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Coefficients of Propeller-hull Interaction in Propulsion System of Inland Waterway Vessels with Stern Tunnels

J. Kulczyk & T. Tabaczek
Wrocław University of Technology, Wrocław, Poland

ABSTRACT: Propeller-hull interaction coefficients - the wake fraction and the thrust deduction factor - play significant role in design of propulsion system of a ship. In the case of inland waterway vessels the reliable method of predicting these coefficients in early design stage is missing. Based on the outcomes from model tests and from numerical computations the present authors show that it is difficult to determine uniquely the trends in change of wake fraction and thrust deduction factor resulting from the changes of hull form or operating conditions.

Nowadays the resistance and propulsion model tests of inland waterway vessels are carried out rarely because of relatively high costs. On the other hand, the degree of development of computational methods enables' to estimate the reliable values o interaction coefficients. The computations referred to in the present paper were carried out using the authors' own software HPSDKS and the commercial software Ansys Fluent

1 INTRODUCTION

For correct design of propulsion system with screw propeller for inland waterway vessel the precise determination of propeller-hull interaction coefficients is required. These coefficients are the wake fraction (denoted with w) and the thrust deduction factor (denoted with t). The former coefficient describes the actual inflow velocity to propeller, that is usually lower than ship speed because of wake behind the ship. The latter describes the increase in hull resistance due to the suction of propeller, and is used to determine the thrust required to achieve the assumed ship speed. Propeller thrust at given ship speed is usually greater than the resistance of towed ship hull.

The proportion $(1-t)/(1-w)$ in naval architecture is called the 'hull efficiency'. Actually, it is not the efficiency in meaning of technology. It is rather the coefficient that accounts for the influence of propeller-hull hydrodynamic interaction on the efficiency of propulsion system. Hull efficiency greater than 1.0 means that there is the beneficial mutual fit of propeller and hull, and increases the overall efficiency of propulsion system.

Errors in determination of values of interaction coefficients in the course of ship design are bad for operation of propulsion system in real operating conditions [8]. The error in determination of wake fraction results in errors in advance speed V_A and in open water efficiency of propeller η_0. The difference between assumed and actual value of efficiency is determined by the following equation:

$$\frac{d\eta_o}{\eta_o} = J\frac{w}{1-w}\cdot\frac{dw}{w}\left[\frac{1}{K_Q}\frac{\partial K_Q}{\partial J} - \frac{1}{K_T}\cdot\frac{\partial K_T}{\partial J} - \frac{1}{J}\right] \qquad (1)$$

and affects the ship speed:

$$\frac{dV}{V} = \frac{w}{1-w}\frac{dw}{w} \tag{2}$$

where:

η_0 - open water efficiency of propeller,
J -advance coefficient of propeller,
w -wake fraction,
K_T -thrust coefficient,
K_Q -torque coefficient,
V -ship speed.

When $w<0.5$ the relative error in speed dV/V is smaller than the error in wake fraction dw/w. Positive value of dw/w results in higher actual speed. In prediction of ship speed the underestimated values of wake fraction may become beneficial, especially when the highest possible ship speed is the goal of propeller design.

For sea-going ships there is a number of reliable empirical formulae in the literature for determination of values of interaction coefficients. Those formulae are based on the results of systematic model tests with various hull forms. For inland waterway vessels such formulae are missing because of lack of systematic model tests. The effects of water depth, ship speed (propeller loading) and height of stern tunnel(s) on wake fraction and thrust deduction factor have not been sufficiently investigated. The outcomes from tests carried out with motor cargo vessel GUSTAW KOENIGS [1] show that the effect of stream in water on wake fraction and thrust deduction factor is also significant.

Available outcomes from model tests and results of numerical computations are not numerous enough to predict the values of interaction coefficients reliably in the case of newly-designed vessels or in the case of variable operating conditions.

2 DETERMINATION OF INTERACTION COEFFICIENTS

Wake fraction and thrust deduction factor for given ship are determined using the results of resistance and propulsion model tests, the results of numerical computations, or empirical formulae.

Model tests are time consuming and expensive. In the case of inland waterway vessel the costs of model tests are high in comparison to the costs of ship design and construction. Therefore they are carried out rarely.

Numerical computations using the commercial CFD software provide reliable results, but are also labour consuming and require the efficient hardware. Computations are also expensive.

Empirical formulae based on outcomes from numerous model tests and on data from operation of real vessels, are commonly used in early design stages, as well as in real-time control of propulsion system. The methods developed for sea-going ships are precise enough owing to numerous experimental data from model tests. For inland waterway vessels the reliable empirical formulae are missing due to much less number of model tests carried out in the past..

