METHOD FOR DETERMINATION OF ENERGY DEMAND FOR MAIN PROPULSION AND ONBOARD ELECTRIC POWER FOR MODERN HARBOUR TUG BOATS BY MEANS OF STATISTICS

Zygmunt Górski, Mariusz Giernalczyk

Gdynia Maritime University
Faculty of Marine Engineering, Department of Marine Propulsion Plants
Morska Street 83, 81-225 Gdynia, Poland
tel.:+48 58 6901324, +48 58 6901307
e-mail: zyga@am.gdynia.pl , magier@am.gdynia.pl

Abstract

The paper presents the method of preliminary estimation of harbour tugs main propulsion power and on board electric power station based on statistical analysis. At the beginning of paper, the classification of tug boats is executed. Tug boats are classified according to their type of service, type of main propulsion, equipment and way of service. For harbour and roadstead tug boats, the analysis of main propulsion plants and on board power station is executed. Pushing and tractor propulsion plants are presented in which different types of thrusters i.e. azimuth, cycloid and classic propellers are analysed. Advantages and defects of each type of main propulsion are pointed. Statistic methods of analysis are elaborated in Department of Marine Propulsion Plants of Gdynia Maritime University. These methods make possible in simple and quick way to estimate parameters of ship energetic system. The estimation is carried out with good correlation coefficient and high determination of regression coefficient. Statistic methods make also possible to forecast energetic systems parameters for ships to be built in the future. Dependencies for main propulsion power and electric power of onboard power station are not universal for all types of ships. They should be elaborated separately for each type of ships. In this paper, the results concerning only harbour and roadstead tug boats are presented.

Keywords: *harbour tug boat, main propulsion, on board electric power station, statistics*

1. Introduction

Harbour tug boats are vessels designed for towing other vessels not equipped with own propulsion, assisting seagoing vessels during berthing and leaving harbours, assisting vessels during manoeuvres, towing and protecting defected ships and participating in rescue operations. Tug boats are commonly driven by diesel engines. Usually the tug boat is equipped with high power engines (from a few to a dozen or so thousand kW) incommensurate with tug boat dimension. It makes possible to achieve very high towing force (from a dozen to even above hundred tons). A serious development of tug boats group has been observed in last years. New types of tugs were constructed according to new tasks often very specialized, for example, AHTS tug boats (Anchor Handling Tug Supply) used for oil rigs maintenance. This is why nowadays towing vessels can be classified by many criterions as follows:

- operation area: open ocean, restricted sea, harbour & roadstead, river, lake,
- way of work: towing, pushing,
- additionally equipped tugs can serve as:
  - rescue tugs – high seaworthiness crafts which can rescue people and ships in heavy sea conditions and ”fight” oil, chemical and other environment pollutions,
  - hydrograph ships,
  - underwater works service ships,
  - icebreakers,
  - fire fighting ships,
  - service AHTS tugs for drilling platforms,
  - others,

- type of main propulsion: direct or gear, single or multi engine propulsion (usually double engine),
- Type and number of propulsors: fixed pitch or controllable pitch propellers, free or in nozzle propeller, azimuth thrusters (for example Schotel, Aquamaster) and cycloid thrusters (Voith-Schneider).

Tug boats can be characterized by towing force measured in *kN* or *tons*. Among many types of tug boats, the biggest in number are harbour & roadstead tugs equipped with towing hooks or towing winches with automatic adjustment of towing line tension. These tugs are used for helping large ocean ships during entrance, manoeuvring in port, departing and shifting. In addition, these tugs can be used in fire fighting actions.

The target of this paper is analysis of main propulsion and onboard electric power station of harbour & roadstead tug boats and determination formulas for main propulsion power and onboard electric power stations depending on basic construction parameters by using statistic methods. To fulfil these requirements the "reference list" of 80 of harbour & roadstead tug boats built in Polish and foreign shipyards was prepared in which tug boat basic construction parameters were listed. Due to construction, differences mainly in hull block coefficient a separate analysis are carried out for tugs driven by azimuth thrusters, cycloid thrusters and classic propellers some of them working in nozzles. From construction parameters these ones were analysed which are logically and functionally tight with energy demand for main propulsion and ship electric network.

