OPTIMISATION OF TUNNEL GEOMETRY OF A NOVEL STERN TYPE FOR PUSHING TWIN-SCREW INLAND CARGO MOTOR SHIPS

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In the present work a tunnelled after-body suitable for highly loaded pushing inland cargo motor ships is further developed. The tunnel geometry of a pre-optirffised novel stem type is varied with the aim of minimising the power required by the motor ship. Experimental results from tow-rope pull tests with self-propelled divided models at water depth/draught ratios in the range of 1.2 to 3 are the basis for this investigation. A special measuring technique was established in order to explain the changes of the driving power obtained with the stem variants by different propulsion quality and stem shape.

يشتمل هذا البحث على النتائج النهائية لخطوات تطور تصميم المؤخرة **Stern Tunnel** الخاصة بسفن النقل التجارية الكبيرة ذات الرفاصين والمخصصه للملاحه فى الأنهار ذات العمق المحدود.

أستخدم الباحث لهذا الغرض مجموعة من النماذج يتضمن أولها النفق الأمثل الأولى ويتضمن الباقين أنفاق أقصر طولا و اشكالا مستنسخة من النفق الأمثل الأول طبقا لمعاملات الشكل الهندسية الخاصة بالنفق المستخدمة فى هذا البحث لأول مرة مع الأبقاء على الجزء الأوسط والجزء الأمامى من النماذج بدون تغيير. وتبعا لمتطلبات التشغيل الخاصة بتلك السفن التى تستخدم كوحدة نقل منفردة أو لدفع صنادل أمامها يصل عددها إلى ثلاثة، فقد أجريت التجارب بمركز أبحاث السفن بديوسبورج (المانيا) على أعماق مياه تتراوح بين ٣ الى ٧ مترا وغاطس قدره ٢, ١ إلى ٣م وتم قياس قوة الدفع والمقاومة الكلية والدفع الفعلى وهى القوة التى تقاس من مكان الأنفصال بين جزء النموذج الخلفى على النفق وجزء النموذج الأمامى المكون من المقدمة والجزء الأوسط وذلك عند سرعات مختلفة.

أضحت طريقة التقييم المستخدمة التى تعتمد على مقارنة قوة الدفع مع ثبات المقاومة الكلية عند سرعة تشغيل مختلفة أن النقص فى القوة المطلوبة جاء كنتيجة مباشرة للتحسين فى شكل السفن متمثلا فى المؤخرة ذات النفق القصير طولا.

ولقد بلغت قيمة النقص فى قوة الدفع المطلوبة حوالى ٤,٧فى حالة أستخدام السفينة كوحدة نقل منفردة وحوالى ٣,٢% إلى ٤,٧% فى حالة أستخدامها فى الدفع.

وجدير بالذكر أن تلك النتيجة تمثل إضافة هامة لاقتصاديات إستخدام هذا النوع من السفن حيث أن قصر طول النفق أدى إلى تغير طول الجزء الأوسط وبالتالى الى زيادة سعة الشحن بنسبة ٦% وترتب عليه انخفاض معامل القدرة المطلوبة بنسبة ١٠% وفى النهاية يوصى الباحث بمزيد من التجارب والدراسة لتحديد الحد الأدنى لطول النفق مع الإحتفاظ بأفضل الخصائص التشغيلية السابق الحصول عليها.

Keywords: Inland cargo ship, Pushing motor ship, Stem tunnel, Tunnel Geometry

INTRODUCTION

The purpose of this investigation is to complete the development of high-quality large inland cargo ships equipped with a novel type of tunnel stem. To enhance the efficiency, an innovative process of optimization is conducted on this stem. The motor ships are intended for serving as single cruiser or as pushing unit in trains with up to 3 barges. The length of the ship is 105 m, the breadth 11.4 m and the length of the after-body 27.3 m. The operating conditions are characterized by ship's draughts of 1.7 to 3.5 m and by waterway depths in the range of 3 to 7.5 m. The high load especially in extremely shallow water necessitates two propellers with diameters of 1.9 m. Previous research works suggested that the newly developed stem type is more advantageous as compared with conventional high-quality sterns of inland cargo ships, [1,2]. Exclusively due to the special hull form of this stem, the required driving power was remarkably reduced and the available thrust power in trains increased, respectively. The best power characteristics can be achieved with a relative large lateral distance between propellers, i.e. 52 % of the ship's breadth, and with an inward sense of rotation, [3, 4]. Although stern shape and propeller

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arrangement were varied in these steps of development, length and volume of the tunnelled area were kept to the same size.

