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DAVID TAYLOR MODEL BASIN

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EXPERIMENTAL INVESTIGATIONS OF PROPELLERS IN NOZZLES AT THE CENTRAL AERO-HYDRODYNAMIC INSTITUTE (Moscow)

Translated from:

Korabelnye Dvizhiteli (1948), pp. 301–312.

by

V.I. Solovev and D.A. Chumak

Translated and Technically Edited by B.V. Nakonechny

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NOTATION

A	Expanded area
A_d	Propeller disc area $\left(= \frac{\pi D^2}{4}\right)$
C_{xn}	Drag coefficient of the nozzle $\left(= \frac{X}{\rho\, n^2 D^4}\right)$
D	Propeller diameter
D_n	Minimum inside diameter of nozzle
F_i	Nozzle inlet area
F_o	Nozzle outlet area
F_p	Nozzle area at minimum nozzle diameter
H	Pitch
K_q	Torque coefficient $\left(= \frac{Q}{\rho\, n^2 D^5}\right)$
K_t	Thrust coefficient of a propeller in open water $\left(= \frac{T}{\rho n^2 D^4}\right)$
K_{tn}	Thrust coefficient of nozzle $\left(= \frac{T_n}{\rho n^2 D^4}\right)$
K'_{tn}	Thrust coefficient of nozzle $\left(= \frac{T_n}{\frac{\rho}{2}\, V^2 S}\right)$
K_{tp}	Thrust coefficient of propeller in a nozzle $\left(= \frac{T_p}{\rho\, n^2 D^4}\right)$
$K_{t(p+n)}$	Thrust coefficient of a propeller-nozzle combination $\left(= \frac{T_p + T_n}{\rho\, n^2 D^4}\right)$
l	Nozzle length
$\frac{l}{D_n}$	Length-diameter ratio of a nozzle
N_p	Power delivered to propeller
n	Revolutions per unit time
Q	Torque
S	Inside surface area of nozzle $(= l\, \pi D_n)$
T	Thrust of propeller in open water
T_e	Thrust, effective

T_n	Thrust of nozzle
T_p	Thrust of propeller operating in a nozzle
V	Advance velocity
X	Drag of nozzle at velocity V
Z	Tow rope pull
z	Number of blades
α_0	Angle of zero lift
ϵ	Efficiency improvement factor of propeller-nozzle combination $\left(= \dfrac{\eta_{p+n}}{\eta}\right)$
η	Propeller efficiency in open water
η_{pn}	Efficiency of propeller operating in nozzle
η_{p+n}	Efficiency of propeller-nozzle combination
λ	Advance coefficient $\left(= \dfrac{V}{nD}\right)$
ρ	Density of water
σ_L	Power loading coefficient $\left(= \dfrac{2\pi\, Qn}{\frac{\rho}{2} V^3 \frac{\pi D^2}{4}}\right)$
σ_p	Loading coefficient of propeller operating without nozzle $\left(= \dfrac{T}{\frac{\rho}{2} V^2 \frac{\pi D^2}{4}}\right)$
σ'_p	Loading coefficient of propeller operating in nozzle $\left(= \dfrac{T_p}{\frac{\rho}{2} V^2 \frac{\pi D^2}{4}}\right)$
σ'_{p+n}	Loading coefficient of a propeller-nozzle combination $\left(= \dfrac{T_p + T_n}{\frac{\rho}{2} V^2 \frac{\pi D^2}{4}}\right)$
ξ	Distance from the leading edge of the nozzle to the location of its minimum inside diameter (i.e., to the location of propeller inside nozzle)
ζ	Quality factor

LIST OF FIGURES

ABSTRACT

This report presents in condensed form the results of experimental investigation of three- and four-bladed propellers in nozzles. The experiments included nine nozzles of different form and various length-diameter ratios. Propellers having different pitch- and disc-area ratios were used. The diameter of propellers was 200 mm. The results of the experiments are presented in form of performance characteristics curves. Several additional graphs on full-scale comparison and a discussion on the merits of propeller-nozzle combinations are also given.

Several experimental investigations of propeller-nozzle combinations have been carried out in the Soviet Union. Of great practical interest are the investigations carried out at the Model Basin of TsAGI (Central Aero-Hydrodynamic Institute).[1,2]

The experiments included nine nozzles having the shape shown in Figure 1.

The minimum inside diameter of each investigated nozzle was 208 mm. The length-diameter ratio l/D_n was equal to 0.5, 0.66, and 1.0.

The inlet area ratio of the nozzles F_i/F_p varied from 1.0 to 1.39 and the outlet area ratio F_0/F_p from 1.0 to 1.33.

The investigations of the nozzles were carried out with and without propellers. The diameter of the propellers D was 200 mm; the pitch ratio H/D was 1.0 and 1.5; the disc-area ratio A/A_d was 0.5 to 1.0; and the number of blades z was 3 and 4. The expanded area ratios of propellers are given in Figure 2.

