The effect of mesh orientation on netting drag and its application to innovative prawn trawl design

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Abstract

Prawn fisheries around the world comprise fuel intensive enterprises currently stressed financially by rising diesel costs. An avenue for relieving the situation is to improve the energy efficiency of trawling by raising the productivity of fishing per litre of fuel consumed. This paper presents work to develop a new prawn trawl design that leads to reduced trawl system drag. The trawl has a 'double-tongue' format, which refers to extensions forward of the upper and lower panels to form two additional towing points for the trawl. For this design concept, named 'W' trawl, drag generated in the trawl is largely directed to the centreline tongues and transferred forward to the trawler through a connected sled and towing wire. The associated reduction of drag-transfer to the wings makes the trawl substantially easier to spread and results in smaller otter boards being required and subsequently reduced overall drag of the trawl system. The study determined the effect on frame-line tensions of implementing T0 (diamond) and T45 (square) mesh in the main body and side sections of trawl models of conventional and 'W' configuration, with the aim to establish an optimal combination of mesh orientation for the principle parts of the 'W' trawl. The objective was to achieve minimum netting drag and beneficial strain transfer within the trawl such that maximum trawling performance (catch per unit of fuel) might be obtained in the field. T45 mesh in the side sections of the trawl was found to exhibit a progressively lower drag compared to T0 mesh as the flow speed increased, but the extent of drag reduction was not of practical significance. The 'W' trawl showed a capacity of redirecting 59% of the total netting drag to the centre line tongues when T45 netting was implemented in the body section, and only 40% when T0 orientation was used. However, the introduction of bracing ropes (at E = 0.71) along the upper and lower centrelines of the T0 version of the "W" trawl improved the drag transfer to the tongues from 40% to 50% of the total drag. Overall, the most practical and economic configuration of the model 'W' designs tested produced an estimated drag reduction of 8.3% ± 0.6%, compared to the conventional trawl. It is expected that drag saving benefits in practice will be more substantial as the tested trawl models were not completely representative of practical commercial gear in that they had minimum twine area to make the experiment most sensitive to the drag-effect of mesh orientation.

Keywords: prawn trawl; mesh orientation; trawl strain transfer; drag reduction; trawl efficiency

Introduction

Rising fuel cost, impending crude-oil deficit, and concern for greenhouse gas emissions are creating intense pressure to improve the fuel efficiency of commercial fishing operations. Even though the problem of fleet-overcapacity in Australian prawn fisheries created by widespread expansion during 1970-80 have been solved, prawn trawler operators struggle to maintain economic viability, particularly over the last half decade.

In Australia, a fundamental part of the historical progression of prawn-trawl gear included the wide-spread implementation of multi-net systems in the 1980's. The driving principle was to reduce the twine area of large single trawl systems by replacing each with a number of smaller sized trawls that had a combined catching span equal or greater than the original. Broadhurst et al. (2013) experimentally estimated that by increasing the number of nets towed simultaneously in a prawn trawling system, the fuel consumption of the system for a given swept area can be reduced by up to 23% due to a reduction of both otter board and twine area.

A more recent innovation to significantly reduce drag has been the use of Ultra High Molecular Weight Polyethylene (UHMW PE) netting materials that allows the use of thinner twine compared to traditional materials. Small diameter UHMW PE twine are of similar or greater breaking strength to traditional material, but the thinner twine (by ~ 40%) results in decreased drag (by ~ 22%) for the correctly matched high strength netting and otter boards (Balash and Sterling 2014).

Another possibility for improving the engineering performance of prawn trawls is through design modification that makes the trawl easier to spread and consequently requires smaller otter boards. The Danish Fisheries Technology Institute [DFTI] (1989), proposed a Y-design fish-trawl that allowed a higher headline height as an inadvertent side effect of installing an innovative seam down the centreline of the trawl such that the wings consist of T45 (square) mesh. The developers of the Y-design trawl identified benefits from catching and selectivity perspectives: a wider mesh opening down the wings and sides allows small fish to escape, and overall larger vertical and horizontal trawl openings produce a greater cross-section area. Following the Y-design concept, Ripon (1991) considered the engineering performance of a so-called pleated-panel prawn-trawl with T45 netting along the wings and sides achieved by installing tapered-seams down the centrelines of the top and bottom panels. The pleated-panel trawl required less force to spread as the netting drag was transferred more directly to the otter boards by high tension along the T45 bars in the sides as opposed to a conventional T0 trawl where the netting tension runs towards the bosom of the trawl and then to the otter boards along the frame lines and along bars that are at a steeper angle to the direction of tow. Despite the pleated-panel trawl generating less in-pull force and having less twine area, overall drag was found to be higher compared to a conventional trawl. The increased drag of the pleated trawl was not conclusively explained but was thought to possibly be a result of the greater number of netting bars oriented perpendicular to the flow.