The object of this study is to investigate the impacts of modified tunnel dimensions, whilst fore- and middle-body, the length of the after-body and the propulsion system remain unchanged. In an almost parallel running research project, in which large motor ships with a length of II 0 m were developed for another h/T-range, a relatively short tunnelled after-body of different kind revealed an excellent power characteristic, [5, 6]. Following this promising trend and apart from the pre- optimised prototype, four variants with shorter tunnels are taken into account. If a power saving can be established, the present length of the after-body could possibly be reduced too. The tunnel dimensions are systematically varied by utilising geometrical characteristic values [7], which are considered for the first time in practice.

The effect on the driving power required for the motor ship is determined on the basis of the results from tests with self-propelled models. Barges were excluded in the tests and their thrust demand was simulated by tow-rope pulls. The evaluation of the stem variants is in principle performed by comparing measured data at certain conditions. The evaluation method employed formerly [2, 4], which compares tow-rope pulls at the same shaft power, implies some complications. A modified method is therefore introduced, whereby shaft powers are compared at the same tow- rope pull. Since the models were divided between after-body and the remaining ship's body, the force transferred at the interface could be measured. This force allow the calculation of additional characteristic values, so that the differences of shaft powers can be explained by partial effects. Some few comparisons for individually selected parameters are already published, [8]. This study analyses for the first time all available test data by using the new evaluation method.

INVESTIGATED STERN VARIANTS AND TEST PARAMETERS

The left part of Figure 1 shows the form of sections of the after-body. This stem type is distinguished by a central gondola-shaped middle part, which resembles a strongly thickened keel fin, see Reference 7. In order to characterize the tunneled area of the stem and to select reasonable modifications, dimensionless geometrical characteristic values are utilized [7], which allow a systematic description of any tunnel type. The definitions are based on geometrical data at a draught T_T, at which pushing motor ships can apply only just its full driving power. The displacement distribution in the tunneled area at this reference draught plays a decisive role concerning hydrodynamic quality of the after-body. According to Reference 7, TT can generally be set as 90 % of propeller diameter, i.e. T_T = 1. 7 m in the present case.

In order to illustrate the most important geometrical values, Figure 1 shows qualitatively sectional area curves of the after-body for two different tunnel dimensions. Both curves, I and 2, start with the midship section area A_{MT}, but at variable positions. The sectional areas reduce down to the same minimum A_{TC} in the tunnel top above the propeller plane. The tunnel roof behind the propellers is slightly arched downwards to the transom. The geometrical characteristic values are:

Degree of tunnel widening

$$C_{TC} = (A_{MT} - A_{TC}) / A_{MT} \qquad (1)$$

Tunnel length ratio

$$C_{TL} = (A_{MT} - A_{TC})^{0.5} / L_{RT} \qquad (2)$$

Tunnel volume ratio

$$C_{VT} = V_T / (A_{MT} - A_{TC})^{1.5} \qquad (3)$$

Block coefficient of after-body

$$C_{BTT} = I - CTC \,.\, C_{TL} \,.\, C_{VT} \qquad (4)$$

with L_{RT} as length and V_T as volume of the tunnel zone before propeller plane. The stem part between propeller plane and transom remains unchanged and is therefore not described with characteristic values. As indicated before, the characteristic sectional areas A_{TC} and A_{MT} are kept constant. Due to the hull form nearby the propellers, the degree of tunnel widening amounts to C_{TC} -I.e., that at reference draught virtually no immersed sectional area exists in the tunnel top.

Table 1 shows the geometrical characteristic values of the stern variants and indicates their systematic alteration. Stern No.1 represents the pre-optimised design. The first two variants are based on the block coefficient of stern No. 1. Tunnel length and proportional to that the tunnel volume are diminished in two equivalent steps. In addition, two designs are considered with small tunnel lengths as selected before, but with larger volume and smaller block coefficient,respectively. The right part of table I shows the parameters h and T of the model tests described below. Since inward rotating propellers are preferable [41, this sense of rotation is applied here too. All tests are carried out with the same steering device.