The main results of experimental investigations of the propeller-nozzle combination in open water are presented. Figure 3 shows the experimental characteristics of the propeller-nozzle combination as a function of the advance coefficient λ. For comparison, the performance curves (K_t and η) for same propeller in open water have been plotted on the same diagram. The drag coefficient of the nozzle was determined by the formula

$$C_{xn} = \frac{X}{\rho n^2 D^4}$$

where X is the drag, corresponding to the velocity V. The variation of the coefficient C_{xn} with respect to λ is given by the broken curve in the lower portion of the diagram.

We see from the diagram that the character of variation of the thrust coefficient of the nozzle

$$K_{tn} = \frac{T_n}{\rho n^2 D^4}$$

[1]References are listed on page 6.

with respect to λ, and the thrust coefficient of the propeller-nozzle combination

$$K_{t(p+n)} = \frac{T_p + T_n}{\rho n^2 D^4}$$

is quite analogous to the variation of the thrust coefficient of the propeller in open water, K_t. The maximum thrust generated by the nozzle is achieved at zero speed of advance and in several cases is almost equal to the thrust of a propeller in the nozzle. The zero thrust of the nozzle usually occurs at a small positive or zero thrust of the propeller. As was shown by the results of the experiments, the forces occurring on the nozzle are determined by its advance velocity V and by the magnitude of the velocity circulation produced by the operating propeller. For a constant location of the propeller with respect to the nozzle length, both parameters indicated are characterized by the loading coefficient of the propeller in the nozzle, σ'_p. The loading coefficient σ'_p, all other conditions being the same, determines the angle of attack of the flow entering the ring-shaped nozzle section. For the same values of σ'_p, the angle of attack will increase with increasing α_0 (i.e., angle located between direction of zero lift force of the nozzle profile and its axis). With an increase of the angle α_0, the thrust generated by the nozzle increases.

Figure 4 presents the variation of the thrust coefficient of different nozzles referred to the surface $S = \pi D_n l$ and velocity head of the entering flow

$$K'_{tn} = \frac{T_n}{\frac{\rho V^2}{2} \times S}$$

as a function of the propeller loading coefficient σ'_p.

Examining the various curves in this diagram, we can draw the following conclusions:

1. The thrust coefficient K'_{tn} for all nozzles depends on the loading coefficient σ'_p and increases with an increase of the σ'_p.

2. With an increase of the ratio F_o/F_p, for a constant value of the inlet opening, the thrust coefficient K'_{tn} increases (nozzles 3, 5, and 6); the effect of the variation of the nozzle inlet F_i/F_p is smaller than that of F_o/F_p.

3. When the length diameter ratio l/D_n increases, the coefficient K'_{tn} decreases.

The phenomenon of unloading of a propeller in a nozzle related to an increase of the flow velocity at the propeller disc was corroborated fully by the data of the experiments. The variation of the loading coefficient of a propeller in a nozzle, σ'_p, in relation to the loading coefficient of a propeller operating without a nozzle, σ_p, is presented in Figure 5.

For the propellers with varying values of A/A_d, but having the same pitch ratio $H/D = 1.5$, all the experimental points fall on one straight line; the only exception is propeller 113 having the pitch ratio $H/D = 1.0$. As follows from Figure 5, σ'_p is always smaller than σ_p for all propellers. The experimental results show that an increase of the ratio F_o/F_p has an unloading effect on the propeller because the velocity behind the propeller (in the slipstream) decreases. Varying the nozzle inlet opening F_i/F_p has practically no effect on the action of a propeller.

When evaluating the performance of various types of nozzle assembly, it must be remembered that the thrust generated by the nozzle is accompanied by the change of the propeller characteristics. Hence, in general, the use of a nozzle may give either positive or negative results. For this reason, the correct notion on the advantages of utilizing a nozzle may be formed only from examining the overall characteristics of the whole system.

The experiments carried out by TsAGI allow to establish approximate lower limits of propeller loading σ_p, for which the nozzle installation increases the efficiency.

To solve this problem, we analyze the case of nozzle installation for an existing propeller. Or, in other words, we compare the characteristics of the same propeller with and without a nozzle for constant value of propeller loading and for constant power.

The dependence of the efficiency improvement factor $\epsilon = \dfrac{\eta_{p+n}}{\eta_p}$ on the loading coefficient of the combination $\sigma'_{p+n} = \sigma_p$ is presented in Figure 6.

From this diagram it follows that for all the nozzles tested the efficiency of the propeller-nozzle combination is higher than the efficiency of a propeller without a nozzle, for the values of σ_p starting from $\sigma_p \geq 1.5$ to 2.0. For very high propeller loadings ($\sigma_p \geq 30$), the maximum value of ϵ for certain nozzles (i.e., 3 and 9) ranged as high as 1.6; i.e., the value of η_{p+n} was 60 percent higher than the value for η.

