ASSESSMENT OF PROPULSION SYSTEMS PERFORMANCE IN TUGBOAT

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ÖZET

The development of maritime transport and trade has a positive effect on tugboat operations in the seas day by day. The existence of tugboats with improved functional features and diversified propulsion systems in ports, canals, and platform support operations has created a new lane in the shipbuilding industry. In this study, developing tugboat technology and propulsion systems are discussed and current developments are emphasized. Also, in this study, open water characteristics will be obtained from a sample tugboat ASD system.

Keywords: Tugboat, Propulsion, ASD, Voith, Drive Systems.

1. Introduction

Tug boats are one of the most important components of the maritime industry. Tugboats are vital in operations such as port berthing and departure, towing operations, escort, salvage and rescue, underwater works, fire fighting, and oil pollution response. As of May 2015 tug market report, the number of sea-going tug vessels reached 17,497 at 2,647 BHP with an average year built of 1993. And 604 of the 6369 ships ordered worldwide in 2016, which is 9.48%, are tugs or "towing/pushing" vessels [1]. The selection of a propulsion system in tugboats is an important criterion for a proper design. Tug boat working area and aim, bollard pull performance, maneuverability, dimension, hull resistance, need for power are the important determining factors in this regard. Also, the energy efficiency for environmental effects and lower maintenance are considered. Thrusting the ship forward at a given power is possible with the alignment of the main machine, shaft, gearbox, and propeller [2].

2. Classification of Tugs

Tugboats are generally built for multipurpose purposes. But it is possible to say that this creates some disadvantages. As with all things, this multipurpose sometimes creates weaknesses in fulfilling its basic tasks. Types of tugboats accepted worldwide are listed below.

2. 1. Ship handling / harbour tugs

It is the service provided to help the ship maneuver in the entry and exit of the ships to the port, berthing and unloading to the berths, anchoring of buoys, anchoring, leaving them, and for any reason. A large ship navigating in narrow waters is faced with many hazards, including the risk of collision or grounding, which may have severe environmental consequences. Tugs are necessary because most large ships have no control over their own steering when operating at very low speeds, and they are hence very exposed to the forces of wind and current in the ports. Today the big majority of modern ship-assist tugs are fitted with Z-drive or VSP propulsion. Harbour tugs are typically 20 to 32 meters long and have power ranging from 2,000 to 4,000 kW, although there are exceptions to this depending on the size of port and types of ships handled. The main design parameter of a harbour tug is bollard pull (in tonnes) [3]. Some of the harbour tugs specifically used for pushing are called pusher tugs and have more rigid construction of hull and fender like ice class construction. Many harbor tugs are simple boats that the crew only uses to do every same job [4].

2.2. Seagoing tugs

They are built to assist ships on the high seas. Ship sizes are getting bigger and service conditions are getting heavier in these vessels. The number of personnel working on it is specialized in the term of quality and quantity. It serves as an auxiliary vessel for offshore transferring of ships, handling deep drilling and oil transmission pipes. In this vessels, good sea keeping characteristics is an additional requirement compared with another type of tugboats. For towing we can list seagoing tugs as log towing, coastal towing, and ocean towing. For deep-water towing services, there are various types and names. These are; PSV (platform support/supply vessel), AHT(S) (anchor handling tug/supply), OSV (offshore service/supply/support vessel).

2.3. Escort tugs

It is the service provided by the ship in order to increase the safety and environmental safety of the ship. The main aim of using an escort towing is to control the course and speed of the ship in an emergency situation, and thereby reducing the risk of ship grounding or collision. Therefore, escorted transitions in risk-bearing regions are subject to some regulations. For example, In the Implementing Regulation for Istanbul Strait 250 meters and over the tankers of the Bosphorus crossing, life, goods, and environmental safety in the guidance of the pilot and tug accompanied by the advice of the is strongly recommended. The escort tug will have a towing winch on the foredeck and in some cases also on the aft deck. To improve the stability of the tugboat and improve the towing, steering and, arresting ability, a towing fairlead (staple) is located at a central position on the foredeck. The towing winches for escort tugs are designed for high tension mode for escort operation. And in emergency situation towing winch has a render-recovery system. There are some advantages of escort tugs such as good sea-keeping conditions, free running as well as in the escort operating mode, sufficiently high freeboard, good static and dynamic stability. One of the most important issues while providing active escort service by tugboats is the dangerous situation caused by dynamic forces.

Fig. 1. An escort tugboat in Turkish coastal safety.