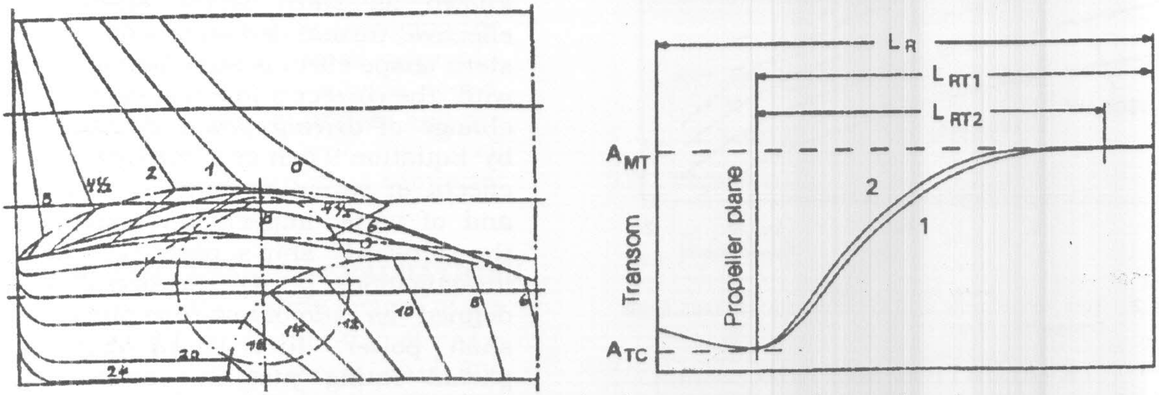


Figure 1 Body-plan and qualitative sectional area curves at reference draught

Table 1 Investigated tunnel dimensions and water depths

Sterm Nc.	Tunnel geometry at reference draught 1.7m					Investigated water depths h[m] for 3 draughts T		
	L_{RT} [m]	V_T $[m_3]$	C_{TL} [-]	C_{VT} [-]	C_{BTT} [-]	1.7[m]	2.5[m]	3.5[m]
1	21.50	160.2	0.209	1.778	0.629	2.5, 3.5	3, 5, 7.5	5
2	19.18	19.18	142.9	0.234	1.586	0.629	2.5, 5	5
3	17.10	127.4	0.262	1.414	0.629	2.5, 3.5,5	3, 5,7.5	5
4	19.18	191.18	0.234	1.778	0.584	2.5, 5	3, 5	5
5	17.10	17.10	0.262	1.586	0.584	2.5, 5	3, 5	5

EXPERIMENTAL TECHNIQUE AND TEST RESULTS

In order to provide the experimental data, the Duisburg Towing Tank and Research Institute for Shallow Water Hydrodynamics (VBD) performed tow-rope pull tests at different speeds with self- propelled divided models on a scale of 1: 16. The model division forms a vertical narrow joint between after-body and the always identical fore- and middle-body. The tow-rope pull Fp acts externally on the forward part of the ship for simulating the thrust demand of barges. Besides **Fp** and shaft power PD, also the longitudinal force transferred at the interface on the front ship's body can be measured, the so-called effective thrust Fp*. The difference Fp- Fp*, the so-called effective thrust demand, is interpreted as the thrust demand of fore- and middle-body.

The test results are converted to full-scale and structured into four power classes in the range of PD = 1000 to 2500 kW according to the service conditions with up to three barges. As an example, figure 2 presents the forces determined with stem variant No. 5 at a water depth of 5 m and a draught of 2.5 m. The resistance of the fore- and middle-body.

represented by the effective thrust demand Fp*-Fp, shows an increase with increasing ship's speed as expected, Thereby, the available tow-rope pull in the upper speed range decreases distinctly.