The executed analysis of "reference list" shows that basic construction parameters of harbour & roadstead tugs are:

- overall length 15-50 m (mostly about 30 m),
- breadth 5-14 m (mostly about 9.5 m),
- draught 2-6 m (mostly about 4.5 m),
- towing force ahead 5-80 tons (mostly about 40 tons), towing force astern about 10 tons less,
- maximum sailing speed when at sea 11-14 knots (usually about 12 knots),
- main propulsion usually consists of two medium speed diesel engines 1000-2000 kW each (total 2000-4000 kW); the biggest of them have total power about 5000 kW,
- contemporary tugs are usually equipped with two azimuth thrusters or two cycloid (Voith-Schneider) thrusters, which have very high maneuverability; less frequently two controllable pitch propellers or fixed pitch propellers usually mounted in nozzles are used; the smallest tugs (tugs of smallest towing force) can be equipped with single main propulsion unit,
- on board electric power station consists of two diesel alternators 70-150 kW in power each; some big tugs have diesel alternators up to 200 kW and in addition, they can be equipped with small power harbour diesel.

The propellers of azimuth thrusters are driven by „Z" type reduction gear. Simultaneously thrusters can turn around vertical axis, thus the towing force can be pointed in any direction. These way thrusters can serve as steering gears (rudder propellers) and ensures high maneuverability. Thrusters can be installed in stern part of hull working as "pushers" or under central part of hull working as "tractors". "Tractor type" tug boats must be equipped with shields and developed keels to protect thrusters against contact with sea bottom. Such a tug boats are shown in Fig. 1.

Cycloid (Voith-Schneider) thrusters are plants with vertical axis of rotation and a number (3-8) of vertical blades mounted to the bottom of horizontally rotating plate. Blades rotate together with plate simultaneously semi rotating around their own axis. Cycloid thrusters similar to azimuth thrusters can be mounted in "tractor" or "pushing" system as shown in Fig. 2. Most of them work in "tractor" system. "Pushing" system is mainly used on pushing tug boats (pushers).

During analysis of propulsion plants of harbour & roadstead tug boats it was recognized, that the main propulsion power N_w *[kW]* depends on towing force *U [tons]*, dimensions of hull (overall length · breadth · draft) $L \cdot B \cdot T$ $[m^3]$ and sailing speed at sea *v [knots]*.

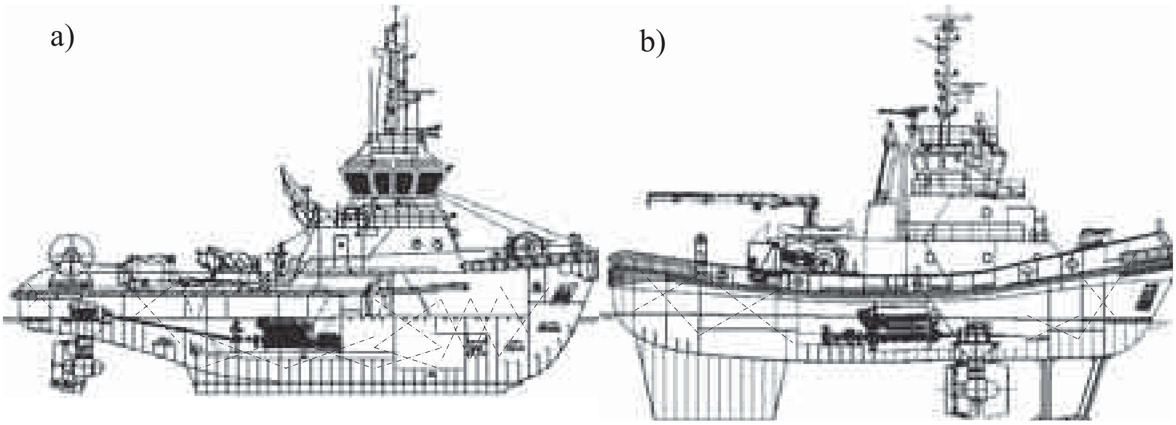

Fig. 1. Tug boats driven by azimuth thrusters. a)"pushing" type propulsion, b) "tractor" type propulsion

