = 2.045 \cdot v^2 - 0.3891 \cdot v + 0.1911$, ($r^2$=0.9998) $\overline{R}_{81500} = f(v) = 2.672 \cdot v^4 - 33.12 \cdot v^3 + 165.9 \cdot v^2 - 403.0 \cdot v + 2323$, ($r^2$=1.0)

Based on the calculated resistance of each barge type and their total number by types which form convoys, the values of total resistances of all the barges per convoys A, B, C, D, E, F, G and H were calculated, which gives value $\sum_{i=1}^{n} R_i$. The total resistance of the pushed convoy (R_S) is gained by adding the resistance of the ship, pushboat (R_T) to the previously calculated resistance of all barges in the convoy, $R_S = \sum_{i=1}^{n} R_i + R_T$.

The resistance of the pushboat is calculated according to the known ITTC-57 method, where the speed of flow of water around the ship's hull has to be used (v_T), instead of the speed of navigation v. The speed (v_T) which is used for the calculation of the resistance of the pushboat is calculated according to the expression [7], [8], [9]:

$$v_T = v \cdot (1 - \psi_S) \qquad (10)$$

where ψ_S is the coefficient of the return flow of water which occurs as a consequence of movement of barges in the convoy and is calculated according to the expression [7], [8], [9]:

$$\psi_S = c \cdot \delta \cdot \frac{\sqrt{\otimes}}{L + l} \qquad (11)$$

where,

c, coefficient, which is c = 0.9;

δ, block coefficient of barges that make the convoy; in the calculation procedure it is taken as the average value of all block coefficients of all the barges in the convoy;

$\otimes$, area of the main frame of barges that are tied immediately to the pushboat (the first row of barges), m²;

L, length of the stern part of the barge tied to the pushboat, m;

l, distance between the propeller-nozzle complex and the stern part of the barge that are tied immediately to the pushboat, m.

Function of the change of resistance of the pushboat (R_T) tied to the convoys shaped as A, B, C, D, E, F, G and H according to the stated procedure is best described by the curve of the following shape:

$$R_T = f(v) = 0.142 \cdot v^2 + 1.440 \cdot v - 0.328 \text{, } (r^2=0.9998) \qquad (12)$$

It is known that on the basis of determined technical parameters the following tasks can be solved for pushboats:

1. determination of pushed convoy navigation speed for the known working parameters of the pushboat and barges that make the pushed convoy;
2. choosing the convoy of barges for known parameters of the pushboat and for given speed of navigation;
3. choosing the pushboat for known convoy for given speed of navigation.

When forming barge convoys it is important to bear in mind the following two assumptions:

1. resistance of the pushboat is negligibly low in comparison to total resistance of all the barges in a convoy
2. it is not recommended that convoys are formed from barges that significantly differ in their shape, and also, barges that have differences in draughts that is 10% or more.

In the case when it is necessary to determine optimal carrying capacity of the pushed convoy $Q_{e(opt)}$, for known technical parameters of the K series pushboat and calculated optimal speed of navigation, the procedure has the following steps:

1. Optimal speed of navigation of a pushboat with a convoy is v_{opt}=16.72 km/h v_{opt}=4.644 m/s;

2. Total and reduced resistance of a barge convoy at speed v_{opt}=16.72 km/h v_{opt}=4.644 m/s are:

$$R_S = f(v) = 0.160 \cdot 16.72^3 - 8.562 \cdot 16.72^2 + 136.3 \cdot 16.72 - 321.8 = 311{,}431.61 \text{ (N)};$$

$$\overline{R} = f(v) = -0.01 \cdot 16.72^3 + 0.736 \cdot 16.72^2 - 18.65 \cdot 16.72 + 167.3 = 14{,}484.817 \text{ (N}\cdot\text{s}^2/\text{m}^2)$$

