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**CREATION OF MULTIFUNCTIONAL
ICE-BREAKING TUG FOR SHALLOW WATER**

Учитывая массовое списание существующего флота речных буксиров, существует необходимость в новых буксирах для речных портов.

На примере ледокольного мелкосидящего буксира проекта TG04 показаны основные принципы проектирования многофункциональных речных буксиров.

***Ключевые слова**: проектирование, речной буксир, мелководье, ледовые условия, функциональность.*

Враховуючи масове списання існуючого флоту річкових буксирів, існує необхідність в нових буксирах для річкових портів.

На прикладі криголамного мілкосидячого буксира проекту TG04 показані основні принципи проектування багатофункціональних річкових буксирів.

***Ключові слова**: проектування, річковий буксир, мілководдя, льодові умови, функціональність.*

Necessity of the new tug boats is very high in the river ports due to extremely decrepitude of existing fleet.

On example of ice-breaking shallow-draught tug of TG04 project main design principles of multifunctional river tugs are shown.

***Keywords:** design, river tug, shallow water, ice conditions, functionality.*

Problem statement. In the sector of river and mixed river-sea transportation shipowners actively invest finances into building of self propelled dry cargo and oil transport vessels as well as non-self propelled barges that provide direct cargo transportation and thus «earn» profit.

Existing tug and tug-pusher river fleet continues becoming out of date steadily. There were 55 vessels with the age up to 10 years, 110 vessels with the age from 10 to 15 years, 972 vessels with the age from 15 to 20 years, 2517 vessels with the age from 20 to 30 years and 3119 vessels with the age more than 30 years with the Russian River Register (RRR) class at the beginning of 2008. Unfortunately for the nearest time there are no plans due to significant investments for buying new representatives of auxiliary fleet.

Though in river ports neediness of new tugs are enough high due to significant dilapidation of existing fleet. One of such ports is river port of Dudinka that is included into Arctic branch of OJS «Mining & Smelting Complex «Norilskiy Nickel» [3].

Design of shallow draught river tugs was described in publications of 70-80-s of last century [5-10]. Since that time vessels of such type weren't designed.

In the process of new generation of tugs creation the greatest interest is lines optimization on the basis of numerical modeling [4]; usage of present-day technique in the field of weight-dimension characteristics diesel engines that let to increase tug power while keeping tug dimensions; decrease available operational risks by involving rational design of hull constructions [2].

Aim of the paper. Justification of definition characteristics of river tug that is effective for shallow water and river ice conditions. Prj. TG04 tug designed by Marine Engineering Bureau for the port of Dudinka was taken as an example.

Main text. Port of Dudinka is situated on the right shore of Yenisei River ate distance of 230 km from river's mouth. This is departmental port that was build in order to provide needs of Norilsk Mining & Smelting Complex.

Auxiliary fleet operation in the port of Dudinka is connected with a lot of problems; main of them as follows:

- short navigational period (from May till October), so efficient fault-free vessels' work is required;
- long period of the winter stay with extremely low outer air temperature (below -50 ºC) and freezing into ice for deepness of full draught (including propulsion complex);
- annual ice-drift that may be accompanied with significant damages or even perish of vessels and port facilities.

Thereafter river tug for severe Arctic conditions has to fit requirements as follows:

- tug has to be design for operation at extremely low outer air temperature;
- equipment and construction of the propulsion complex have to permit to put tug into operation at extremely low temperature from condition of full into-ice freezing;
- tug's hull should be of reinforced type for operation in the conditions of freeze basin;
- tug's weight should not exceed 100 t for providing ability to raise tug onto berth for the winter stay (crane capacity restriction);
- tug's maximal draught should not exceed 1.80 m (due to depth of the boatyard where fleet is placed for the winter stay and due to way conditions of the Dudinka River).

Tug must fulfill works due to providing port fleet safety during ice shifting, so her overall dimensions should me of minimal type. Tug's pollard pull should be not less than 6 t; that provides ability to service all fleet owned by the Arctic branch of Norilsk Complex.

Main tug characteristics and characteristics of some analog vessels (including tug «Tayezhniy» of prj. 1427 that was substituted by TG04 one) are shown in the Table 1.