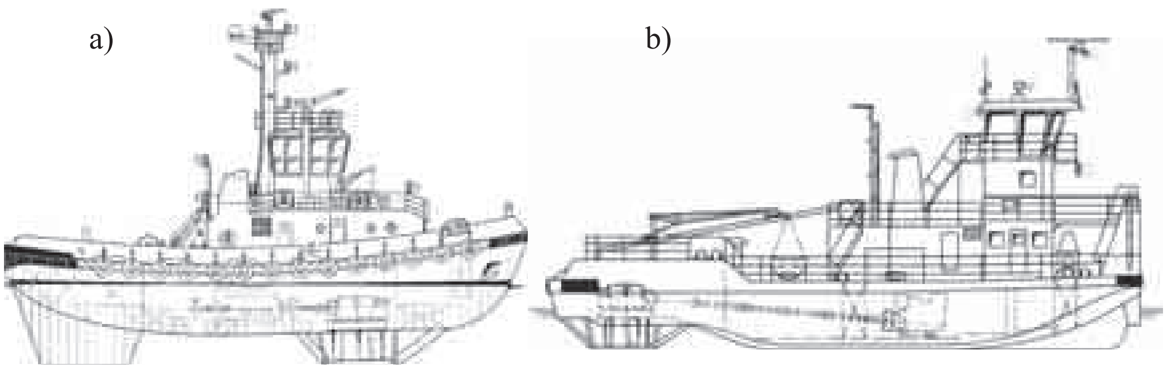

Fig. 2. Tug boats driven by cycloid thrusters. a) "tractor" type propulsion, b) "pushing" type propulsion

2. Analysis and determination of main propulsion power

The basic service parameter of harbour & roadstead tug boat is towing force. Thus, it was necessary to determine the dependency of tug main propulsion power on its towing force. This dependency was obtained by means of statistic researches on harbour & roadstead tug boats population separately for each of three kinds of main propulsion (azimuth, cycloid and classic). Analysis was executed according to linear regression pattern using least squares method. Results are shown in Fig. 3-5. The appropriate formulas are given in figure captions. High values of regression determination coefficients and correlation coefficients are to be noticed.

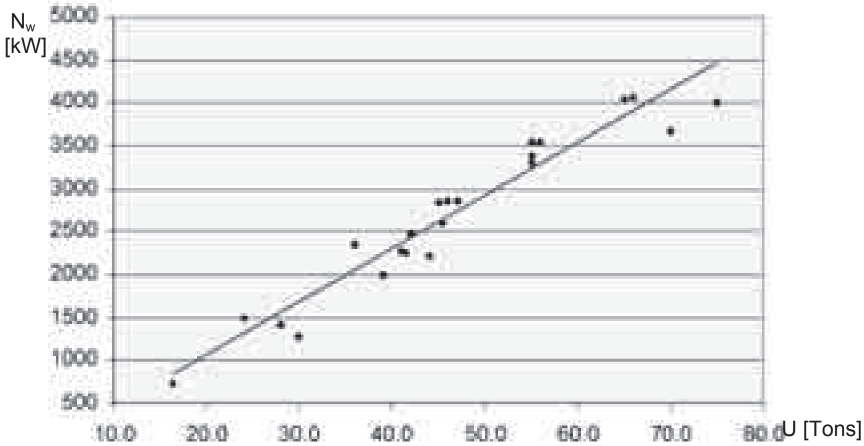

Fig. 3. Linear regression of dependency of main propulsion power on towing force $N_w=f(U)$ for tugs equipped with azimuth thrusters

$$Ne = -168.91 + 61.844 \cdot U, \; r^2=0.9283 \; r = 0.9635.$$

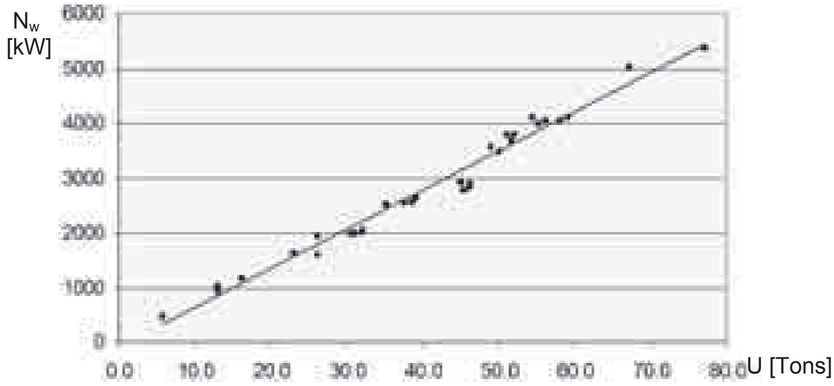

Fig. 4. Linear regression of dependency of main propulsion power on towing force Nw=f(U) for tugs equipped with cycloid (Voith-Schneider) thrusters