It is important to note that for propellers with high pitch ratio, the advantages of a nozzle begin to appear at lower propeller loadings.

This is entirely confirmed by the diagram given in Figure 7. Here, for the propeller with $H/D = 1.5$, the magnitude of η_{p+n} is larger than η, starting from $\sigma_p \approx 0.75$, whereas for the propeller with $H/D = 1.0$, the gain in efficiency is obtained only for $\sigma_p > 2.0$ The lesser gain in efficiency of the propeller with $H/D = 1.0$ may be explained by the fact that for equal values of σ_p, the efficiency of propellers with smaller values of H/D is higher than the efficiency of propellers with larger values of H/D.

The results of tests at TsAGI concerning the determining of the advantage of nozzle installation for constant power are shown in Figure 8. On the ordinate axis are plotted values of the efficiency improvement factor

$$\epsilon = \frac{\sigma'_{p+n}}{\sigma_p} = \frac{\eta_{p+n}}{\eta}$$

and on the absissa the values of the power loading coefficient

$$\sigma_L = \frac{2\pi Qn}{\frac{\rho V^3}{2} F_p}$$

For such a comparison, the application of the nozzle shows the smaller positive effect in efficiency. The smallest effect gives nozzle 5 with propeller 113 ($H/D = 1.0$).

The experimental investigations have shown that the installation of the nozzle on an existing propeller without increasing the values of H/D may result not only in an increase, but also can lead to a decrease of thrust of the propeller-nozzle combination, as compared to a propeller operating without a nozzle. For propellers with $H/D = 1.5$, the installation of a nozzle gives an increase of thrust for the propeller-nozzle combination for small values of λ without going over to the other values of H/D.

From the diagram in Figure 8 it may be concluded that for a constant power, the nozzle installation is advantageous for values of $\sigma_L \geq 5$ to 8. The results of experimental investigations at TsAGI agree entirely with the full-scale trial results of propellers operating in nozzles.

The operation of ships equipped with nozzles confirms the great effectiveness of such an installation for heavily loaded propellers. In particular, the propulsive characteristics of tugs (tow boats) may be increased from 25 to 45 percent by the use of a nozzle.

In Figure 9 are shown the results of tests at bollard pull condition for propellers with and without nozzles for a numbe of soviet and foreign tugs.

Here the tow rope pull force Z, equal in this case to the total effective thrust of the propeller T_e, is related to the power delivered to a propeller N_p. The variation of the value Z/N_p is given as a function of the loading of the hydraulic section N_p/F_p ($F_p = \pi D^2/4$ = area of propeller disc). The curves of constant values of coefficient ζ plotted on the diagram, represent the ratio of the actual propulsive thrust force T_e to the thrust of an ideal propeller in a nozzle at bollard pull. The solid curves refer to tugs with nozzles and the broken curves to tugs without nozzles. As can be seen from the diagram, for the bollard pull operation of propeller-nozzle combination the increase in thrust attains about 50 percent. To illustrate the useful effect of the nozzle with respect to speed, the results of tests performed on the tow boat "Izhorets" are presented in Figure 10. This figure shows the curves of the variation of the towline force per unit of the indicated power $\frac{Z}{N_i}$ (kg/hp) with and without a nozzle as function of speed. All curves are for the constant value of loading $N_i/F_p = 130$ hp/m^2. As can be seen from Figure 10, the nozzle guarantees the gain in propulsion even at comparatively high speeds. However, with increasing speed the efficiency of nozzle decreases.

Space limitation precludes the detailed analysis of the problems related to the design of nozzles and to the determination of the characteristics of a propeller operating in a nozzle.

We refer the reader to special textbooks on this matter; e.g., Basin A.M., "Practical Guidance for Designing the Propeller-Nozzle Combinations and Calculation of Propulsive Characteristics of Tow Boats." Here we limit ourselves to a few recommendations with respect to the selection of the basic nozzle parameters and to the general instructions for calculating a propeller operating in a nozzle.

The main design parameters of a nozzle are:

The outlet coefficient F_o/F_p.

The inlet coefficient F_i/F_p.

Length-diameter ratio l/D_n.

In the foregoing it has been mentioned that the increase in F_o/F_p of the nozzle is advantageous. However, we should not forget that an excessive increase in F_o/F_p might lead to flow separation in the after portion of the nozzle and, consequently, reduce the efficiency of the nozzle. According to the available experimental data, the value of the outlet coefficient F_o/F_p should be chosen within the limits 1.0 to 1.10. The inlet coefficient F_i/F_p, which depends on the outlet coefficient and practical nozzle designs, is within the range of 1.30 to 1.65.