2.4. Salvage / rescue towing

Ship or floating object from one place to a place to be pulled back by the salvage tugs. Emergency rescue and salvage tugs, usually among the largest of their type, are designed for fast response speed, long-distance towing capability, and the best possible seakeeping for crew safety in rough sea conditions [5]. It is possible to see tugboats for rescue purposes in more navies. The primary mission of these ships can be lifting submerged objects, off-ship fire fighting, rescue and open ocean towing with wire rope or synthetic fiber line, air diving operations with recompression facility, emergency underwater repair, refloating stranded ships and other craft, dewatering of sinking/sunken ships, underwater salvage operations, independent of off-ship logistic support, on short notice [6].

3. Type of Main Drive Systems In Tugboats

The power of a tug boat depends entirely on the propulsion system types. Today the primary source of propeller power, especially for tugboats, is the diesel engine, the power required and rate of propeller revolution, however, depends on the shape and size of the tug hull and the design of the propeller. We effectively design the propulsion system of a tugboat and show clearly the relationship between the initial driving system, reduction gearbox, shaft, and the propeller, and how they relate to the overall propulsion system of the tugboat [7].

In case of extreme and long-time operation of the vessel, advanced propulsion systems are most suitable to help the maneuvering. Tugs require full bollard pull when towing and require limited power during transit or standby. The propulsion main drive systems can be divided into five main types, preferring from most popular to least in tug boats.

-Diesel mechanical (DM)
-Diesel electrical (DE)
-Hybrid propulsion (HP)
-LNG as Marine Fuel
-Use of Bio Fuels

Due to these diverse operating profiles, the power and propulsion plant has to perform well on many performance criteria, such as [8]:

-Fuel consumption,
-Emissions,
-Propulsion availability,
-Manoeuvrability,
-Comfort due to minimal noise, vibrations, and smell,
-Maintenance cost due to engine thermal and mechanical loading.

3.1 Diesel mechanical

Mechanical propulsion is particularly efficient at design speed, between 80 and 100% of top speed. In this range, the diesel engine operates in its most efficient working. Besides, diesel-mechanical propulsion consists of only three power conversion stages, the main engine, the gearbox, and the propeller, which leads to low conversion losses [8].

3.2 Diesel electrical

Four lower fuel consumption, emissions, life cycle cost, and high motor torques, diesel-electric propulsion system is a bit preferable and becoming most popular than the diesel-mechanical propulsion system. However, although electrical propulsion is more efficient at low speed, it introduces additional conversion losses of the propulsive power in electrical components. Also, electrical propulsion can be divided by the type of energy storage; fuel cells, AC ,or DC distribution.

Losses associated with electrical conversion lead to increased fuel consumption for electrical drive systems. The extra electrical equipment also leads to increased weight, size, and cost. Also, an electric motor is known as a shaft generator, which can be driven by a gearbox, or a propeller, makes it easy to get the low speed and partition load of the main engine [9].

3.3 Hybrid propulsion

In hybrid propulsion, a direct mechanical drive provides propulsion for high speeds with high efficiency. Because hybrid propulsion is a combination of electrical and mechanical propulsion, it can benefit from the advantages of both. However, the main challenge for the hybrid propulsion design is to balance the trade-off between all requirements and design a control strategy to achieve this balance.

The current control strategies applied in practice and covered in literature for hybrid propulsion are based on two operating modes: mechanical drive and electrical drive. The presence of fully propelled vessels with only battery-electric sources is increasing, particularly in ships transporting in Scandinavian regions. We can also add to power sources in electrical power; Electrochemical power supply from fuel cells; or stored power supply from energy storage systems such as batteries, flywheels, or supercapacitors [8].

Batteries have only recently been applied in maritime applications, but their popularity is growing very quickly. At the expense of increased purchase and replacement cost, batteries can provide load levelling, efficient backup power, and a zero noise and emission propulsion mode.

3.4 LNG as marine fuel

The maritime sector is also focused on and invests in systems that will further reduce exhaust emissions in the future. The needs of the customers to improve their environmental sensitiveness can be achieved by clean technology. Therefore, gas-powered propulsion systems have naturally lower fuel consumption than diesel or dual-fuel engines [10].

Gas engine technology is not new, having been proven in both land-based and large ship installations. But tugs are a precursor in this sector of the marine market demanding a significant step forward in the technical field. For example to new construction; Mitsui OSK Lines has two dual-fuel tugs under construction at Japan's Kanagawa Dockyard Co. And first was launched at the end of September. The second delivery is scheduled for completion in February 2019 and it is expected to commence operations in April 2019 [11].