$$Ne = -82.265 + 71.855 \cdot U, \; r^2 = 0.9773 \; r = 0.9886.$$

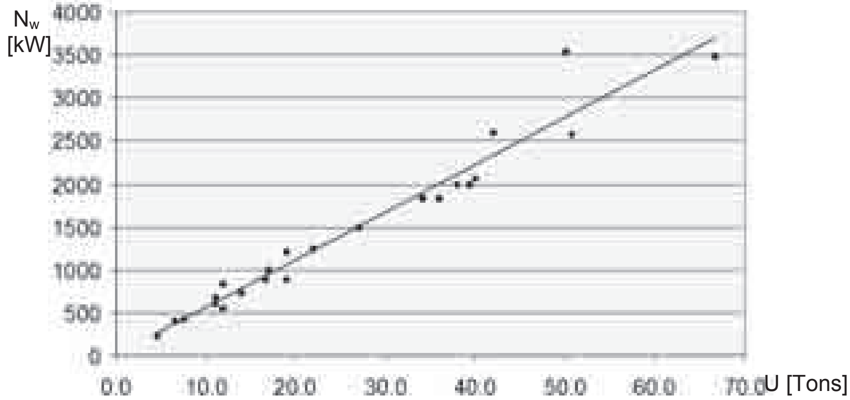

Fig. 5. Linear regression of dependency of main propulsion power on towing force Nw=f(U) for tugs equipped with classic propellers

$$Ne = 11.484 + 55.144, \cdot U \; r^2 = 0.9521 \; r = 0.9758.$$

The second part of research concerned on dependency of main propulsion power on dimensions of tug hull and sea sailing speed. The Admiralty Formula where the propulsion power N_w depends on ship deadweight or displacement D, ship speed and Admiralty Coefficient c_x was used in analysis:

$$N_w = \frac{D^{\frac{2}{3}} \cdot v^3}{c_x}. \tag{1}$$

Due to lack of data concerning block coefficient of tugs hull it was impossible to determine displacement of these ships. For this reason, it was recognized that tug boats have similar hull block coefficient and for farther analysis, the product of main hull dimensions can be used. Formula (1) changes to the form:

$$N_w = \frac{(L \cdot B \cdot T)^{\frac{2}{3}} \cdot v^3}{c_x}. \tag{2}$$

From the reference list consisting *i=73* tug boats (23 with azimuth thrusters, 31 with cycloid thrusters and 19 with classic propellers) were analyzed. Using formula (2) for each *i* ship from reference list the coefficient c_x was calculated. Next, it was used for calculation of main propulsion power N_{wi} for each *i* ship from reference at 7 chosen sailing speed *v*. For each sailing speed *v* a diagram of dependency $N_w = f(L \cdot B \cdot T)$ was constructed. The linear character of this dependency was affirmed:

$$Nwv = aov + a1v \; (L.B.T). \tag{3}$$

Calculation of a_{oi} and a_{1i} coefficients for each ship was based on linear regression by means of least squares method. Analysis of formula (3) for different ship speeds affirmed that coefficients a_{oi} and a_{1i} are functions of ship speed:

$$ao = f(v) \text{ and } a1 = f(v). \tag{4}$$

To determine a_o and a_1 coefficients in dependence on ship speed the approximation by power function was used:

$$y = b \text{ x } d. \tag{5}$$

In described case the following dependences were assumed: $a_o = b_o \cdot v^{do}$ i $a_1 = b_1 \cdot v^{d1}$. Coefficients b_i and d_i were calculated by means of least squares method and it was assumed that formula (5) is third power function of ship speed:

$$\begin{aligned} ao &= f(v) = bo \,.\, v3, \\ a1 &= f(v) = b1 \,.\, v3. \end{aligned} \tag{6}$$

Dependecies (6) were applied to formula (3) and as result a final formula for ship main propulsion was obtained:

$$Nw = (ao + a1 \,.\, L.B.T)\ v\ 3\ [kW], \tag{7}$$

where:
$L \cdot B \cdot T\ [m^3]$ – main dimensions of ship hull,
v *[knots]* – ship speed,
a_o, a_1 – coefficients depending on ship type.