The length-diameter ratio l/D_n should not be taken higher than 0.7. The length of the forward portion of the nozzle (from the leading edge to the propeller plane) should not exceed 0.35 D_n. The propeller should be placed at the narrowest section of the nozzle with a minimum clearance between the tip of the propeller blade and the inside of the nozzle. In practice, the magnitude of this clearance generally ranges from 5 to 10 mm. The shape of the nozzle profile should be designed so that the direction of the zero lift force of the profile includes as large an angle α_0 as possible with the axis of the nozzle. The design of a propeller for the operation in a nozzle is made in the usual manner with the aid of E.E. Papmel's diagrams. The only difference, however, consists of the introduction of corrections for the increase of the axial velocity in a propeller disc (negative wake flow) and the alteration of the loading distribution on the blade tips.

In conclusion, the main advantages obtainable from the application of nozzles to the screw propellers, which result from the foregoing theoretical and experimental analysis, will be enumerated:

1. The efficiency of a propeller-nozzle combination with large loading coefficients ($\sigma_p > 1.5$ to 2.0) is always higher than the efficiency of a propeller alone.

2. The thrust developed by the propeller-nozzle combination is greater than the thrust of propeller alone, especially for large values of slip.

3. With a suitable form of nozzle, the suction force in the ship-propeller combination is practically eliminated.

4. A screw propeller, mounted in a nozzle with a sufficiently small blade tip clearance, will have almost no tip losses, since the nozzle will prevent the pressure equalization between the suction and pressure sides in the vicinity of the blade tips.

5. Nozzles improve substantially the operation of a propeller in waves and, hence, assure smoother engine operation.

6. The use of nozzles considerably reduces the chances of propeller breakage and eliminates entirely the chances of fouling of cables on a propeller.

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2. Vesolovskii, M.I., "O vzaimodeistvii grebnogo vinta i koltsevoi nasadki," Transactions TsAGI No. 590 (1946).