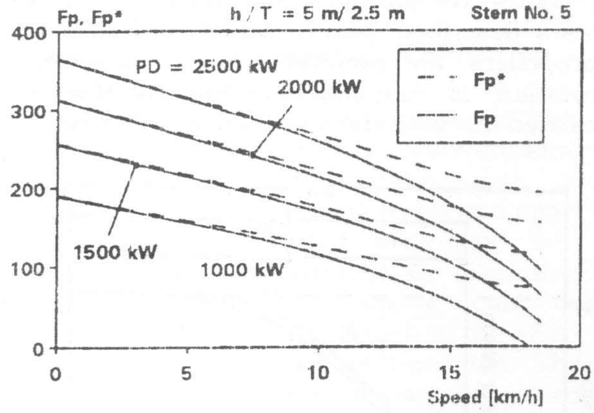


Figure 2 Tow -rope pulle and effective the thrusts from tests with stern no 5

EVALUATION METHOD

The rating of the stem variants is based on comparisons of experimental results at the same speed as well as at same water depth and draught. In this context, the ratio of shaft powers at identical tow-rope pull is constituted as main rating criterion. When contrasting variant 1 and variant 2 for instance, this ratio

$$Q_{PD} = P_{DI} / P_{D2} \qquad (5)$$

indicates the different power demand of the motor ship. Corresponding to the data structure, Q_{PD} can be calculated for four power levels. The measured effective thrust allows additionally the calculation of an effective thrust efficiency by which the propulsion characteristics of an after-body is globally represented. Thereby, ratios of effective thrust efficiencies and of effective thrusts can be introduced

and the overall rating, Equation 5, can be split into two partial rating factors

$$QPE = \eta^{*}_{F2} / \eta\eta^{*}_{F2} \qquad (7)$$

$$QPD = QPE - QSE \qquad (8)$$

And the overall rating, (Equation 5) can be split into two partial rating factors

$$QPD = QPE - QSE \qquad (9)$$

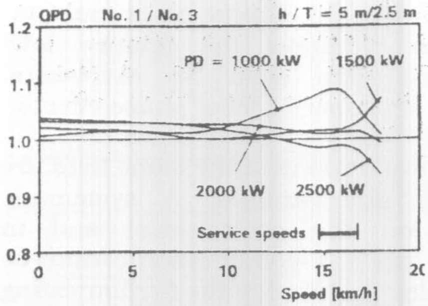
Due to the identity of the tow-rope pull, QsF reflects the differences of thrust demand for fore- and middle-body, which are created by the different stem shapes, and is therefore known as stern shape effect [1]. If the effective thrust demands are identical, the stern shape effect is automatically considered with the correct numerical value of Q_{SE}= 1. A change of driving power demand expressed by Equation 9 can be ultimately explained by effects of varied propulsion qualities, QPF, and of varied impacts of the stem shapes on the forward ship's part, Q_{SE}. In previous investigations [2, 4], the overall rating was defined as ratio of tow-rope pulls at identical shaft power. In order to obtain an exact partial rating just in cases of the same effective thrust demand, an additional correction factor was necessitated. Consequently, the partial rating factors did not agree with the really ratios of measured data and the evaluation suffered from some complexity. The present evaluation system avoids these disadvantages. However, comparisons of stem variants according to the former and to the actual method lead always to the same ranking.

The numerical values (P_D, F_p, F_P*) for calculating the rating factors at a certain speed are directly known for one of the variants, for example from Figure 2. The data needed for the second variant must be interpolated or extrapolated from its test results at the same speed. The shaft power at constant Fp is to determine first, then the effective thrust belonging to this power. Since stern variant No. 3 has been used in the model tests at all parameters h and T, see Table 1, this one is selected here as reference variant for all comparisons.

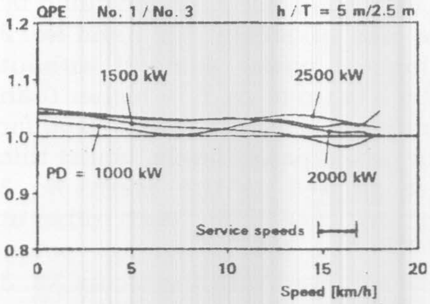
The first step of evaluation yields rating factors according to Equation 7 to 9 as function of speed, but the final ranking of the stern variants is based on results at typical service speeds. The latter depend on the parameters h, T and intended use or power demand, respectively, in such a way, that they increase with increasing under keel clearance h-T and increasing P_D, see References 4 and 9. Corresponding to the present parameters, the service speeds ranges at h-T = 0.5 m between 9.3 and 10.8 km/h and at h-T = 5 m between 15 and 20 km/h depending on power level. The decisive rating factors are calculated by averaging the speed-dependent factors in a small range of ± 0.3 km/h around the given service speed. Because of the large amount of data and the numerous arithmetic operations, all calculations are carried out by a computer program.