Since the performance benefits of the pleated-panel trawl were negated by the concomitant drag disadvantages, the pleated-panel trawl was not developed any further. However, Sterling & Eayrs (2010) suggested the double-tongue trawl might be a design that similarly has low in-pull forces, and it would not be subject to high-drag side sections with exposed bars perpendicular to the water flow. The proposed double-tongue design had T45 mesh orientation in the upper and lower panels which would enhance drag transfer to the tongues as the bars are aligned to the direction of the transfer and will not allow the trawl to stretch in this direction. In the side sections of this double-tongue trawl the netting would be T0 orientation relative to the length-direction of the side, as the square-mesh (T45) in the top and bottom panels fold around the sides of the elliptical, 45° cone-shaped, body of the trawl.

Fig. 1 shows an unpublished photo of the double-tongue trawl suggested by Sterling & Eayrs (2010), in the form of a model being tested in the Australian Maritime College flume tank. The model double-tongue trawl streamed in the flume in Fig. 1 was asymmetric because this T45 trawl was constructed from knotted netting. The arrangement in this case produced netting of T90 orientation down the starboard side and T0 orientation down the port side. Since knotted netting has a shorter stretched mesh-length in the T90 compared to T0 direction, it caused the port side of the trawl to have loose netting and the cod-end to be pulled to the starboard side of the centre line. One way to remove this distortion is to use knotless netting which is of the equal stretch-mesh length in the transverse and longitudinal directions.

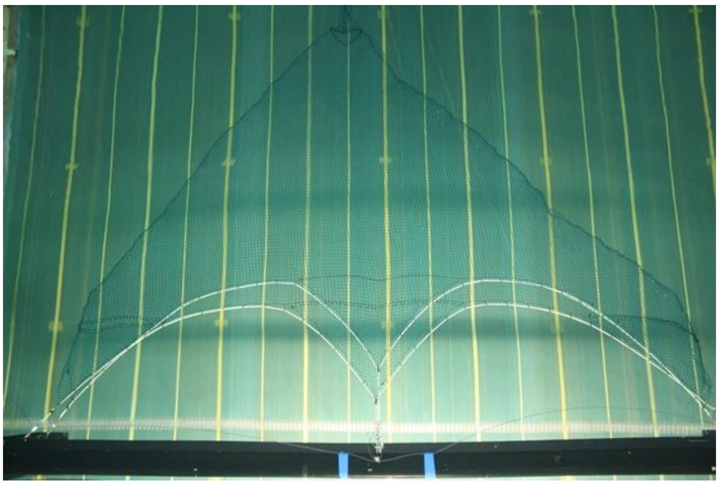


Fig. 1. A model double-tongue trawl with netting hung square (T45) to the framelines, and built from knotted polyethylene – the model is asymmetric about the centre-line due to different mesh lengths down the port (T0) and starboard (T90) sides caused by differences in knot lengths in those two directions.