The determination of thrust deduction factor based on data from model tests or results of numerical computations of ship flow (with operating propeller and without propeller) is straightforward. Using values of hull resistance R and propeller thrust T the value of thrust deduction factor is calculated according to its definition: $t = (T-R)/T$.

Two wake coefficients are used in design of screw propellers: the nominal wake fraction (in propeller disk behind the hull towed without propeller, denoted with w_n) and the effective wake fraction (for propeller operating in ship wake, denoted with w_e). The nominal wake fraction represents the actual mean velocity of wake flow in propeller disk V_n. It is defined as proportion $w_n = (V_S-V_n)/V_S$, and is determined based on direct measurements or computations of flow velocity. The effective wake fraction represents the men inflow velocity to the propeller operating in ship wake or, otherwise the advance speed of propeller V_A. It is defined as proportion $w_e = (V_S-V_A)/V_S$, and accounts for the influence of the running propeller on flow in hull boundary layer and wake. Effective wake fraction is determined using the magnitudes measured in propulsion test and the open water hydrodynamic characteristics of propeller. Performance of propeller operating in ship wake (thrust or torque) is compared to the performance of the same propeller in open water, with assumption of thrust identity or torque identity, in order to determine advance speed V_A. Thrust identity is usually applied in model tests. Torque identity is applied to full scale measurements when only torque is measured on propeller shaft. Values determined with the assumption of torque identity may differ considerably from values determined with the assumption of thrust identity. Recommended procedures prepared by the International Towing Tank Conference [9] standardize the methodology of determination of propeller-hull interaction coefficients.

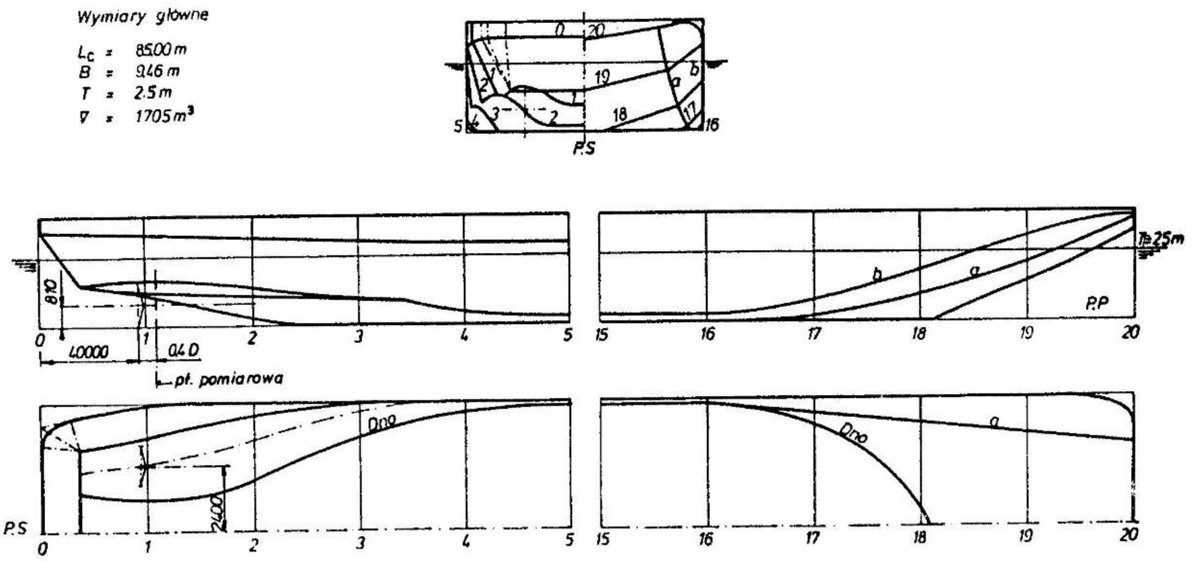
In the following sections the authors present the analysis of the influence of operating conditions (i.e. ship loading, water depth and ship speed) and height of stern tunnel on propeller-hull interaction coefficients for inland waterway vessels. The analysis is based on outcomes from model tests and results of numerical computations. It refers to conventional inland waterway cargo ships with stern tunnels - motor cargo vessels and pushed barge trains made up of dumb barges coupled with a pushboat.