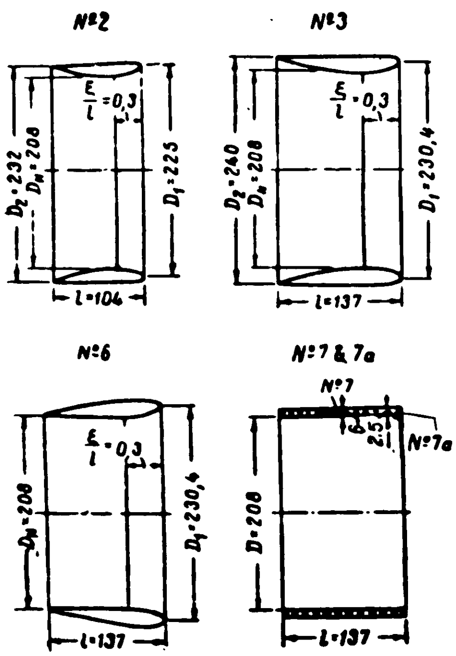

Figure 1 – Nozzles Tested at the TsAGI Model Basin

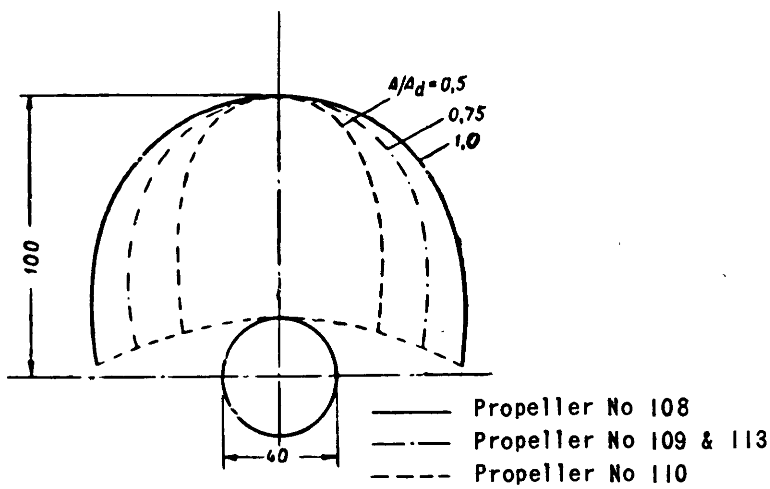

Figure 2 – Expanded Blade Areas of Propellers Tested in Nozzles at TsAGI

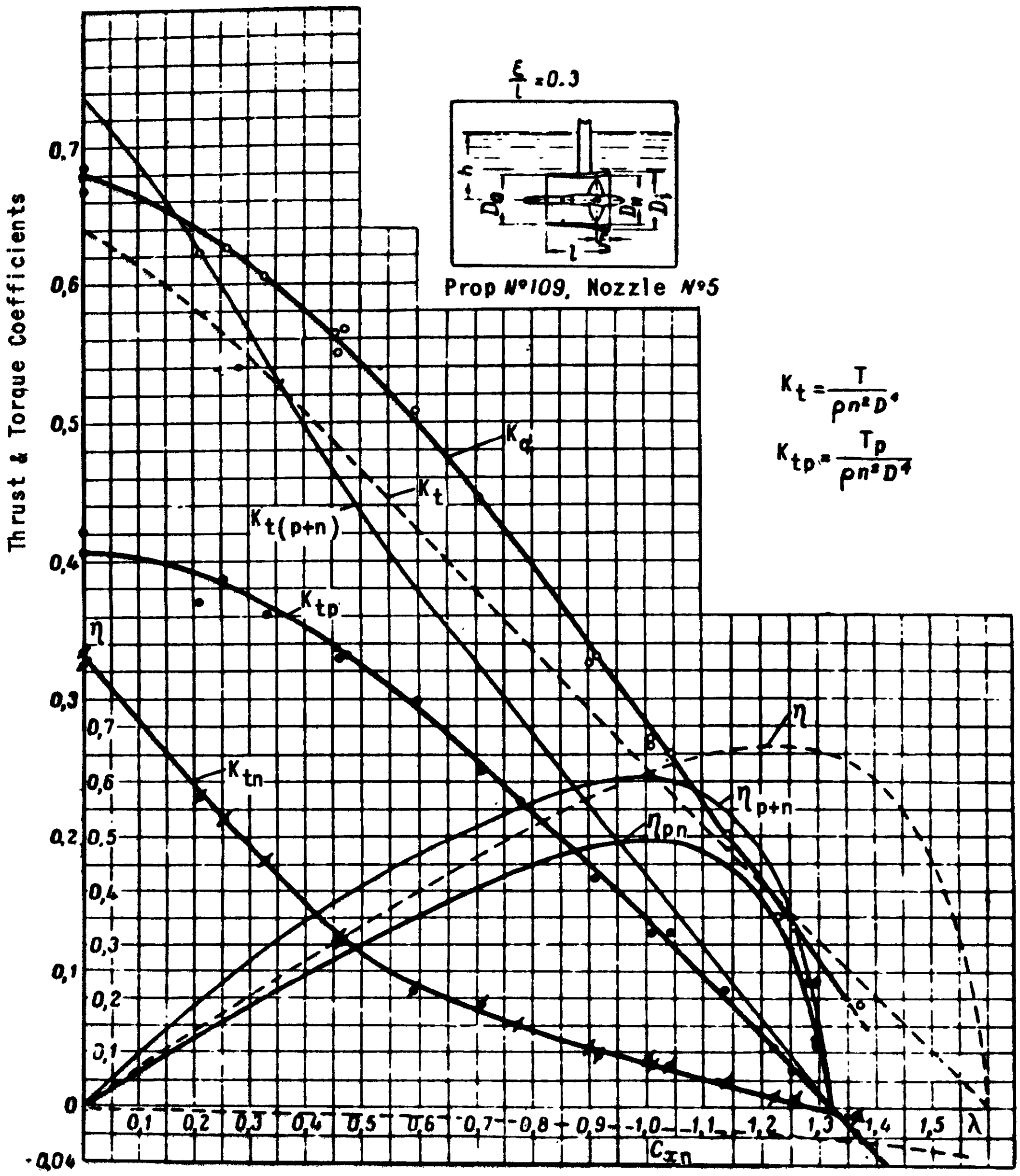

Figure 3.– Characteristics of a Propeller-Nozzle Combination in Open Water (Nozzle 5, Propeller 109)