Table 1

Comparative characteristics of TG04 tug and her prototypes

Denomination	TG04 prj.	1427 prj.	P14A prj.
Length overall, m	20.45		31.50
Length due waterline L, m	18.50	18.20	30.40
Breadth due waterline on the middle B, m	6.00	4.20	6.60
Breadth overall, m	6.56	4.40	6.80
Depth on the middle H, m	2.40	2.56	1.80
Draught due waterline d, м	1.80	1.43	1.08
Maximal continuous ME power N, kWt	2×221	2×110	2×166
Pull effort, т	6.50		4.15
Gross Tonnage, reg. t.	84.81		171
Crew	6		11
Type and number of propulsion devices	2 FPP	2 FPP	2 FPP

Beforehand setting of tug's light weight (100 t) and maximal draught (d = 1.80 m) determines main dimension of the vessel (LxBxH = 18,5 x 6 x 2,40 m).

Tug's architect-constructive type was selected as classic type for port tugs, notably single deck double screw vessel with upper deck fore recess, with wheel house and ER located middle, with ice-breaking stem (see Figure 1).

Sailing regions are basins and mouth reach of the rivers with sea navigation regime of «O» class. The vessel can be operated at sea roughness with 1 % probability wave height no more than 2.0 m.

Registry class is determined in accordance with planned sailing region. Class notation is «✠ O 2,0 (ice 30)» of Russian River Registry (RRR). Ice category is assigned higher that recommended by RRR Rules for vessels of «✠ O 2,0» type due to actual operational conditions at the port of Dudinka.

Tug hull's shapes were determined with help of CFD-modeling (see lines in the Figure 2).

Same time choice of revolutions and hydrodynamic characteristics of screw propellers (SP) was carried out in order to achieve bollard pull not less than 6.0 t a the project mode.

The project mode means SP work at mooring regime (zero speed) with nominal revolutions and full (100 %) loading of main engines (ME).

Initial data for the screw:

- diameter of opened screws D_p = 1.200 m;
- number of screws x = 2;
- number and power of Main Engines 2 × 221 kWt.