3 INTERACTION COEFFICIENTS FOR MOTOR CARGO VESSELS

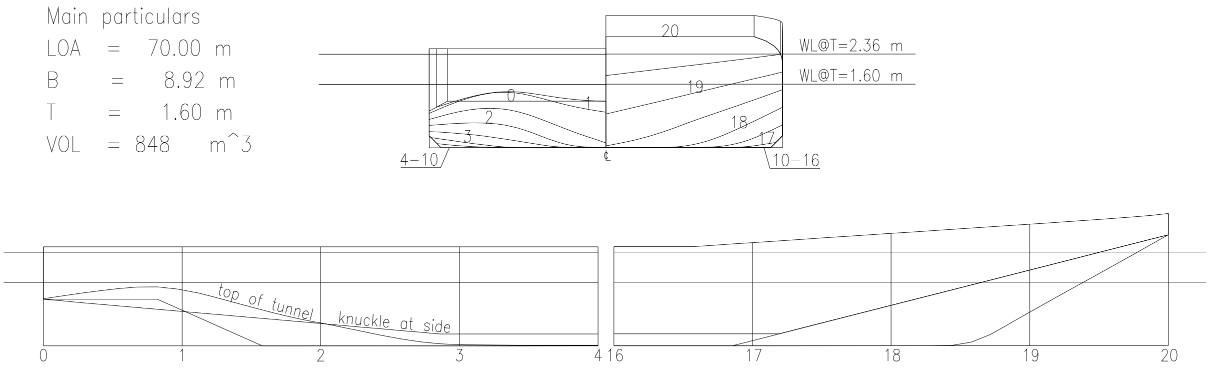
Main particulars and hull forms of considered motor cargo vessels are presented in Table 1 and in Figures 1 and 2.

Model tests of motor cargo vessel BM-DUISBURG [3] included the measurements of flow velocity in propeller disk without propeller (nominal wake) and the measurements of flow velocity in plane located in distance 0.4 of propeller diameter in front of operating propeller (Fig. 1). Effective wake fraction was determined with assumption of thrust identity. Tests were carried out at various operating conditions (ship draught, water depth and ship speed - see Table 1).

Conventional resistance and propulsion tests were carried out with motor cargo vessel OBM [2]. Effective wake fraction was determined with the assumption of thrust identity as well as torque identity, in wide range of ship speed, for the vessel sailing alone ('solo') and coupled with a single dumb barge ('kombi'). Model tests of OBM in both arrangements were also reproduced in numerical computations [7]. Tests and computations were carried out at two values of draught, in deep and in shallow (*h*/*T*=1,56) water. Results are presented in Table 2.



Figue 1. Hull form of motor cargo vessel BM-DUISBURG



Figue 2. Hull form of motor cargo vessel OBM

Table 1. Main particulars and operating conditions of model ships, [3], [2]

Vessel		BM-DUISBURG			OBM	
Scale		1 : 12.5			1 : 16	
L_{WL} [m]	6.604	6.760	6.768	6.604	4.239	4.329
B [m]	0.757	0.757	0.757	0.757	0.558	0.558
T [m]	0.200	0.224	0.256	0.200	0.100	0.148
C_B [-]	0.874	0.875	0.876	0.874	0.876	0.899
h [m]		0.40		0.28	0.156	0.156
V [m/s]	1.336	1.267	1.171	1.100	0.417	0.417
				Propellers		
type		screw propeller			ducted propeller Ka4-55	
D [m]		0.120			0.0813	
P/*D* [-]		0.65			0.90	
A_E/A_O [-]		0.56			0.55	

Table 2. Results of model tests and numerical computations

Vessel		BM-DUISBURG				OBM	
Scale		1 : 12.5				1 : 16	
T [m]	0.200	0.224	0.256	0.200		0.100	
h [m]		0.40		0.28		0.156	
h/T	2.00	1.79	1.56	1.40		1.56	
V [m/s]	1.336	1.267	1.171	1.100	0.417	0.556	0.695
Fn_h	0.67	0.64	0.59	0.66	0.34	0.45	0.56
n [rps]	26.22	26.10	26.00	25.80			
			Coefficients of propeller-hull interaction				
Test w_n	0.276	0.245	0.232	0.438	-	-	-
w_{eT}	0.27	0.23	0.20	0.26	0.143	0.054	0.020
w_{eQ}	-	-	-	-	0.685	0.2462	0.1565
w_{zp}	0.09	0.06	0.01	0.11	-	-	-
t	0.245	0.270	0.270	0.292	0.320	0.274	0.244
Comput. w_n	0.223	0.220	0.217	0.234	0.335	0.332	0.312
Fluent w_e	-	-	-	-	-	-	-
w_{zp}	-0.383	-0.309	-0.260	-0.276	-0.304	-0.382	-0.391
t	0.267	0.243	0.262	0.288	0.345	0.326	0.353
Comput. w_n	0.234	0.240	0.300	0.322	0.275	0.270	0.270
HPSDK w_e	0.172	0.200	0.258	0.213	-	-	-
w_{zp}	-0.126	0.161	0.211	-0.148	-	-	-
t	-	-	-	-	-	-	-

w_{eT} - effective wake fraction based on thrust identity

w_{eQ} - effective wake fraction based on torque identity

$w_{zp} = (V_S - V_{zp})/V_S$ where V_{zp} denotes the mean velocity in front of operating propeller, and V_S is the corresponding ship speed