3.5 Biofuels and feedstock potential show the potential to completely replace fossil fuels in the maritime sector. A number of regulations regarding the introduction of bio-fuel into marine fuel have to be done in the maritime sector. The current commercial production for marine biofuels is almost exclusively limited to various biodiesel or hydro processed vegetable oils (HVO). However, other biofuel production technologies are increasing the presence of new biofuels compatible with marine propulsion engines [12].

4. Type of Propulsion Systems

The types of propulsion mechanisms are generally available in three groups. The first is the jet propulsion system. Secondly, it is the mechanisms of propulsion that provide thrust for the ship by using the resistance force on the moving parts. Again, we can take into account the third type of propulsion system that the thrust is generated by the buoyancy on the moving mechanisms [13]. VSP system with propeller blades hydrofoil section can be considered in this category. For example, the third one we can consider the classic propellers.

Design studies have focused on the minimization of losses on the propulsion system. Because all of the energy transferred onto the propeller does not turn into propulsion. It can be some losses. Part of this energy is left as the kinetic energy to the back of the propeller in rotational and axial losses. Another possible loss is the loss of resistance by the viscosity of water. So, open water propeller efficiency (ηo) can be expressed as the function of energy losses as follows [14]:

$$\eta o = 1 - AXL - ROTL - FRL \qquad (1)$$

ηo = Open water propeller efficiency
AXL: Axial energy losses
ROTL: Rotational energy losses
FRL: Propeller blade friction losses

However, most of the time the ship's aft form and the depth of the water that the ship is operating do not allow. New propeller systems have been developed to minimize energy losses in such situations where there is a diameter limitation. There are also systems for increasing the maneuver performance of the boat or for other purposes. In this particular topic, we can list the most popular tugs propulsion systems as follows;

- Conventional screw propellers (FPP, CPP)
- Nozzle propellers
- Contra rotating propellers (CRP)
- Propeller-Stator system
- Z-Drive system (ASD)
- Water jet propulsion system
- Vertical propellers (VSP)

Especially for the escort and high maneuvering performance are preferred vertical propellers (Vertical Axis – Cycloidal Propellers) and for the narrow water and, harbour operations, the Z-Drive systems are popular in tugs. Also for transferring varying loads from the main engine, pitch-controlled propellers are preferred by most of the tugs.

Table 1. Trends in aplication of propulsion and power supply for harbour tugs [3].

No. of Propellers	CPP	FPP	Azimuthing	Cycloidal (VS)	No Data
1	482	1805	36	11	267
2	698	5178	2926	466	2631
3 and more	1	49	39	3	32
TOTAL	1181	7032	3001	480	2930

For further considerations, only vessels with twin conventional screw propellers or with dual unconventional propellers (azimuth or cycloidal) have been chosen. Having two propellers of either type is currently rather typical in the harbour maneuvers in assistance to berthing/unberthing, transit, and/or harbour entrance/exit. The conventional propellers often have nozzles to increase their performance in bollard and astern conditions [3].

It can be explicable that the azimuth propulsion is practically always mounted at the stern of a tug, popularly referred to as azimuth stern drive (ASD). In practice, the system resembles the letter z, so it is known as the Z-type system. Also in tug literature, ASD tug may be defined as a reverse tractor vessel. In this system, the propulsion system takes less space and provides more economic benefits in terms of maintenance. Today, most machine manufacturers recommend systems that are compatible with their own machines and producing their own ASD systems. Schottel, Rolls Royce, Kamewa, Ulstein, Wartsila Stern Thruster has become a well-known brand in the market. For both technical and to a certain degree market-related reasons, the selection of azimuth propulsion will often lead to the aft propulsion of a tug.

Fig. 2. Wartsila WST-24 model ASD in 70 BP harbour tugs owned by Coastal Safety.

On the other hand, the cycloidal propulsion, also called the Voith-Schneider propulsion (VSP or Voith), is installed mostly at the bow. In VSP systems the propellers are protected by a guard. General propeller efficiency (ηd) is low and mechanical losses are high in vertical axis propellers. However, their maneuverability is quite high. For this reason, such propulsion systems are preferred in operations requiring acceleration and rotation.

Fig. 3. VSP systems with 6 six blade in 80 BP escort tugs in Kurtarma 10 vessel.