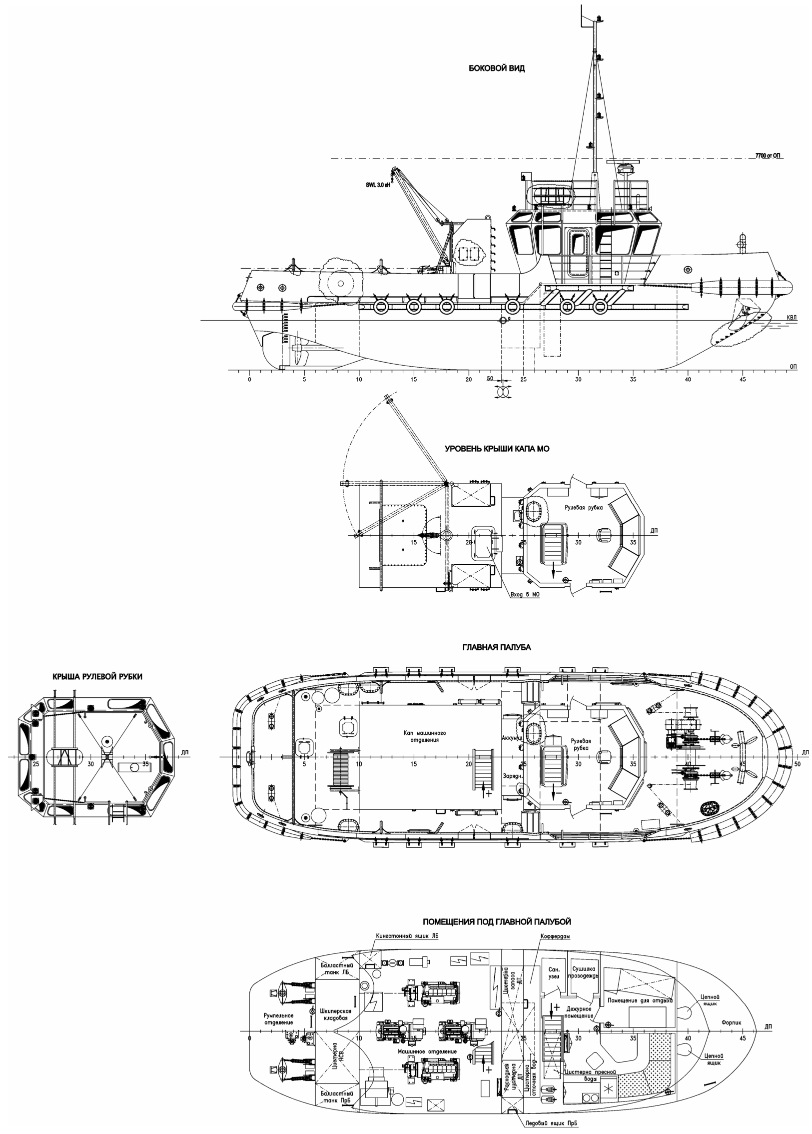

Fig. 1. Shallow draught ice-breaking river tug boat General Arrangement

Screw propellers are places in the light semi-tunnels of the hull in accordance with estimated ice conditions and shallow draught. At the calculated conditions SP are fully immerged, accordingly $D_p/T = 0.667$.

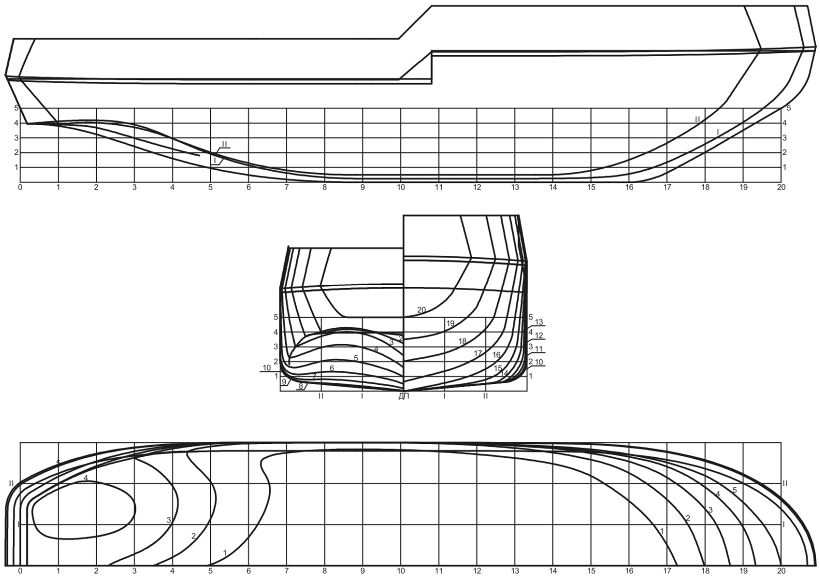

Fig. 2. Lines of shallow draught river tug

Calculation of optimal revolutions of SP is made in the Table 2.

Revolutions value was varied in the limits 350-420 rpm with the step of 10 rpm during calculation. For each revolutions value pitch ratio was fitted in order to provide 100 % load of ME. Correlation between geometric and hydrodynamic characteristics of SP is accepted in accordance with test of 4-blade propellers of «B» series at the Netherlands towing tank.

Blade-area ratio A_E/A_O is accepted of 0.650 on the basis of minimal value $A_E/A_{O\,min}$ determination for condition when hard cavitation is absent for each revolutions value. $A_E/A_{O\,min}$ value determination is carried out with help of well known Keller formula (1) that sets relations of blade-area with SP pull effort and work conditions.

$$A_E / A_{O\,min} = \frac{0.05 + (1.3 + 0.3z) \cdot T_p}{D_p^2 (p_0 + \rho g h - p_v)}, \qquad (1)$$

where z – SP blades number;

T_p – SP pulling effort;

$p_0 + \rho g h$ – static pressure onto SP axis;

p_v – saturated vapor pressure onto SP axis.

$p_0 - p_v$ = 99047 Pa is accepted for calculations, that corresponds water conditions at temperature of 15 ºC.

ME load due to effective power N_E (Table 2, lines 8 and 9) is calculated accounting efficiency factor of 0.95.

SP bollard pull during mooring regime T_E (Table 2, line 10) is calculated accounting suction; suction coefficient for mooring regime t_{P0} is accepted of 0.100 preliminary.