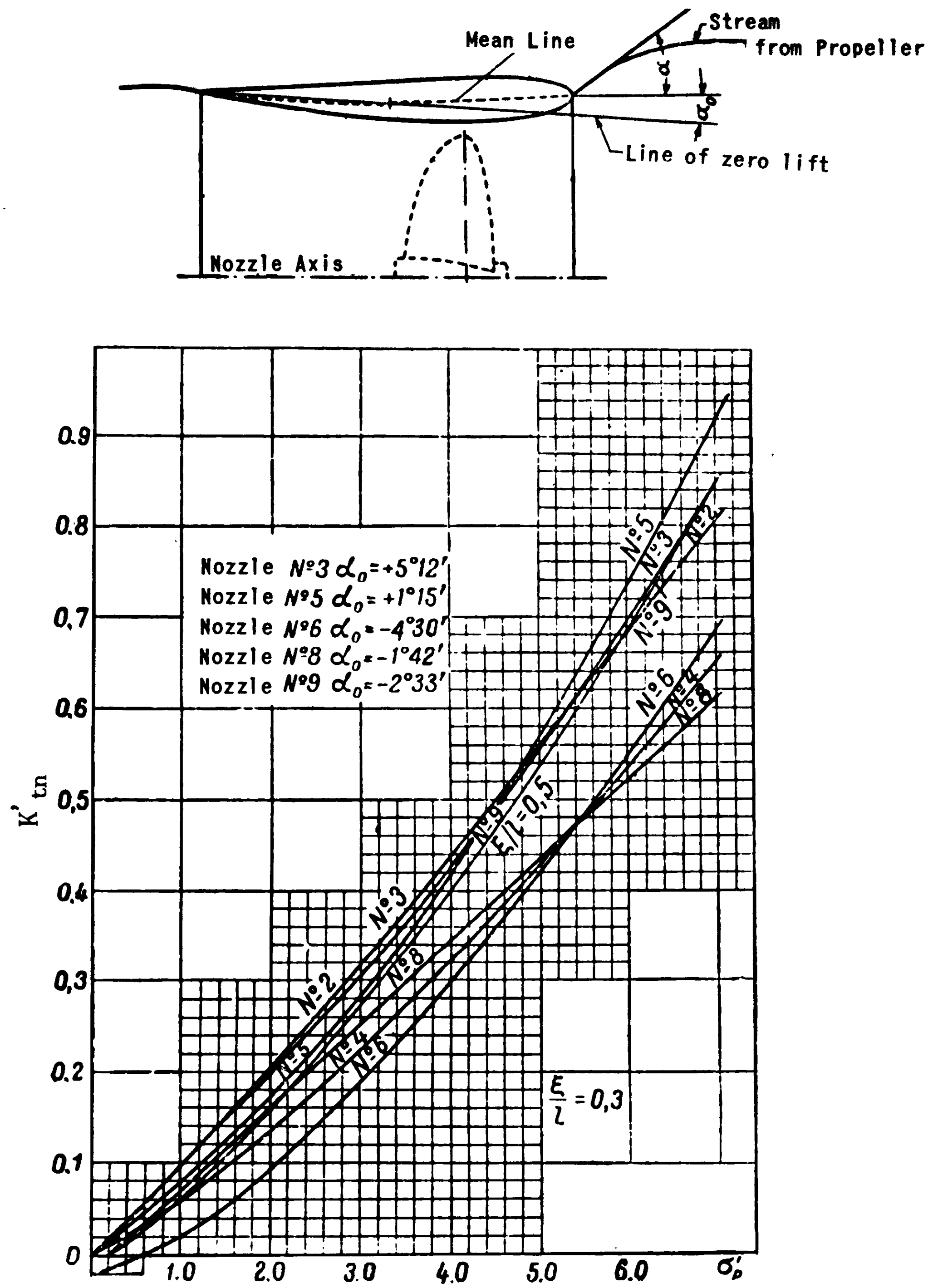

Figure 4 – Relationship between the Nozzle Thrust Coefficient K'_{tn} for Various Nozzles and Loading Coefficient σ'_p for Propeller in Nozzle

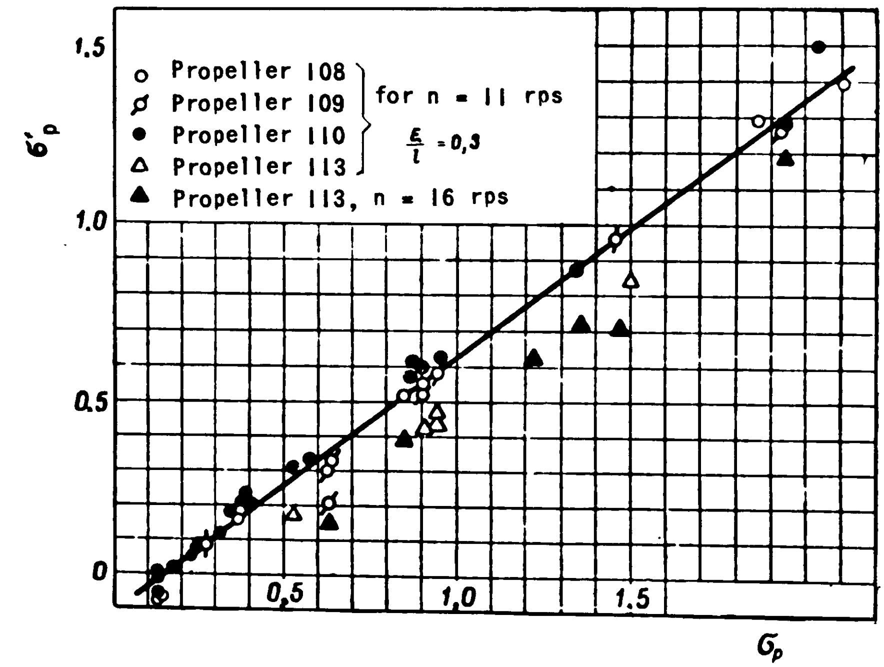

Figure 5 – Relationship between the Loading Coefficient of a Propeller in a Nozzle σ'_p and the Loading Coefficient of a Propeller without Nozzle σ_p