5. Propeller Design Criteria in Tugs

Propeller design is now evident on any ship, but there are many demands and desires that are difficult to choose in tugboat design. A tugboat propeller is designed to give the entire engine or desired static bollard pull or at a free cruise speed or any intermediate towing speed. For example, on a towing tug, even at low speed, a good bollard pull is required. At the same time, the tug has to move quite fast between the two tasks. It has to keep up with the speed of the ship that it servicing. The propellers on a tug are dependent on the type of tug and the draft. The two propellers are generally used in such a way that the single propeller cannot provide the necessary power and not affect the body design and draft.

There are many numerical and empirical approaches for the determination of optimum propeller design. However, these approaches are often addressed for merchant ships. The geometric shape of the propeller, diameter, tilt, pitch, a number are important criteria that affecting the propeller performance. In addition, the performance of the propeller must be compatible with the ship's machine power and the vessel' body and speed. Tug power depends on the selection of the appropriate propeller. Demand for high bollard pull performance there is wide design research on nozzle shape and propeller shape. In general, we can add the draft strength to the propeller front design as follows:

-Blade number,
-Blade area ratio,
-Twin-screw; Direction of rotation
-Optimal shaft speed / Optimum Diameter
-Propeller Series
-And Bollard Pull performance

In addition, displacement of the ship, carina pollution and sea conditions are the factors affecting propeller performance. In order to achieve the maximum efficiency of the propeller given in section 3, all these factors must be taken into account in optimization.

Vs : Ship speed
Pe : Effective power (kW) $PE = R \cdot Vs$
Pd : Power transmitted to propeller $Pd = Pe / \eta d$ (kW)
ηd : General propulsion efficiency $\eta d = \eta H \, \eta 0 \, \eta r$
ηH : Hull efficiency $\eta H = (1-t) / (1-wt)$
η0 : Open water propeller efficiency
ηr: Relative rotative efficiency
wt: Wake factor (for the determination of the speed of the water to the propeller)
t : Absorption (thrust deduction) coefficient (negative pressure around the propeller)

The ability of the ship to navigate at the desired speed depends on the propeller thrust (T) against the resistance of the boat (R). In the case of tugboats, in addition to the boat resistance, bollard pull force (Bp) in the rope must also be taken into account in the towing operations. The speed of the tugboats slows down during the pull and even comes to a stop.

Propeller thrust in tugboats;

$$T \geq R + Bp \qquad (2)$$

With consider the thrust deduction;

$$T(1-t) = R + Bp \qquad (3)$$

The wake of a ship (w) is expressed as the difference between the speed of the ship (Vs) and the speed of water to the propeller (VA) . By dividing this difference by the speed of the ship, the wake factor is obtained;

$$w = \frac{V_S - V_A}{V_S} \tag{4}$$

The fullness and shape of the aft form, propeller location, diameter, shape, tilt condition, number, rpm, and pitch ratio have a significant effect on the wake factor. For example, it is observed that the wake factor decreases with the hull form fullness decreases. According to the experimental data obtained from the model test results for tugboats wake factor is a more accurate approach. It was determined by the experimental results that the wake factor decreased with increasing propeller diameter [15].

When the propeller is running, it creates a sucking effect on the body of water in front of it. This effect results in an increase in the ship's resistance. This resistance increase is defined as a thrust deduction in the propeller. If only the towed resistance of a hull is known, the thrust deduction is particularly useful and can be estimated from published values and different model tests. Thrust deduction coefficient is obtained;

$$t = kw \quad \text{or} \quad t = (T-R) / T \tag{5}$$

For the design of tugs at a low rate of speed and at a high thrust load, the factors of the wake and thrust deduction are very important. Also, some experimental studies have proven that the wake factor is constant, especially in towing operations.

The factors influencing open water propeller efficiency (η_0) in tugboats include; advance propeller speed (V_A), thrust (T), propeller diameter (D). and the number of revolutions (n). We can express propeller advance number;

$$J = \frac{V_A}{nD} \qquad \rightarrow V_A = V(1-w) \tag{6}$$

Also for thrust the coefficient;

$$K_T = \frac{T}{p\, n^2\, D^4} \tag{7}$$

Also for torgue on shaft and coefficient;

$$K_Q = \frac{Q}{p\, n^2\, D^5} \tag{8}$$

Also for tug boats in the condition of towing, thrust must overcome the towing strength in addition to the ship's resistance. For the design, we can obtain propeller characteristics curves, open water efficiency, and advance number from the previously measured model test results. Many series were designed, tested, analyzed, and results published by model institutions. For example, Wageningen B-Series Propellers one of the famous series are tested in Netharlands.