The relation between mesh orientation (T0 vs. T45) and drag has not been comprehensively studied. Zhan et al. (2006) analytically derived formulae for the drag force acting on T45 and T0 netting sheets (called by the authors square mesh and square-diamond mesh respectively) as a function of the angle of incidence. The analytical formula were calibrated by adjusting the pressure and friction force coefficients used in the formula such that drag predictions agreed with minimum error with experimental data for 'square-diamond' (T0) netting over a range of netting solidities and angles of incidence to the flow. The experimental work did not include cases of square mesh (T45) netting and did not investigate the difference in drag for panels with square (T45) and square-diamond (T0) mesh orientations. Calculations by the authors here using the published empirical formula for pressure and friction coefficients in both the proposed analytical formulae for square-diamond (T0) and square mesh (T45) panels suggest that there is a significant drag difference between the two mesh types. Fig. 2 shows the result of drag ratio estimations for angles of incidence between 0° and 90° to the flow and a flow velocity of 1.6 m s^{-1}. As can be expected mesh orientation has no effect on drag when the panel is normal to the flow. However, as the panel progressively tilts towards becoming parallel to the flow, the predicted drag for the T0 (diamond) panel reduces more rapidly compared to T45 (square) mesh. For incidence angles typically found in prawn trawls, 0° – 45°, T45 mesh is predicted to have 40 to 50% more drag for the same twine area. Stewart & Ferro (1987) investigated the drag of square (T45) and diamond (T0) mesh cod-ends and found that the drag was significantly higher for a square (T45) mesh cod-end. The authors believed that friction drag was greater for the square (T45) mesh cod-end where the netting was parallel to the flow compared to the diamond mesh (T0) cod-end, which was of a 'trumpet' shape, because the square (T45) cod-end had substantially more open meshes. The authors reached the conclusion that cod-end drag was related to the surface area of the cod-end. In this respect the study did not investigate the difference in drag that might occur between T45 (square) mesh and T0 (diamond) mesh in a situation where the surface area or mesh opening of the cod-ends were similar.

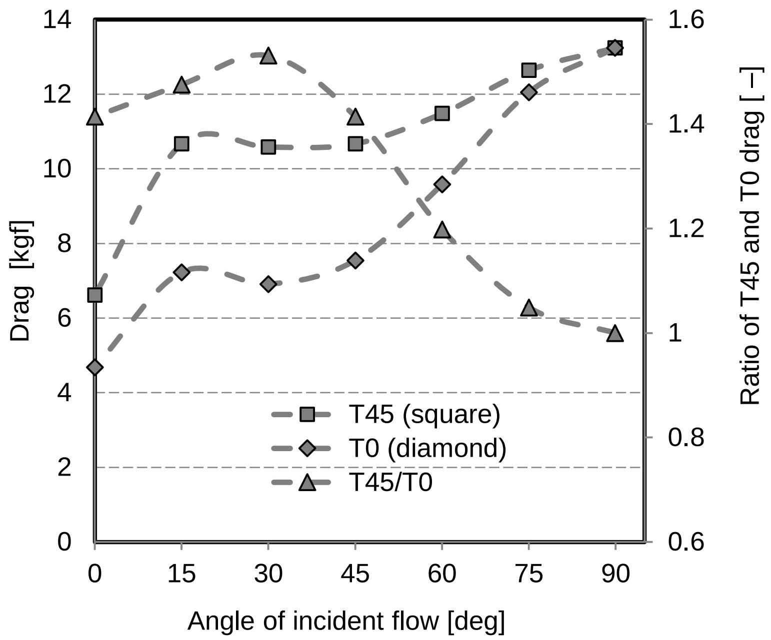


Fig. 2. Drag prediction for a trawl panel (T45 and T0) at various flow-incidence angles based on the formulae developed by Zhan et al. (2006).

A number of other authors studied the drag for net panels that were of various mesh patterns. Even though the effect of mesh pattern was out of their work scope, some conclusions were reached on the potential effect of mesh pattern on drag. Tsukrov et al. (2011) compared the drag of copper and nylon nets positioned normal to steady flow, and detected significant differences in drag coefficient for a given solidity. The authors noted that while the copper and nylon samples were of diamond (T0) and rectangular (T45) mesh orientation respectively, the most likely cause for the drag differences for netting normal to the flow were the higher roughness of the nylon netting giving rise to a higher effective twine diameter. Gansel et al. (2012) studied the effects that flow speed and angle of attack (between 15° and 90°) had on netting of high and low bending stiffness. While the studied netting were of various mesh shapes (diamond, square and hexagonal), the paper did not explore their effect on drag or draw conclusions in that respect. The major theme of the paper was to compare measurements with prediction formulas that quantified the effect of angle of attack and solidity on drag.

In the present paper, the authors investigated the drag variation of conventional and double-tongue, named ‘W’, prawn trawls due to T0 (diamond) and T45 (square) mesh alteration in the main body and side sections of the trawls, with the aim to propose a minimum drag solution for a ‘W’ prawn trawl. The performance indicators of interest were both the drag and in-pull of trawl models so that consideration of design features could be based on comparing the total drag of the trawl system (including predictions of otter board drag).