Table 2

Optimal SP revolutions calculation

1	n, rpm (preset)	350	360	370	380	390	400	410	420
2	$A_E/A_{O min}$	0.609	0.615	0.620	0.625	0.630	0.633	0.637	0.640
3	P/D_p	1.016	0.973	0.933	0.895	0.860	0.828	0.797	0.768
4	A_E/A_O	0.650	0.650	0.650	0.650	0.650	0.650	0.650	0.650
5	K_T	0.452	0.433	0.414	0.396	0.379	0.363	0.348	0.333
6	K_Q	0.068	0.062	0.057	0.053	0.049	0.045	0.042	0.039
7	T_p, kN	0.452	0.433	0.414	0.396	0.379	0.363	0.348	0.333
8	N_E, kWt	221.0	221.0	221.0	221.0	221.0	221.0	221.0	221.0
9	N_E, b.h.p.	300.6	300.6	300.6	300.6	300.6	300.6	300.6	300.6
10	T_E, t	2.928	2.962	2.993	3.021	3.046	3.069	3.089	3.106
11	$T_{E\Sigma}$, t	5.855	5.924	5.986	6.042	6.092	6.137	6.177	6.213

Approximate bollard pull during mooring regime $T_{E\Sigma}$ is given in line 11 of Table 2.

Reduction ratio i_r = 4,409:1 of reduction gears was determined while taking into consideration data from Table 2. This value corresponds to the nominal SP revolutions of 408 rpm.

Bollard pull distribution during mooring regime in accordance with Table 2 data is given in the Figure 3; determined nominal SP revolutions is marked.

One may see in the Figure 3 that pull curve has no maximum; pull increases while RPM increases. Pull curve approaches to some constant value asymptotically.

So when determining optimal RPM one should try to increase it in the limits set by SP cavitation, SP construction and providing of suitable free run abilities of tug. Taking into consideration abovementioned the determination of reduction ratio looks reasonable enough in our case.

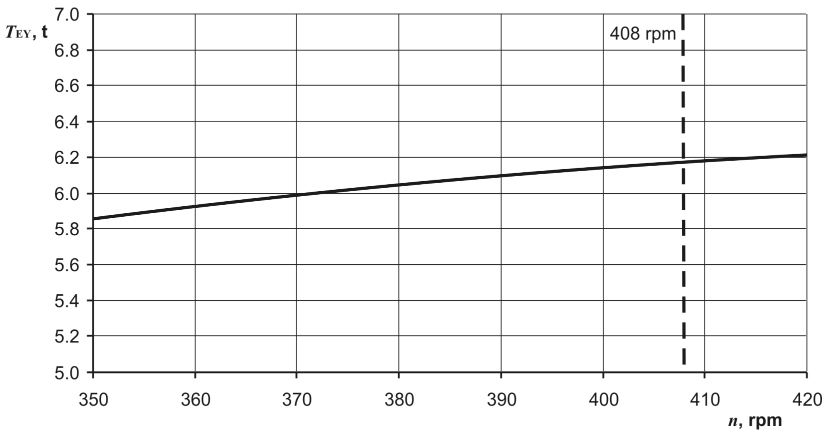

Fig. 3. Pull curve

SP characteristics of TG04 tug is accepted as follows accounting determined nominal RPM (on the basis of "B" series of SP):

Diameter D_P = 1.299 m;

Pitch ratio P/D_p = 0.803;

Blade-area ratio A_E/A_O = 0.650;

Blade number z = 4.

For more detail determination of pull characteristics of the tug it's necessary to take account of interaction between SP and hull.

Wake factor for SP in tunnels for examined vessel's type can be determined by E.E. Pupmel formula

$$w = 0.11 + \frac{0.16}{x} C_B{}^x \sqrt{\frac{\sqrt[3]{\nabla}}{T}} = 0.247\,, \tag{2}$$

where x = 2 – SP number;

C_B = 0.603 – block coefficient;

∇ = 120.4 cub.m – volumetric displacement;

T = 1.80 m – draught.

Wake factor is accepted as constant value for various velocities and ME regimes.

Suction coefficient is approximately equal to wake factor for fully immersed SP located in tunnels (in accordance with recommendations [1]). Assume t_p = w = 0.247 for tug free run at the speed of 10 kn.