RESULTS OF COMPARATIVE EVALUATIONS

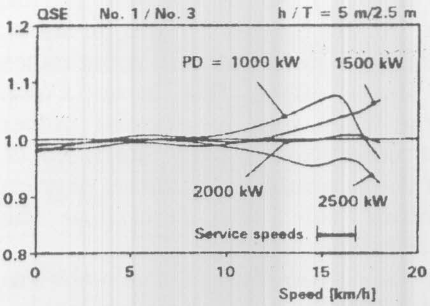
Figure 3 shows the rating factors of the comparison of sterns No. I and No. 3 at h/T = 5 m/2.5 m depending on power level and speed. The differences due to the changed tunnel size are moderately as expected, in particular in the range below the service speeds. But it is obvious, that stern No. 3 causes a lower power demand except at the highest power level for V > 13 km/h. The propulsion qualities, figure 3b, differ at most by 5 %. As indicated by figure 3c, the use of stern No. 3 leads at service speeds to a smaller effective thrust in the lower power classes. That means, that this variant creates a lower thrust demand of fore- and middle-body than stern No. 1. Reverse relations appear at the highest power level similar as in case of the power ratios.



(a) Overall rating



(b) Rating of propulsion quality



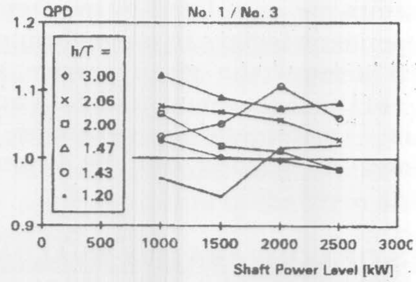
(c) Rating of stern shape quality

Figure 3 Comparison of sterns No. 1 and No. 3

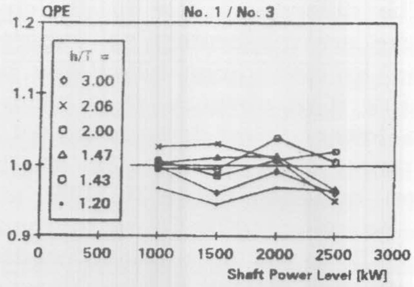
The values at service speeds are plotted against power level in Figure 4 together with the results of the remaining h, T-combinations. It may be concluded, that stern No. 3 represents on average the better variant, see Figure 4a. Considerable advantages of stern No. I can be found only at low driving power and at the smallest h/T-ratio. This is due to effects of propulsion characteristics, whereas the relative low power demand with stem No. 3 results mainly from its superior stem shape effects, see Figures 4-b and 4-c.

Comparative evaluations of the same kind are available for all variants. A systematic dependence on the power level and in particular of the h, T-combination cannot be found. In order to simplify the further rating of the stem variants, the rating factors at service speeds are averaged over 0 parameters h and T. Figure 5 presents the results for all comparisons with stem No. 3. As indicated by figure 5a, the use of stems No. I and No. 2 entails the highest power demand without exception, which is up to ca. 6 % higher than in the comparative cases. This is also valid for stem No. 4 at raised power levels, whilst this stem otherwise as well as the sterns No. 3 and No. 5 in any case differ each other at most by 2 %. The lowest average power demand can be achieved with the stems No. 3 and No. 5. Their small power differences amount to I % at the lowest power level in favour of stem No. 3, otherwise to 0.6 % to 2 % in favour of stern No. 5. As the partial rating factors in the figures 5b and 5c show, the overall rating is dominated in most cases by the stem shape effect. The latter is also responsible for the just mentioned power advantages of stem No. 5 over stern No. 3. Influences of the propulsion qualities play on average a minor role and deterrffine the overall rating only sporadically.