Methods

Models

The experimental program in the flume tank comprised frame-line tension measurements for two groups of prawn trawl models over a range of flow speeds. The first set of models was based on ¼ scale 8 fathom Florida Flyer prawn trawls that are commonly used by Australian prawn trawler operators (similar to the flat and balloon shrimp trawls used in the USA and described by Watson et al. (1984)). Within this group: Model A [T0 mesh body with T45 sides] was a conventional two seam trawl, meshes hung at the bosom at E=0.71, with T45 mesh side-sections achieved inherently by applying an all-bar side taper cut; Model B [T0 body with T0 sides] was a four seam trawl, meshes hung at the bosom at E=0.71, with T0 side panels sown to the all-bar side tapers at a hanging ratio of E=0.75; and Model C [T45 body with T0 sides] was a two seam trawl, bars hung tight at the bosom, with T0 side-sections achieved by applying an all-mesh side taper cut. The net plans for models A, B and C are shown in Fig. 3. The hanging lengths for all tapers connected to the upper and lower frame lines were calculated such that the netting was fully open to squares irrespective of mesh orientation. The models were simplified (short) versions of commercial trawls: 45° side tapers were selected (i.e. either B or N/T) instead of the more gradual body reduction achieved by typically using a 1N3B side taper in a commercial trawl. For the models, the amount of twine in the upper and lower (body) sections were minimised to sensitise the results to the drag-effects of mesh-orientation in the side sections. The second set of models contained adaptations of models A and C to form ‘W’ trawls, namely TA and TC (Fig. 4).

All models had equal frame-line length and each set had similar number of meshes (Table 1) so the effect of mesh orientation on drag could be quantified with minimal standardisation for twine area. All models were built from 50 mm 4 ply (1 mm twine diameter) Ultracross UHMW PE, material that is used for full-scale prawn trawl construction and can be advantageously used in our model experimentation for the following reasons: (1) Ultracross construction produces netting with the same mesh size in longitudinal and lateral directions and no corresponding shape-distortion produced for trawls with T45 body sections (upper and lower panels); (2) use of full-scale material ensures a representative Reynolds number (ratio of inertia and viscous forces) occurs if tests are conducted at full-scale speed; and (3) hydrodynamic forces continue to dominate netting mechanical forces at model-scale due to the very low twine stiffness of the multifilament material.

Table 1. Number of meshes and twine area for each model trawl.

Model	Number of meshes	Twine area [m^2]
A	2219.5	0.22195
B	2211.5	0.22115
C	2268	0.22680
TA	3419	0.34190
TC	3642	0.36420

Twine area A_{twine} was calculated as shown in eq. (1):

$$A_{twine} = 2ldn \qquad (1)$$

where d is twine thickness (1 mm), l is full mesh size (equal to two bars – 50 mm), n is number of meshes in the trawl. The resulting twine areas for the model trawls are presented in Table 1.