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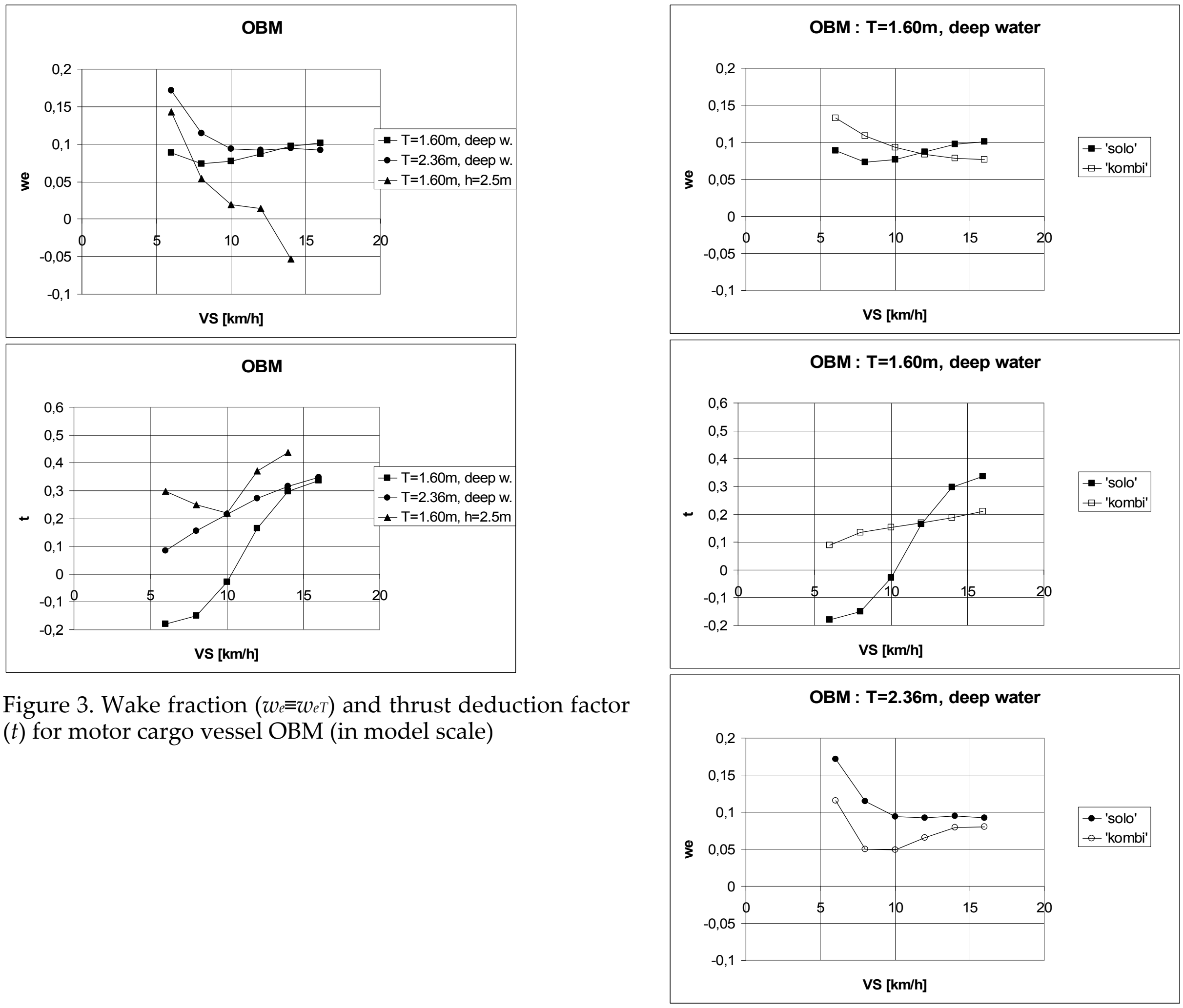


Figure 3. Wake fraction ($w_e \equiv w_{eT}$) and thrust deduction factor (t) for motor cargo vessel OBM (in model scale)