Also, we can able to compare test model results with the computational fluid dynamics (CFD) calculations. It can be possible to get high accuracy results from CFD even in the most complicated flow around the hull. In a research published by Kınacı et al. [16], in large motions of a planning hull with high Froude numbers can be calculated with the CFD and the experimentally, numerically, and empirically generated results are compared.

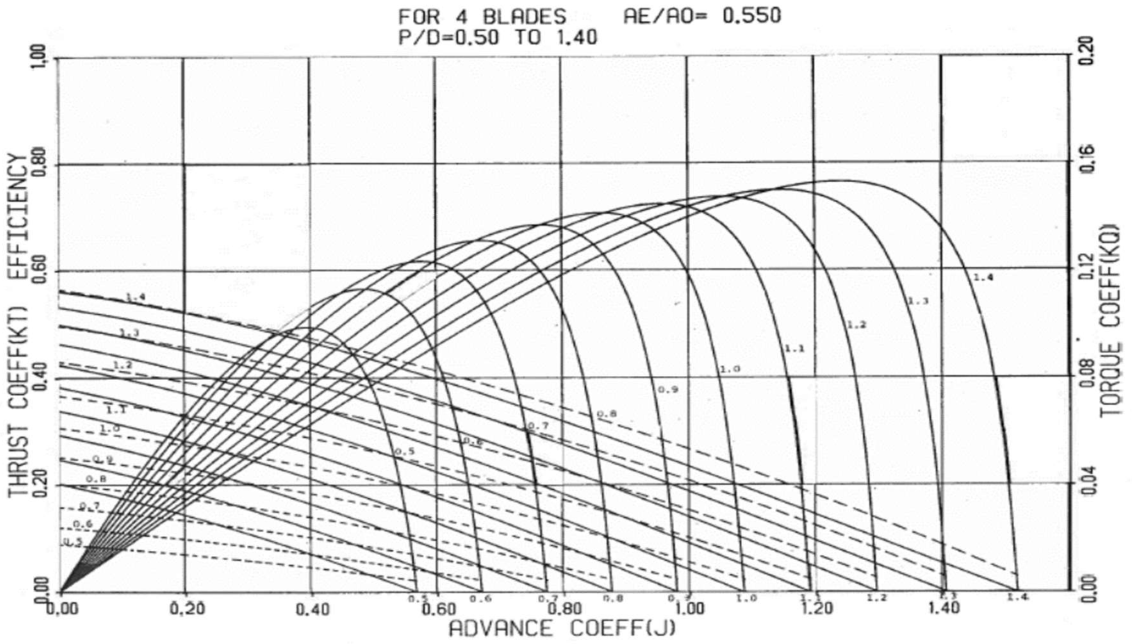

Fig. 4. A typical open water diagram and chracteristic curves for Wageningen B-4.55.

Propeller efficiency η_0 is related to working in open water. The propeller works in a homogeneous wakefield with no hull in front of it. Generally, for the ship type η_0 (0.50-0.70), but for tug this values range are not suitable. The open-water propeller efficiency can be written then as;

$$\eta_0 = \frac{J\, K_T}{2\, \pi\, K_Q} \tag{9}$$

For example, in Fig. 2 as we mentioned 70 bollard pull escort-tug boat WST-24 CP type Wartsila propeller open water efficinecy values are given belows table and graphic. This azimuth stern thruster propeller has 4 blades and P/D = 0.847. D is 2.80 meter.

Table 2. Open water charecteristics for Wartsila WST-24 CP.

J	KT	10 KQ	η_0
0.0500	0.3950	0.3280	0.0958
0.1000	0.3690	0.3240	0.1813
0.1500	0.3440	0.3200	0.2566
0.2000	0.3200	0.3150	0.3234
0.2500	0.2960	0.3090	0.3811
0.3000	0.2720	0.3020	0.4300
0.3500	0.2500	0.2930	0.4753
0.4000	0.2270	0.2830	0.5106
0.4500	0.2050	0.2720	0.5398
0.5000	0.1830	0.2590	0.5623
0.5500	0.1610	0.2440	0.5776
0.6000	0.1390	0.2260	0.5873
0.6500	0.1170	0.2070	0.5847
0.7000	0.0940	0.1860	0.5630
0.7500	0.0710	0.1630	0.5199
0.8000	0.0480	0.1370	0.4461

And we can calculate thrust T and resistance R_T by the known the thrust deduction coefficient from model tests and given revolution n;