Suction coefficient dependence from ME work regime is set by E.E. Papmel by the next formula:

$$t_p = \frac{t_0}{1 - \dfrac{J}{P_1/D_p}}\,, \tag{3}$$

where J – SP advanced ratio;

T_1/D_p – pitch ratio for zero thrust; for our case T_1/D_p = 0.866.

Using (3) one can defines suction coefficient for mooring regime t_{P0} by inserting known values t_p = 0.247, P_1/D_p = 0.866 and SP advanced ratio J = 0.475 (for speed of 10 kn and nominal RPM). Suction coefficient for mooring regime is of t_{P0} = 0.110.

Tug pull capacity data was defined using abovementioned SP characteristics and «hull-SP» interaction coefficients. Corresponding calculations were made for speed range of 0 (mooring regime) to 10 kn and RPM range from 310 to 408. This data is shown in the Table 3 and Figure 4.

Table 3

Pulling effort $T_{E\Sigma}(t)$ for different regimes

n, rpm.	V_S, kn							
	0.00	1.43	2.86	4.29	5.71	7.14	8.57	10.00
408	6.10	5.71	5.28	4.82	4.33	3.80	3.25	2.68
390	5.57	5.20	4.79	4.34	3.87	3.36	2.83	2.27
370	5.02	4.66	4.27	3.84	3.38	2.90	2.39	1.85
350	4.49	4.15	3.78	3.37	2.93	2.47	1.97	1.46
330	3.99	3.67	3.32	2.93	2.51	2.06	1.59	1.10
310	3.52	3.22	2.88	2.51	2.11	1.69	1.24	0.77

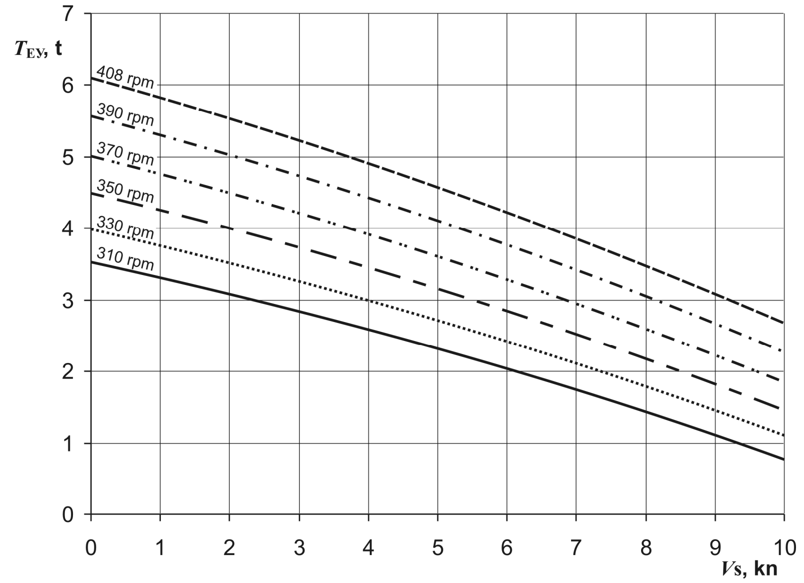

Fig. 4. Pulling effort $T_{E\Sigma}$ for different regimes

For achieving free running speed or speed during towage on the basis of Table 3 or Figure 4 it's necessary to set resistance values for tug and towing object taking into consideration lashing coefficient (depending on the speed value). ME load rises to the maximal capacity (100 %) during mooring regime.

Due to calculations bollard pull during mooring regime reaches value of 6.1 t at the nominal ME revolutions.

Tug's movement is provided by two open cast steel 4-blades fixed pith propellers. Screw propeller's diameter is of 1200 mm, pith ratio is of 0.793, blade-area ratio is of 0.65. Propellers drive from two ME (221 kWt each) is of mechanical type trough reverse gear. Ability of ME work with load of 110 % during 1 hour is foreseen.

With the design draught of 1.8 and ME load of 90 % tug's speed reaches 10.2 kn.

Maneuvering characteristics of the tug are provided by two balanced (with double bearings) rudders arranged by sides. Rudder blades are made of streamlined type. Ice «claw» is foreseen for each rudder blade protection against ice operation damages.