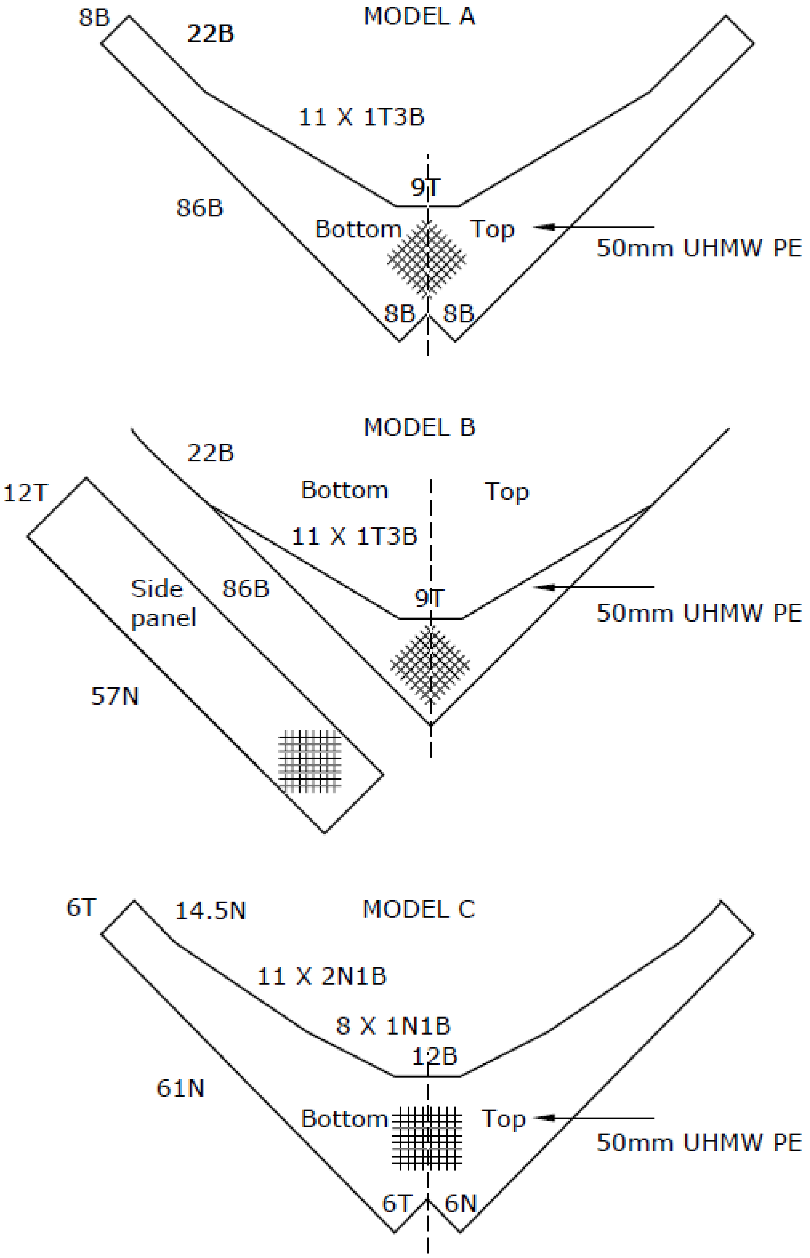


Fig. 3. Net plans for Standard trawls: Model A [T0 body with T45 sides], Model B [T0 body with T0 sides], and Model C [T45 body with T0 sides]. N – normal, T – transversal, B – bar. Hanging ratio: E=0.71 for meshes on framelines and E=0.75 for side panel meshes to AB body taper of trawl B.

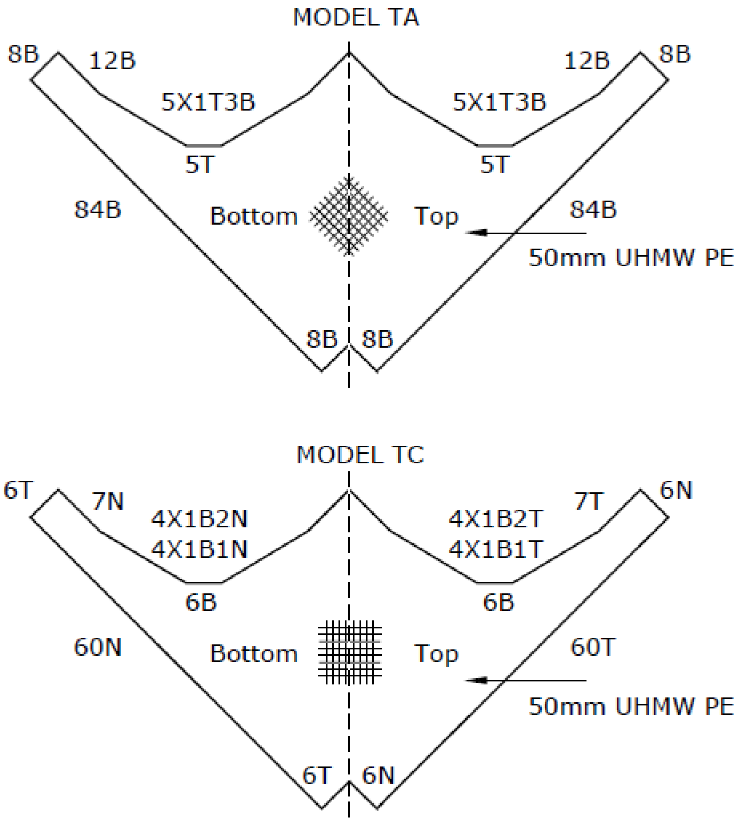


Fig. 4. Net plans for 'W' trawls models - TA [T0] and TC [T45]; hanging ratio E=0.71 for frameline.