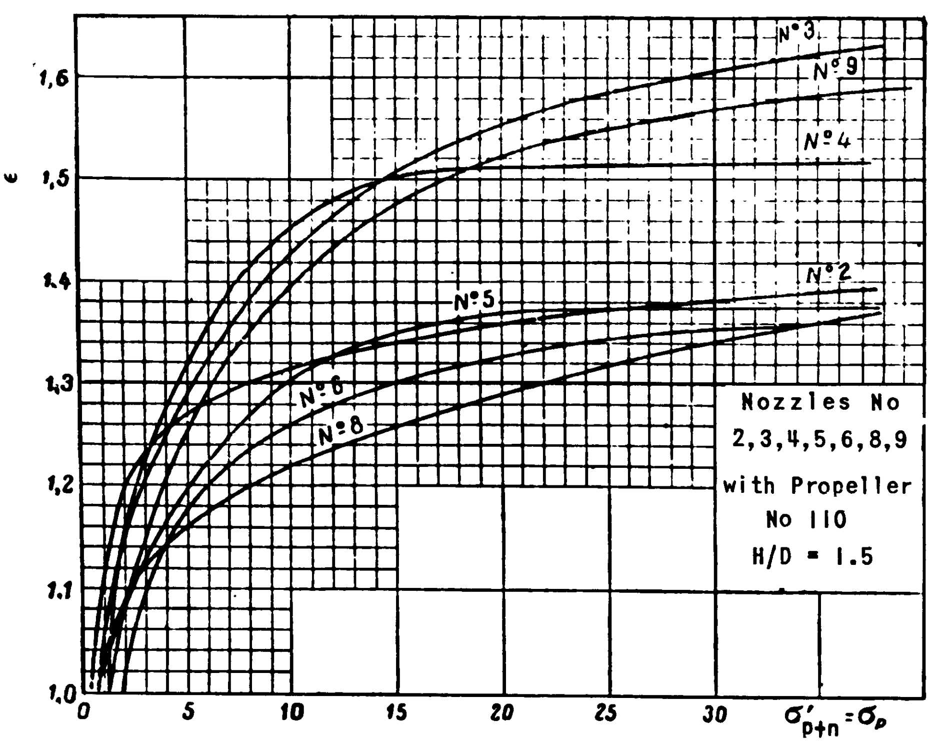

Figure 6 – Relationship between the Efficiency Improvement Factor of a Propeller-Nozzle Combination and the Loading Coefficient of the Combination $\sigma'_{p+n} = \sigma_p$

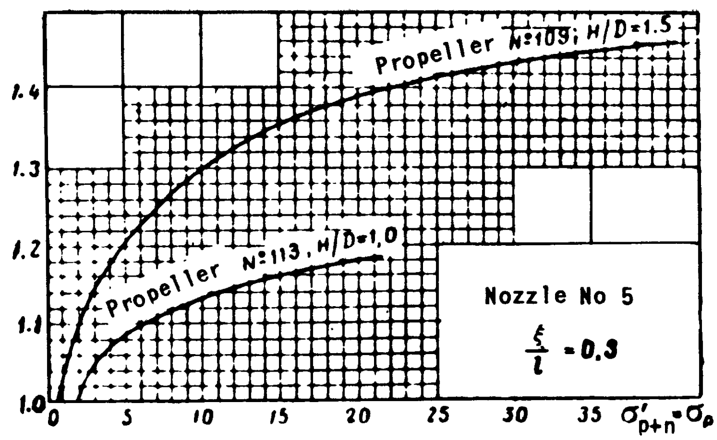

Figure 7 – Efficiency Improvement Factor ϵ for Propellers with Pitch Ratios H/D = 1.0 and H/D = 1.5

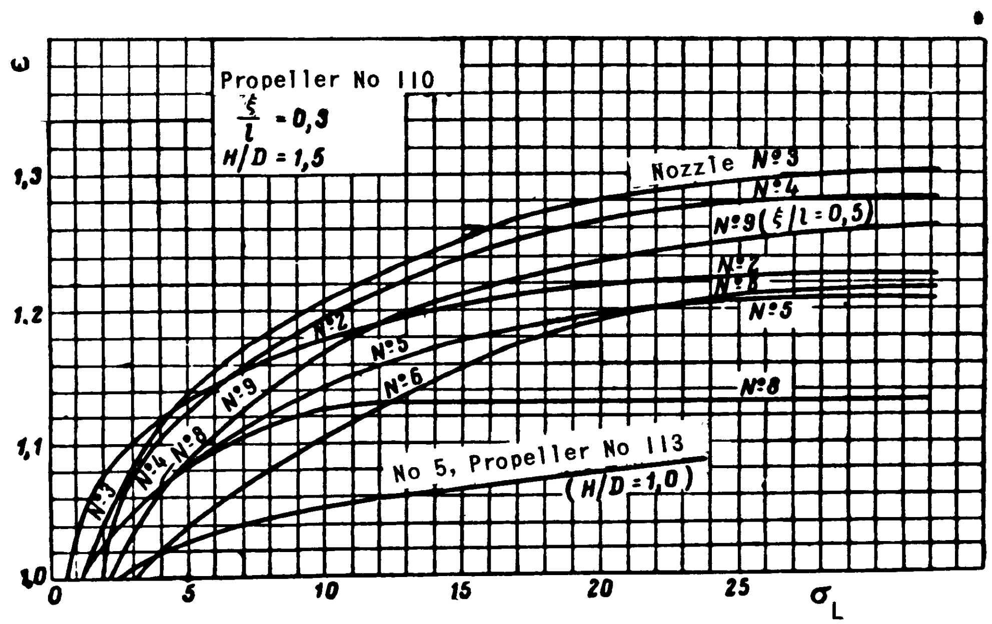

Figure 8 – Relationship between the Efficiency Improvement Factor ϵ of a Propeller-Nozzle Combination and the Power Loading Coefficient σ_L