2.1. Example of calculation of propulsion power for harbour & roadstead tug boats with azimuth thrusters

A number of $i=23$ tug boats were analyzed. Using formula (2) coefficient c_x was calculated for each tug from reference list. Next coefficient c_x was used for calculation of each tug boat main propulsion power N_{wi} for seven chosen speeds v: 14.5, 14, 13.5, 13, 12.5, 12, 11.5 and 11 knots. Calculation of a_{ov} and a_{1v} coefficients in formula (3) was executed by means of linear regression using least squares method. Dependencies of main propulsion power on hull main dimensions and chosen sailing speed $N_{wv}=f(L \cdot B \cdot T)$ are as follows:

$$\begin{aligned} \text{for: } & v = 14\ w,\ N_{w14} = 1772 + 1.4442 \cdot (L \cdot B \cdot T), \\ & v = 13.5\ w,\ N_{w13.5} = 1580 + 1.2949 \cdot (L \cdot B \cdot T), \\ & v = 13\ w,\ N_{w13} = 1411 + 1.1563.(L.B.T), \\ & v = 12.5\ w,\ N_{w12.5} = 1254 + 1.0280.(L.B.T), \\ & v = 12\ w,\ N_{w12} = 1109 + 0.9095 \cdot (L \cdot B \cdot T), \\ & v = 11.5\ w,\ N_{w11.5} = 976 + 0.8005 \cdot (L \cdot B \cdot T), \\ & v = 11\ w,\ N_{w11} = 855 + 0.7005 \cdot (L \cdot B \cdot T). \end{aligned} \tag{8}$$

As coefficients a_o and a_1 in formula (7) are power functions (3^{rd} power functions) of ship speed using coefficients from formulas (8) their dependencies on ship speed were obtained by means 3^{rd} power regression and least squares method. In this case they are as follows:

$$a_o = 0.6182 \cdot v^3 \text{ i } a_1 = 0.0005264 \cdot v^3.$$

Thus the final formula for main propulsion power according dependency (7) is:

$$Nw = [0.6182 + 0.0005264.(L.B.T)].v3\ [kW], \quad (9)$$

where:
L·B·T [m³] – main dimensions of ship hull,
v [knots] – ship speed,
a_o, a_1 – coefficients depending on ship type.

An example of correlation between propulsion power calculated according formula (9) and power from reference list for harbour & roadstead tug boats equipped with azimuth thrusters is shown in Fig. 6. Obtained coefficient of regression determination is r^2=0.7471, and correlation coefficient is r=0.8643.

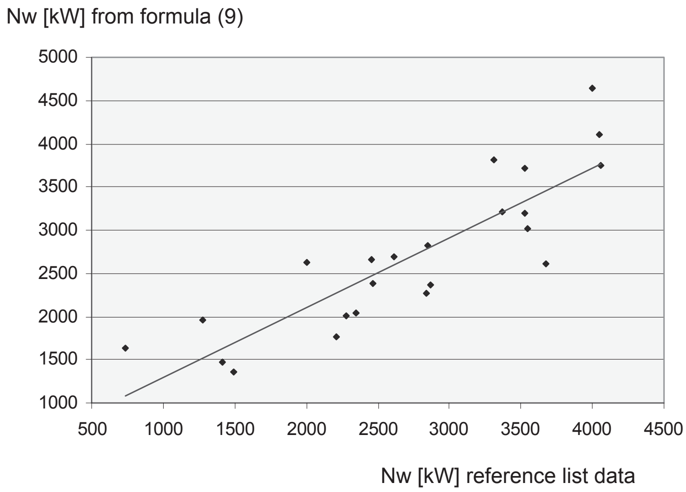

Fig. 6. Correlation between main propulsion power, calculated according to formula (9) and power from reference list of main propulsion tug boat with azimuth thrusters

Analogous calculations for tug boats with another kind of propulsion gave the following results:
- for tugs with cycloid thruster:

$$Nwi = [1.0787 + 0.0001516.(L.B.T)].v3, \quad (10)$$

- for tugs with classic propeller:

$$Nwi = [0.2946 + 0.001107.(L.B.T)].v3. \quad (11)$$

3. Analysis and determination of on board electric power station

Due to small amount of data and much diversified power of tugs, diesel generators it was impossible to execute reliable statistic research separately to each group tug boats. It was assumed that total power of on board electric power station is function of main propulsion power and it is linear dependency. Statistic calculations were executed for 31 tugs from reference list by means of linear regression using least squares method. As a result a following formula was obtained**:**

$$\Sigma N_{el} = 36.49 + 0.0458 \cdot N_w\ [kW], \quad (12)$$

where: N_w *[kW]* – main propulsion power.