Table 3. Thrust T and Resistance R_T Wartsila WST-24 CP.

n (rpm)	t	T (N)	R_T (N)
25	0.329	4.327	2.904
50	0.317	16.144	11.027
100	0.304	60.202	41.901
150	0.298	126.004	88.455
200	0.293	207.207	146.496
300	0.286	428.415	305.888
400	0.280	700.025	504.018
500	0.274	993.160	721.034
600	0.266	1291.546	947.995
700	0.259	1569.281	1162.837
750	0.253	1584.900	1183.920
800	0.246	1556.855	1173.869
850	0.239	1479.371	1125.802
900	0.231	1332.497	1024.690
950	0.225	1121.396	869.082
1000	0.210	840.030	663.624

We can obtain the curves series as in Fig. 5;

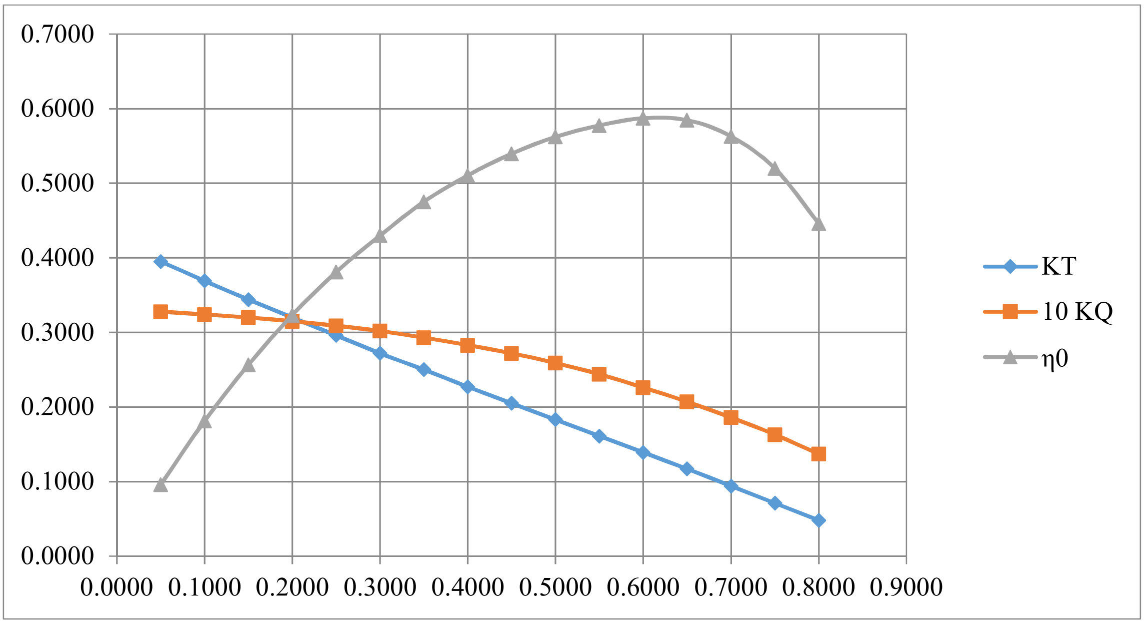

Fig. 5. Open water curves

We can calculate the optimum static bollard pull power from the propeller curve, which KT at J is zero and the engine's rated RPM. As the ship's bollard pull is increased, open water propeller efficiency is reduced.

On the other hand, escorting of ships is the main aim of tugs. Requirements for this operation are excellent maneuverability, high thrust, and large steering and breaking forces as well. So dynamic and static escort forces must be calculated in preliminary design. Manoeuvering and stopping forces are calculated on the tug during different towing angles.

6. Conclusion

In tugboats, we can see the propeller systems of tugboats should be handled not only in terms of speed but also in a wide design window to meet the performance requirements. In order to increase the propeller efficiency, it is possible to see various applications in certain subjects, such as the design of the court nozzle systems. Optimum conditions can be achieved when the flow around the propeller is regulated within the nozzle. And generally, in the case of tugboats, aerofoil propellers provide good efficiency. Critical requirements such as bollard pull (Bp) and escort capabilities compared to other ships are effective on propeller efficiency in tugboats. High static bollard pull can be achieved at low speeds. So the propeller efficiency is decreased by the point of excellent bollard pull. By the type of propeller system, it can be placed fore and aft of the tugs. VSP and Azimuth Drive Systems are most preferred as an example. These preferences vary according to the intended use of tugboats.

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