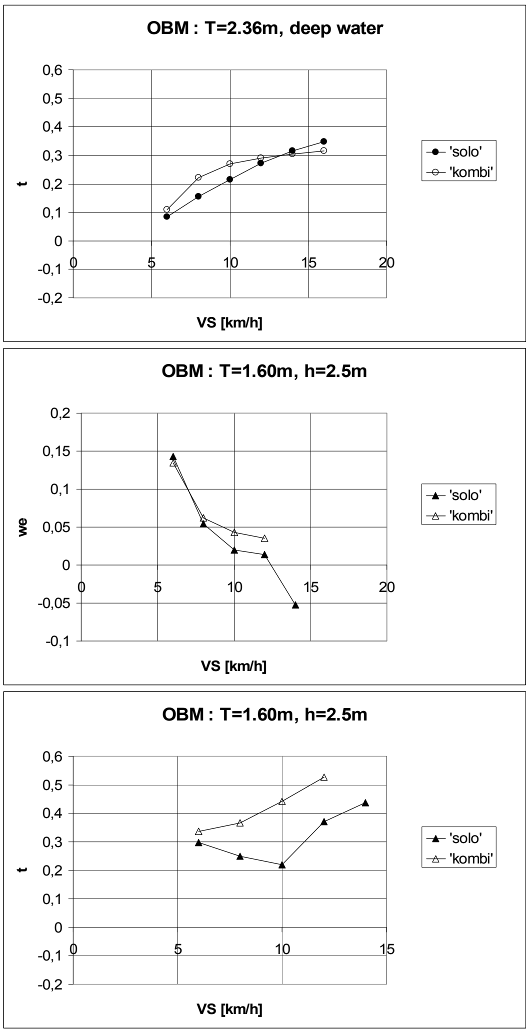


Figure 4. Comparison of wake fraction ($w_e \equiv w_{eT}$) and thrust deduction factor (t) for motor cargo vessel OBM sailing alone ('solo') and coupled with a single dumb barge ('kombi')

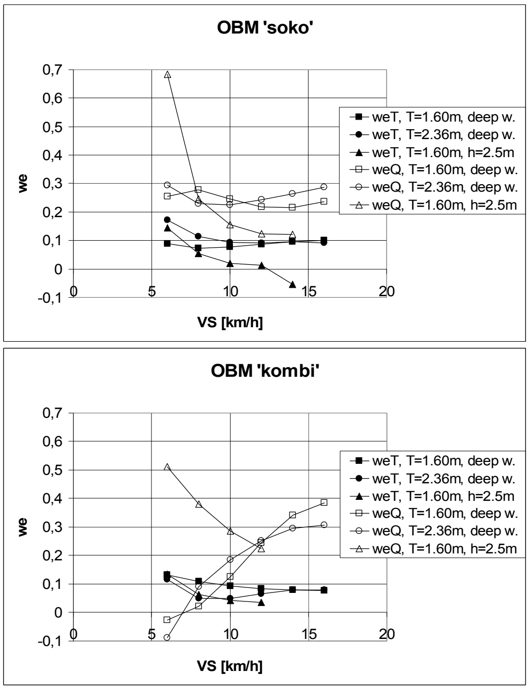


Figure 5. Comparison of effective wake fraction determined with assumption of thrust identity (w_{eT}) and determined with assumption of torque identity (w_{eQ}) for motor cargo vessel OBM sailing alone ('solo') and coupled with a single dumb barge ('kombi')

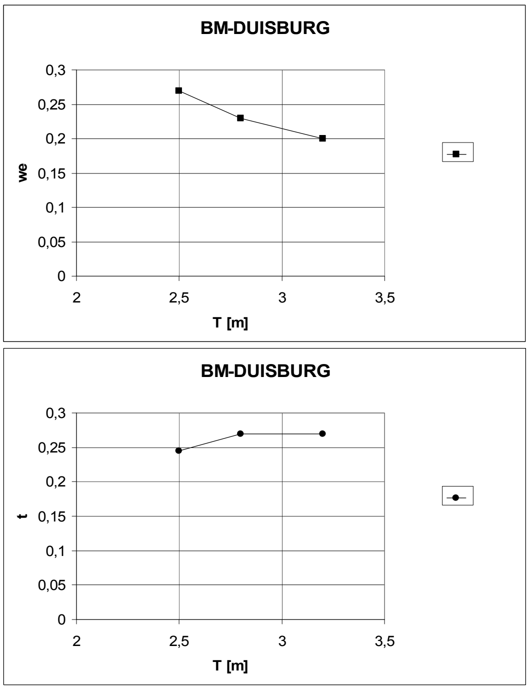


Figure 6. The effect of ship loading (ship draught) on wake fraction (w_e) and thrust deduction factor (t) for motor cargo vessel BM-DUISBURG at constant depth of water h=5.0m (in model scale)