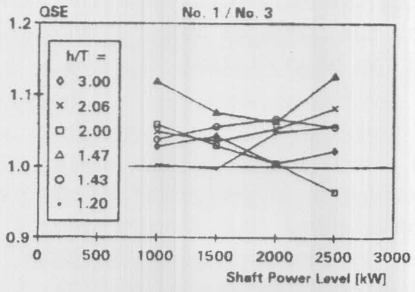
When averaging the rating factors shown in Figure 5 additionally over the power levels, so the remaining impact of tunnel geometry reveals. These total mean values are plotted against the tunnel length ratio in Figure 6, where stem No. 3 is marked in with numerical values of one to complete the picture. Figure 6-a illustrates once more, that the lowest power demand is gained with the shortest tunnel,. i.e. when using sterns No. 3 and No. 5. Compared with the initial tunnel design (stem No. 1), the driving power reduces on total average by 4.2 % to 4.6 % with slight advantages of stern No. 5. The partial rating values in Figure 6-b and 6-c confirm the effects of propulsion characteristics and stem shape as mentioned before. Apart from the slightly lower propulsion quality of stem No. 5, the mean relative propulsion qualities remain almost constant. Figure 6-c shows, that the mean effective thrust demand for the forward ship's part reduces continuously with decreasing tunnel length due to an improving stem shape effect.



(a): Overall rating

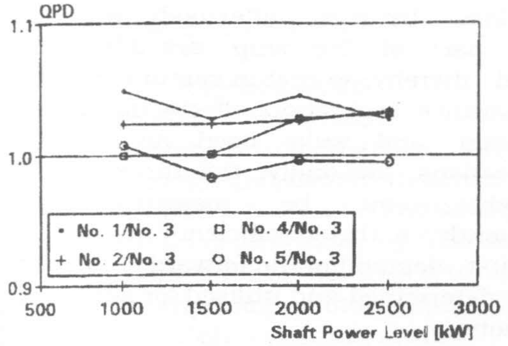


(b): Rating of propulsion quality

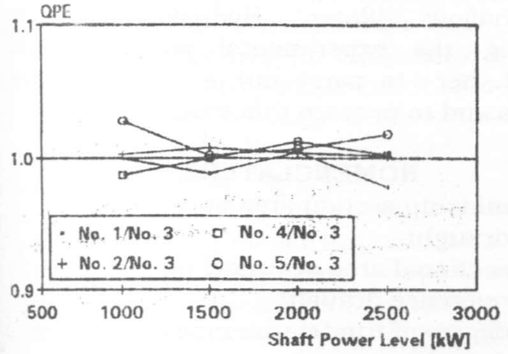


(c): Rating of stern shape quality

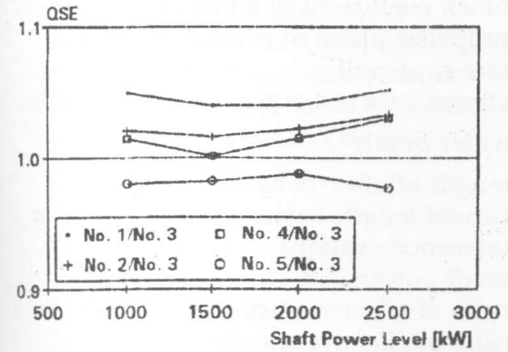
Figure 4 Comparison of sterns No. 1 and No. 3 at service speeds