Experimental set-up and data collection/analysis

The experiments were conducted in the flume tank at the Australian Maritime College, Beauty Point, Tasmania, Australia. The test section of the flume tank is 17.2 m long, 5 m wide and 2.5 m deep, and as a whole contains approximately 700,000 litres of fresh water. The flow is circulated with four impellers, each driven by a variable speed drive.

During prawn-trawl fishing, the horizontal opening of the trawl is maintained by otter boards and is therefore not precisely fixed (Fig. 5). For controlled netting drag measurements in the flume tank, the model trawls were attached by the four end points of the upper and lower frame lines to a Trawl Evaluation Rig (TER) instead of otter boards, as shown in Fig. 6. For the 'W' trawl cases, each trawl was connected to the TER via 6 points. Each trawl-connection point contained a load cell so that the frame-line tensions at all connection points were measured for each case.

The TER was an aluminium rectangular frame where the two vertical sides slide along upper and lower low-profile foil-sections, and can be firmly fixed at any desired location (trawl spread). The horizontal spread was set to the design spread ratio for the trawls of 82.5%, given the combination of tapers selected for the framelines and the hanging ratio used (E=0.71).

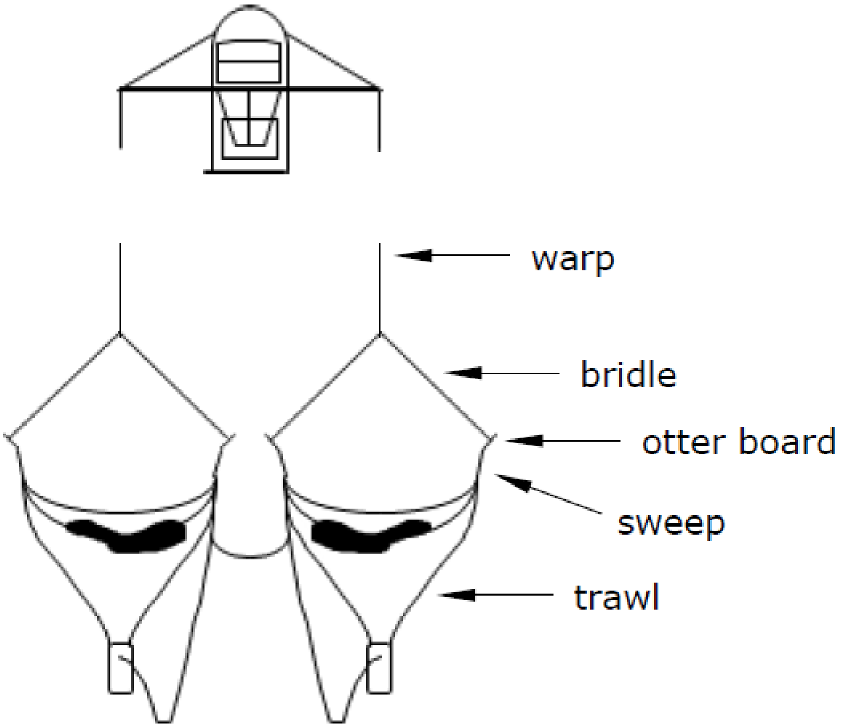


Fig. 5. Prawn trawl set up for a twin rig.

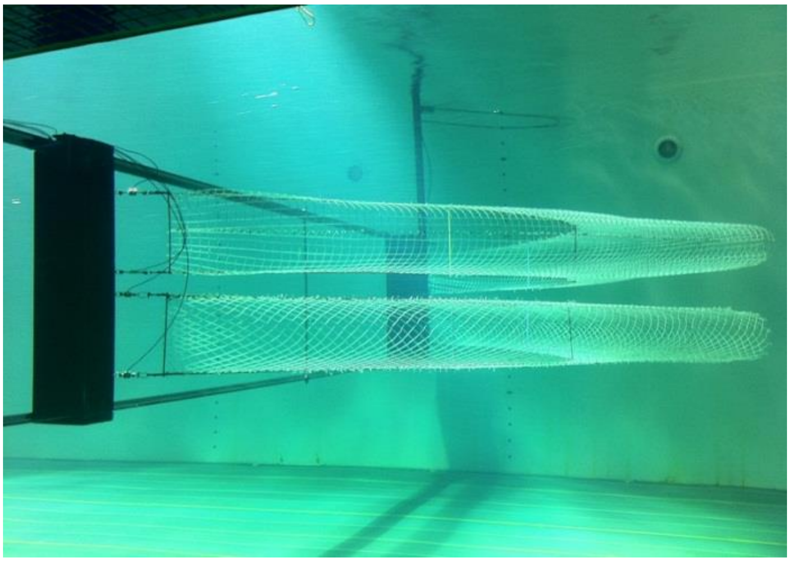


Fig. 6. Two model trawls (A on top and B on bottom) attached to the Trawl Evaluation Rig in the middle section of the flume tank – T45 and T0 mesh in the wings can be noted in the upper and lower model respectively.