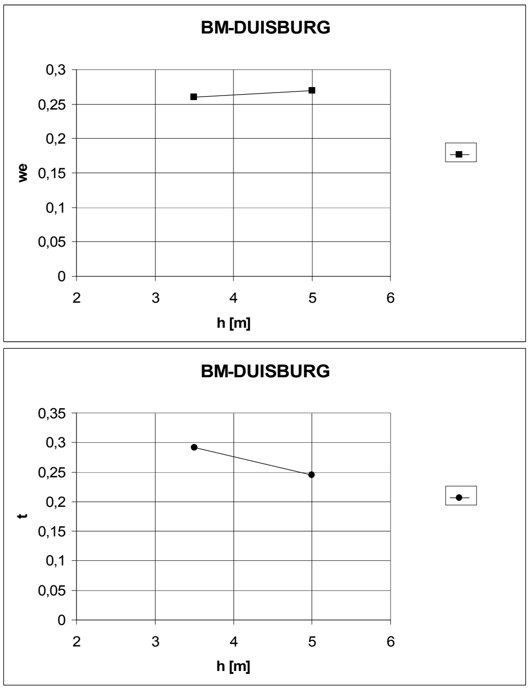


Figure 7. The effect of water depth on wake fraction (w_e) and thrust deduction factor (t) for motor cargo vessel BM-DUISBURG at constant draught T=2.50m (in model scale)

When ship speed increases the effective wake fraction is getting weaker (Fig. 3). In deep water, at speeds higher than 12km/h becomes almost steady. In shallow water (h/T=1.56) the wake fraction decreases faster, and at speed of 12km/h (Fn_h=0.67) is considerably less than in deep water, because of intensive sinkage and trim by stern. The change of draught in deep water does not affect the wake fraction as far as top of stern tunnel is below the free surface in calm water. In arrangement with dumb barge ('kombi') both values and trends in change of the effective wake fraction are almost the same as when sailing alone (Fig. 4).

When ship speed increases the thrust deduction factor also increases (Fig. 3). In shallow water the values are greater than in deep water. The effect of draught at highest speed in deep water is negligible. Based on data shown in Fig. 4 one can not conclude the changes in thrust deduction factor caused by enlargement of ship length (by coupling with a barge).

The diagrams shown in Fig. 5 illustrate the difference between values of wake fraction determined with the assumption of thrust identity and determined with the assumption of torque identity.

The extent of model tests with the motor cargo vessel BM-DUISBURG allows to identify the variation of interaction coefficients caused by change of draught in shallow water ($1.56 \leq h/T \leq 2.00$; see Fig. 6). When ship draught increases the wake fraction evidently decreases due to decreasing under-keel clearance between ship and bottom of waterway. At the same time the thrust deduction factor slightly increases.

Reduction of water depth at constant ship draught caused the weakening of wake and intensification of propeller suction (Fig. 7). Reduction of under-keel clearance is considerable and one might expect greater difference between values of wake fraction. However, the trends are the same as in the case of reduction of under-keel clearance by increasing ship draught at constant water depth, or in the case of transition from deep to shallow water in tests with motor cargo vessel OBM.

4 INTERACTION COEFFICIENTS FOR PUSHED BARGE TRAINS

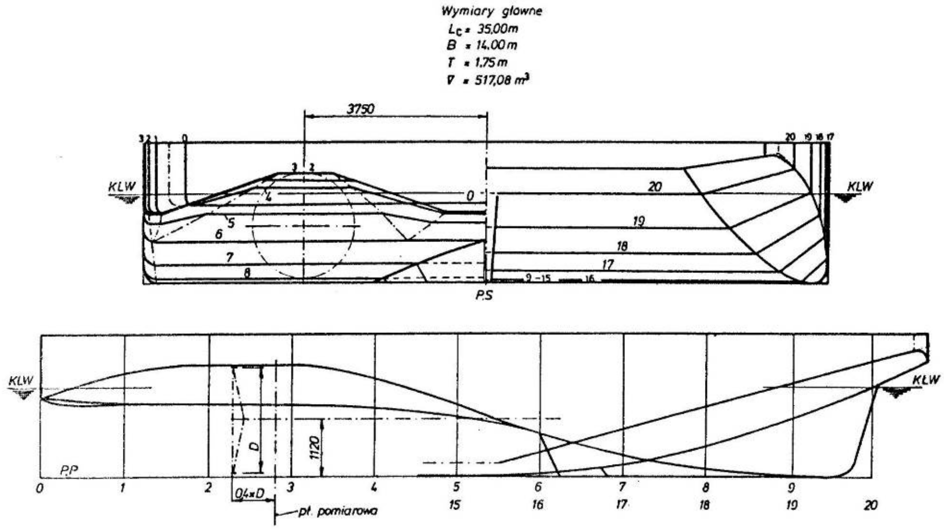
Model tests of pushed barge trains with twin-propeller pushboat and triple-propeller pushboat were carried out in research centre in Duisburg [4], [5]. The twin-propeller pushboat was tested in train with 4 dumb barges arranged in two rows, at barge draught of 2.8m (0.175m in model scale) and 3.2m (0.200m in model scale). The triple-propeller pushboat was tested in train with 6 dumb barges arranged in two rows, at barge draught of 3.0m (0. 188m in model scale). Numerical computations were carried out using theoretical model described in [6], at the same operating conditions as in model tests. Main particulars of pushboats and dumb barge EUROPA II are given in Table 3. Hull forms of considered pushboats are shown in Figures 8 and 9.