(a): Overall rating

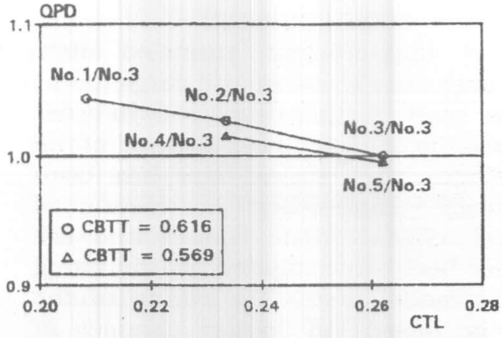


(b): Rating of propulsion quality

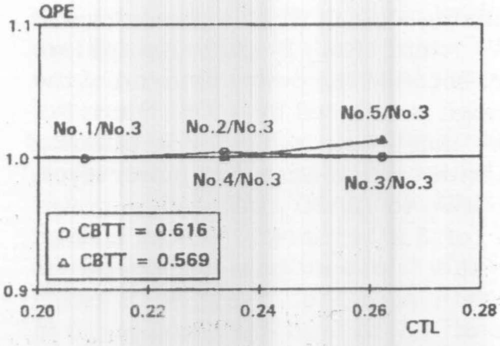


(c): Rating of stern shape quality

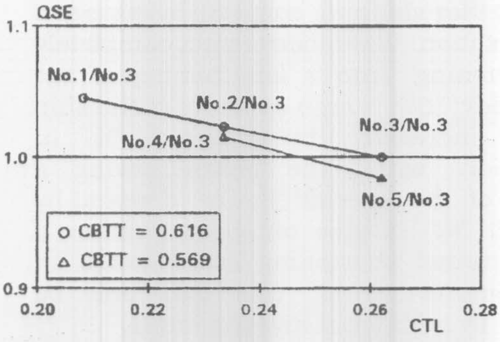
Figure 5 Comparisons with stern No. 3 at service speeds, values averaged over h, T



(a): Overall rating



(b): Rating of propulsion quality



(c): Rating of stern shape quality

Figure 6 Comparisons with stern No. 3 at service speeds, values averaged over h, T, P_D

CONCLUSIONS

A novel high-efficient tunneled after-body for large twin-screw inland cargo motor ships has been further developed. In order to ninimise the driving power demand of the initial design, the tunnel size has been systematically diminished by means of geometrical characteristic values and the effects has been investigated by evaluating data from model tests. The rating of the variants is based on power changes at service speeds averaged over all water depths and draughts. The results reveal, that the power demand of the initial design with stern No. I can be decreased. For a single cruising vessel with a power level of 1000 kW, stem No. 3 and No. 4 are preferable, because the power demand of the initial design is reduced by 4.7 %. Stern No. 5 is the most favourable for a pushing operation with up to 3 barges at power levels of 1500 kW to 2500 kW and a power reduction of 3.2 % to 4.7 %. On a total average, the lowest power demand is obtained with stem No. 5 and No. 3 with a reduction of 4.6 % and 4.2 % compared to the initial design. These two variants have the smallest tunnel length and allow a shortening of the initial after-body by 4.2 % of the ship's length. This result is highly important for shipping companies in view of hold utilisation. When converting completely the shortening into a lengthening of the middle-body, the cargo capacity of the ship can be increased by about 6 %. In combination with the power saving a decrease of the specific power demand by about 10 % is also obtained. Wether a further tunnel shortening could result in further improvements, this can only be answered by additional investigations.

During the development of the novel after-body, the experimental technique with self-propelled divided models has been proved to be very useful. Compared with conventional methods, two significant advantages should be emphasized. Firstly, the model tests are executed at conditions similar to those in practical operation. The hydrodynamic interactions between after-body and the forward part of the ship are adequately included thereby, so that in conjunction with a comparative evaluation effects like thrust destruction and wake need no separate considerations. Secondly, the thrust of the after-body can be measured and consequently, a thrust efficiency as well as the thrust demand of the forward ship's part can be determined and utilised for additional evaluations.

ACKNOWLEGDMENT

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NOMENCLATURE

A_{MT}	midship section area at reference draught
A_{Tc}	sectional area at tunnel top at reference draught
C_{TC}	degree of tunnel widening at reference draught
C_{TL}	tunnel length ratio at reference draught
C_{VT}	tunnel volume ratio at reference draught
C_{BTT}	block coefficient of after-body before propeller plane at reference draught
F_p	tow-rope pull
F_p^*	effective thrust of the ship's after-body
h	water depth
L_R	length of after-body
L_{RT}	tunnel length before propeller plane at reference draught
P_D	shaft power
Q_{PE}	ratio of effective thrust efficiencies
Q_{SE}	ratio of effective thrusts
Q_{PD}	ratio of shaft powers, overall rating
T	draught
T_T	reference draught for geometrical characteristic values of tunnel
V	speed
V_T	tunnel volume before propeller plane at reference draught

η_F' effective thrust efficiency

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