Coefficient of regression determination is $r^2 = 0.6267$. Graphic determination of formula (12) is shown in Fig. 7. Coefficient of linear Pearson correlation between results from approximation and data from reference list is $r = 0.7916$. It confirms good accuracy of formula (12) and its usefulness in preliminary calculations.

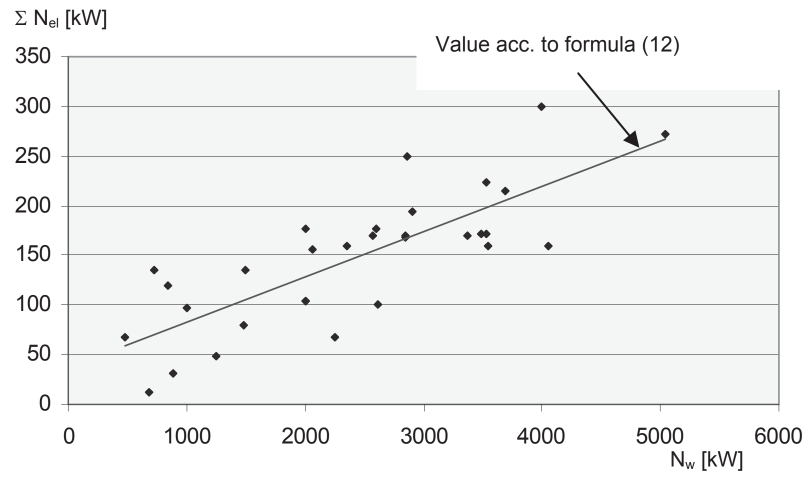

Fig. 7. Linear regression of dependency between total power of on board electric power station on harbour tug main propulsion power

Some of the harbour & roadstead tug boats are additionally equipped with harbour diesel generator smaller power about 15-30 kW used during ship berthing. It is due to high prices of energy delivered from shore.

5. Conclusions

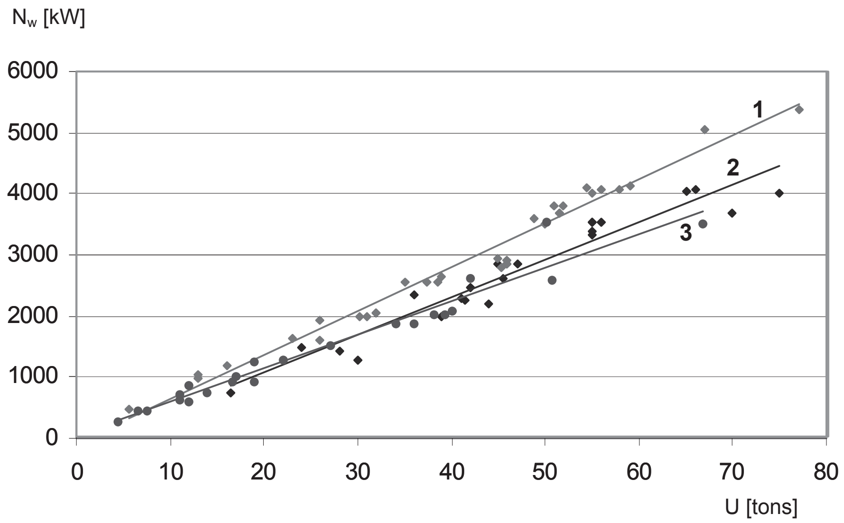

Fig. 8. Comparison of main propulsion power dependency on towing force for different types of thrusters 1. Voith-Schneider thrusters. 2. Azimuth thrusters. 3. Classic propellers

Contemporary harbour & roadstead tug boats belong to group having main engines incommensurable powerful to hull dimensions. That is why formulas concerning other types of ships cannot be adopted in calculations of main propulsion power. Among harbour & roadstead tugs, predominate more powerful azimuth and cycloid (Voith-Schneider) main propulsions, which assure very high maneuverability. Cycloid thrusters have higher maneuverability but smaller efficiency what is shown in Fig. 8. In the diagram is possible to observe that to achieve the same towing force they need more power of main propulsion. Nowadays built harbour & roadstead tug boats are mostly equipped with azimuth thrusters due to their higher efficiency. On very small tugs having small towing force and less powerful engines single main propulsion plants are mounted.

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