3. Total and reduced resistances of barges per barge types for the speed v_{opt}=16.72 km/h v_{opt}=4.644 m/s, by using expressions given in Table 6, are:

$$R_{71300} = f(v) = 38{,}912.915 \text{ (N)}; \qquad \overline{R}_{71300} = f(v) = 1{,}809.735 \text{ (N}\cdot\text{s}^2/\text{m}^2);$$

$$R_{81200} = f(v) = 35{,}920.817 \text{ (N)}; \qquad \overline{R}_{81200} = f(v) = 1{,}665.106 \text{ (N}\cdot\text{s}^2/\text{m}^2);$$

$$R_{81500} = f(v) = 42{,}488.094 \text{ (N)} \qquad \overline{R}_{81500} = f(v) = 1{,}955.036 \text{ (N}\cdot\text{s}^2/\text{m}^2);$$

4. Required number of barges in a convoy per types

$$n_{71300} = \frac{R_S}{R_{71300}} = \frac{311{,}431.61}{38{,}912.915} = 8.003 \text{ or } n_{71300} = \frac{\overline{R}_S}{\overline{R}_{71300}} = \frac{14{,}484.817}{1{,}809.735} = 8.003$$

$$n_{81200} = \frac{R_S}{R_{81200}} = \frac{311{,}431.61}{35{,}920.817} = 8.669 \text{ or } n_{81200} = \frac{\overline{R}_S}{\overline{R}_{81200}} = \frac{14{,}484.817}{1{,}665.106} = 8.669$$

$$n_{81500} = \frac{R_S}{R_{81500}} = \frac{311{,}431.61}{42{,}488.094} = 7.329 \text{ or } n_{81500} = \frac{\overline{R}_S}{\overline{R}_{81500}} = \frac{14{,}484.817}{1{,}955.036} = 7.408$$

5. Total thrust of the propellers of the K series pushboat at optimal speed of navigation v_{opt}=16.72 km/h is:

$$F_t = f(v) = -0.0655 \cdot 16.72^3 + 1.4852 \cdot 16.72^2 - 10.604 \cdot 16.72 + 384.6 = 316{,}340.078 \text{ (N)}$$

8. Conclusion

The importance of experiments on pushboats in actual navigating conditions with different barge types and different convoy shapes is unquestionable. Based on this research the real (actual) technical condition of propelling engines and propeller-nozzle complex can be determined.

Described experiments were done on a river deep enough with a low speed of water flow (water reservoir) which gave specific results which are applicable only for waterways with sufficient depths. To determine the influence of different shapes of pushed convoys it is necessary to conduct identical research in a waterway with a limited depth in which case different shapes of curves for thrust and thrust output are to be expected.

Calculations based on experiments show that the value of thrust F_t almost has the identical value as the total resistance of pushed convoy R_S (the difference is 1.57%), which is the reason why the claim of equality $\Sigma F_t = R_S$ can be assumed.

None of the eight pushed convoys that the measurements have been made for suits the designed shape P+4+4+4, which makes it hard to comment on the data obtained during the measurements of the working parameters of the pushboat of the K series in actual navigating conditions.

Based on the calculated number of barges per type and by comparing it to the optimal solution in optimal conditions, symmetrical pushed convoys are recommended with a favourable relation between the length and the width *L/B*, as for example P+4+4 or P+3+3+3. Such pushed convoys achieve speeds of navigation close to optimal, while at the same time their shape coefficients k_S have most favourable values. From all of the tested pushed convoys the closest solution to the optimal has the convoy marked with letter A.

It can be also seen from the tested convoys that those marked with letters D, E and F are significantly worse than the optimal solution. This is because those convoys have irregular shape formed from two different barge types together with tow units, which makes it impossible to form regular shapes of convoys, which can be also seen from their shape coefficient of the pushed convoys which are: $k_{S(D)}$=1.425; $k_{S(E)}$=1.443; $k_{S(F)}$=1.447.

In order to determine the real optimum for the tested ship-pushboat of known characteristics it is also necessary to conduct experiments with the same barge types (since previous experiments involved different barge types) and with symmetrical barges (since previous experiments involved only asymmetrical barges. Also, it is important to use as many different convoy shapes as possible.

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