For rudder blade turning two independent electro-hydraulic steering engines are installed in the steering gear room. They provide simultaneously (synchronic) and independent rudders putting over to any side. The steering gear ensures putting rudder over from 35 ° on one side to 35 ° on the other side at maximum ahead speed within not more than 22 sec.

Tug's docking weight is of 88 t about. Design tug's hull life period of 15 years was accepted in order to achieve such weight.

Vessel's hull is made from D category steel. Hull is set up by transverse framing system; frame spacing is of 600 mm. Floors are located on each frame. Thickness of outer shell, deck and deck-house bulkheads (from 4 till 9 mm) is accepted due to strength providing and RRR requirements.

Main watertight transverse bulkheads are placed at frs. 6, 10, 23, 29, so divide hull into 5 independent compartments. Bulkheads are of flat type with thickness of 4 or 5 mm. Bulkhead's girders are made from non-symmetrical bulb iron №.8 and from welded T-profile (4x150/8x80 mm).

Vessel's stem is of ice-breaking type. It is made from plate with section 30x125 mm that is enforced by transverse girders and welded T-profile s6/8x80 mm. Side girders is made from non-symmetrical bulb iron № 8 (frames) and from welded T-profile 5x250/8x80 mm (web frames and stringers). Floors and bottom stringers are made from welded T-profile with beam web of 5 mm and belt of 8x80 mm outside ER and with beam web of 6 mm within ER. Deck girders are made from non-symmetrical bulb iron № 8 (beams) and from welded T-profile 4x200/8x80 mm (web beams and carlings). Thickened plates and corresponding enforcements are installed at the places where anchor-mooring and towing equipment is arranged.

Wheel house is arranged on the elevated fore part of upper deck. At this end electrical anchor-mooring-towing winch (pull of 75 kN) and towing bitt that provide ability for different objects canting.

Basic pulling effort of tow winch is of 50 kN for the first layer of drum, maximum pulling effort is of 75 kN for the first layer. Rope capacity of tow winch drum is of 100 m of synthetic rope with diameter of 48 mm.

Vessel's fuel autonomy is of 3.3 days, water autonomy is of 4.8 days. Heavy fuel stores are placed in tanks arranged in deep-tank in area of the ER fore bulkhead. Fuel tanks have no contact with the outside water due to RRR Rules.

Independent fresh water tank is arranged in the middle part of the hull.

Battery box and charging compartment are located in the middle part of the deck.

Engine room with 900 mm height cape, boatswain's locker and steering gear room are located in the aft end of the vessel.

Towing hook (working load about 70 kN) with automatic and remote release is installed onto ER cape for towing operations providing. both synthetic or steel towing rope can be used when working with towing hook.

Boxed band made of 10 mm plate is mounted onto the sides in order to avoid hull damages during towing and canting operations. Additionally cylindrical rubber fender is mounted fore and aft for the same purpose.

Auxiliary power plant consists of two diesel generators of 62 kWt each. Auxiliary power plant provides energy for the vessel and is able to forward energy to the shore or another floating object.

It's foreseen that the vessel can be withdrawn from operation by her freezing in ice for 6 months without ER and everyday quarters warming-up.

Putting into operation after winter staying is carried out with negative outdoor air temperature (down to -20 °C) and with positive temperature (provided by electrical air heater) in ER.

Keel of tug-boat «Portoviy 1» (building number is of 701) was laid down on 12.09.08. Tug was launched 27.08.09 and put into operation 17.09.08.

Tests carried out on the Volga River in the September, 2009 and first operation 2009-2010 confirmed accepted tug design decisions fully.

Conclusions. Main characteristics of new river tug boat for the port of Dudinka were justified, including:

- roadstead- maneuvering works with river going vessels and floating cranes;
- auxiliary works such as berthing, unberthing, handling of barges and vessels;
- vessels' placing in backwater during spring flood;
- ice-breaking works in the port of Dudinka during autumn period;
- placing of non-self propelled fleet for winter stand (placing over a distance from berth in autumn ice with holding until vessel freezes in.

Within auxiliary fleet of «Mining & Smelting Complex «Norilskiy Nickel» the tug-boat «Portoviy 1» (TG04 prj.) substituted tug-boat of 1427 prj. (1969 built) at the port of Dudinka.

Three more tugs of modernized project TG04M have been built since 2010.

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