Table 3. Main particulars of tested pushboats and dumb barges [4], [5]

Vessel	Twin-screw pushboat	Triple-screw pushboat	Dumb barge EUROPA II		
Scale	1 :16	1 : 16	1 : 16		
L_{OA} [m]	2.1875	2.1875	4.7813		
L_{WL} [m]	2.1188	2.1181	4.565	4.587	4.611
B [m]	0.875	0.9344	0.706	0.706	0.706
T [m]	0.1093	0.10625	0.175	0.1875	0.200
C_B [-]	0.622	0.6426	0.947	0.946	0.945
Screw propeller					
z	4	4			
D [m]	0.13125	0.13125			
P/D [-]	1.052	1.052			
A_g/A_0 [-]	0.71	0.71			
h [m]			0.3125		

Table 4. Results of model tests and numerical computations

Vessel		Twin-screw pushboat		Triple-screw pushboat		
h [m]		0.3125		0.3125		
T [m] (pushboat)		0.1093		0.10625		
T_B [m] (dumb barges)		0.175	0.200	0.188		
h/T_B		1.79	1.56	1.67		
V [m/s]		0.888	0.835	0.873		
Fn_h		0.51	0.48	0.50		
n [rps]		16.07	16.13	15.20		
				Central propeller	Side propeller (screw prop.)	Side propeller (ducted prop.)
Model test	w_n	0.438	0.471	0.625	0.520	0.520
	w_e	0.318	0.324	0.39	0.46	-
	w_{zp}	0.072	0.090	0.064	-0.029	-0.4126
	t	0.20	0.21	-	-	-
Comput. (HPSDK)	w_n	0.409	0.463	0.628	0.629	0.629
	w_e	0.211	0.244	0.657	0.543	0.543
	w_{zp}	0.107	0.113	0.253	0.125	-0.188
	t	0.111	0.107	0.268	0.239	0.344
	K_T	0.371	0.383	0.440	0.424	0.435



Figur 8. Hull form of twin-screw pushboat

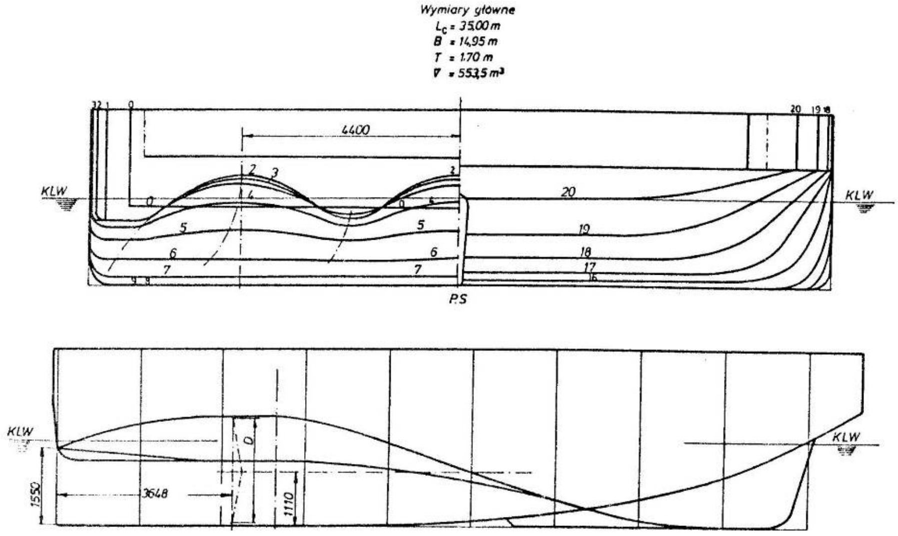


Figure 9. Hull form of triple-screw pushboat

The results of model tests and numerical computations are presented in Table 4.

In the case of tested pushed barge trains in shallow water the increase of barge draught at constant water depth caused increase of wake fraction. The trend is opposite to that observed in the case of motor cargo vessels and described in the preceding section. The reason is that the draught of pushboat remained unchanged and, in fact, it was the change of hull form and not only of ship draught. Some regularities in variation of interaction coefficients observed in the case of motor cargo vessel do not refer to pushed barge trains.

Moreover, in the case of pushboats that operate at almost constant draught, regardless of the draught of barges, the height of tunnels is usually greater than draught, in order to accommodate propeller of sufficient diameter. That is why the values of nominal and effective wake fraction are, in general, greater than in the case of motor cargo vessels where the top of stern tunnel is below the free surface of water.