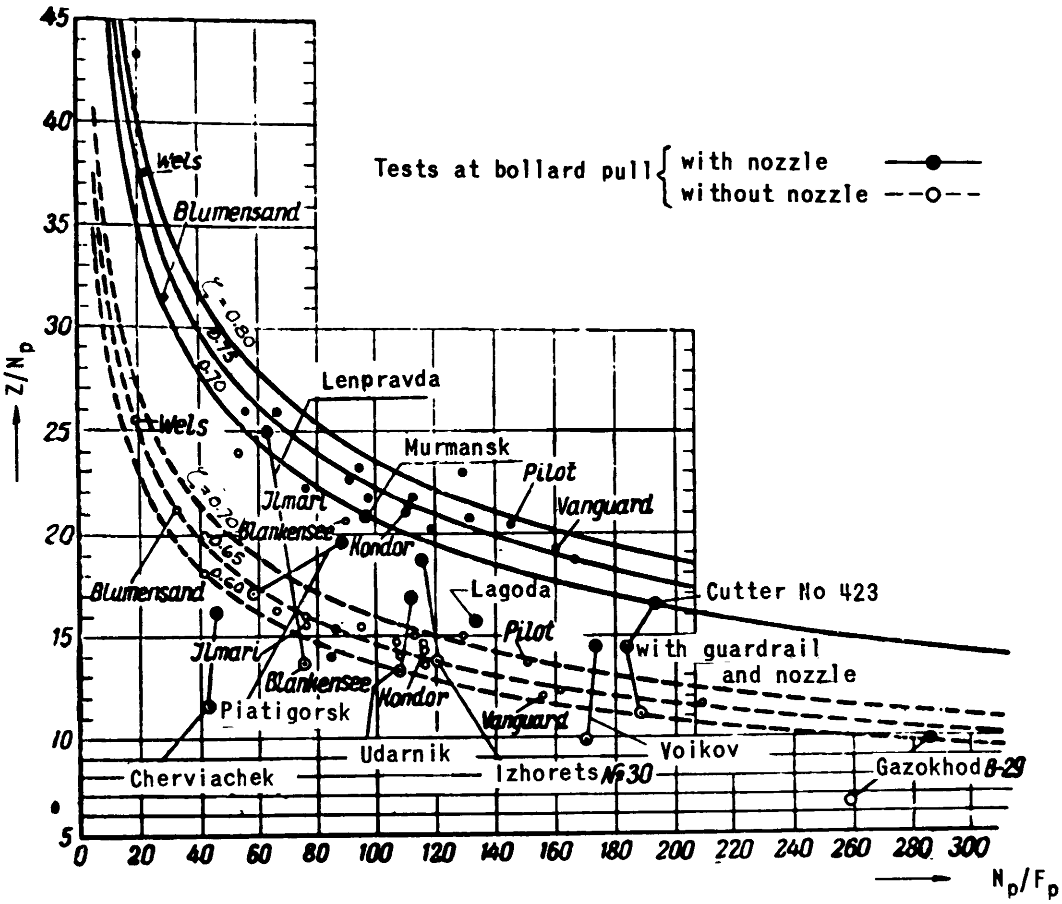

Figure 9 – Thrust per Horsepower for Tugs at Bollard Pull with and without Nozzles

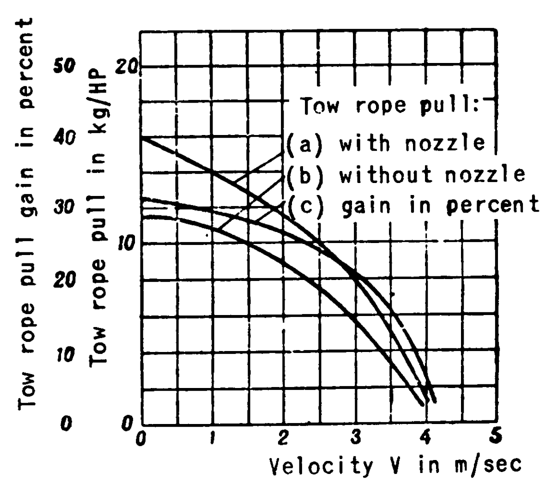

Figure 10 – Results of Tests for the Tug "Izhorets" with and without a Nozzle

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3. Propellers (Marine)--Performance--Model tests
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