The effect of tunnel height on coefficients of propeller-hull interaction was studied theoretically for virtual pushboat of simplified hull form [7]. Main particulars of virtual pushboat are given in Table 5. The section along the stern tunnel of virtual pushboat is shown in Fig. 6. According to the practice in design of inland waterway vessels, the tunnel height of 1.3m is considered the maximum applicable at ship draught of 1.0m.

Table 5. Main particulars of virtual pushboat [7]

Length, L [m]	20.0
Beam, B [m]	9.0
Draught, T [m]	1.0
Height of tunnel, h_w [m]	1.1; 1.3; 1.5
Slope of tunnel, α [deg]	25

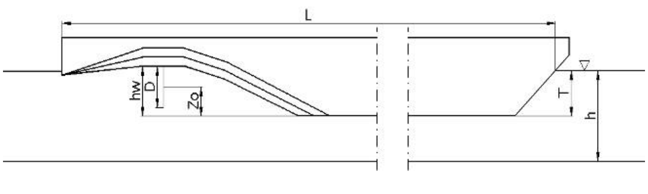


Figure 6. Section along the stern tunnel of virtual pushboat

Three values of tunnel height were considered (Table 6). For each height the diameter of ducted propeller was determined with assumption, that nozzle is integrated with ship hull. Using the test data of Ka4-70 screw series in nozzle 19A the propeller pitch was designed so as to achieve maximum thrust at given advance speed V_A=2.1m/s. Thrust of propeller and mean pressure gradient in propeller disk were determined for three values of ship speed, based on propulsive characteristics. The results are presented in Table 6.

Table 6. Diameter and thrust of ducted propellers designed for virtual pushboat

h_w [m]	D [m]	Z_0 [m]	n [rps]	V_S [m/s]	T [kN]	Δp [kPa]
1.1	0.91	0.64	12.0	0.10	37	56.9
				1.56	33	50.7
				3.12	24	36.9
1.3	1.08	0.75	7.5	0.10	44	48.0
				2.31	35	38.2
				3.47	31	33.8
1.5	1.24	0.87	6.67	0.10	48	39.7
				2.36	37	30.6
				3.54	32	26.5

Using CFD software Ansys Fluent and the actuator disk with pressure gradient to simulate the action of propeller a series of numerical computations were carried out at water depth of 1.5 and 3.0m. The values of nominal wake fraction and thrust deduction factor determined for virtual pushboat are presented in Table 7.

Table 7. Nominal wake fraction and thrust deduction factor determined for virtual pushboat

h_w [m]	V_S [m/s]	h/T	w_n	t
1.1	3.12	1.5	0.837	0.302
		3.0	0.679	0.285
1.3	3.47	1.5	0.861	0.299
		3.0	0.752	0.320
1.5	3.54	1.5	0.899	0.394
		3.0	0.733	0.403

5 CONCLUSIONS

Due to the little amount of data the conclusions are rather qualitative than quantitative and refer to model scale, however, shall be valid also in full scale.

The results of model tests and numerical computations show that operating parameters considered in this paper, i.e. ship loading (or corresponding ship draught), water depth and ship speed, affect the values of both wake fraction and thrust deduction factor.

Considering inland waterway vessels with stern tunnels that do not rise above free surface of water ($h_w < h$), as motor cargo vessels with full or partial loading, one may expect that:

- The increase of ship speed in deep as well as in shallow water causes the decrease of wake fraction and increase of thrust deduction factor. At higher speeds in deep water the wake fraction becomes steady. In shallow water the wake fraction decreases until depth Froude number ($Fn_h = V_S/(gh)^{1/2}$) reaches the value of 0.65. Operation of cargo vessels at higher speed is unprofitable and may cause grounding due to intensive trim and sinkage of ship.
- Change of ship loading (and corresponding change of ship draught) in deep water does not affect the propeller-hull interaction coefficients.
- In shallow water both the reduction of water depth as well as the increase of ship draught result in decrease of under-keel clearance and in the same trends in variation of interaction coefficients: when the distance between hull and waterway bottom (or h/T ratio) decreases, wake fraction also decreases and thrust deduction factor increases.
- The effective wake fraction determined with assumption of torque identity differs significantly from that determined with assumption of thrust identity.

In the case of pushed barge trains the change of barge loading (or change of barge draught) does nor affect the draught of pushboat, and implies the change of hull form. Regularities in variation of interaction coefficients observed in the case of motor cargo vessel may not obey in the case of pushed barge trains.

The results of model tests and numerical computations also show that the height of stern tunnels affects the flow around ship considerably, and, in consequence, the value of thrust deduction factor.

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