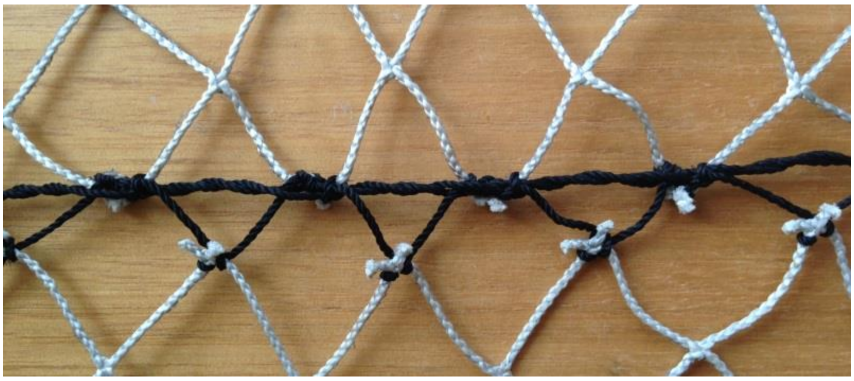


Fig. 7. Bracing rope implementation along the longitudinal centre line of model MTA (hanging ratio E=0.71).

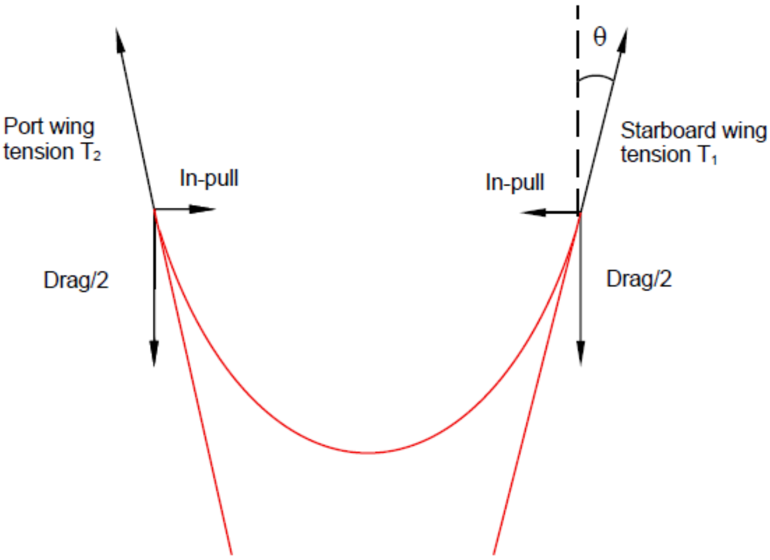


Fig. 8. Force vector breakdown for a prawn trawl.

As can be seen from the net plans in Fig. 3 and Fig. 4, the top and bottom panels were identical for each model and produced a symmetric trawl about the central horizontal plane. This situation of no lead-ahead allowed the vertical opening along the frame-lines to be fixed by attaching four equally spaced fibre-glass struts of 3 mm in diameter. This methodology standardised the vertical opening of the mouths of the trawls against the effect of varying vertical netting-forces between the models. The distance between the lower and upper connection points on the TER (vertical mouth opening), and the length of the struts, were equal to 225 mm.

The tensions at the tow points of each model were measured with four/six load cells of 20 kgf capacity each, as required. The load cells were calibrated at the beginning of the test program and zeroed before each test run (at zero water speed). Data was sampled at 1Hz for 30 sec.

The TER causes minimal flow disturbance due to its very streamlined construction and the flow upstream of the models is un-obstructed by any of the TER structure. The TER has the capacity to hold two models at the same time (one above the other) and this was utilised so that all drag tests were paired comparisons of two models, and replicate drag measurements were taken with swapped model locations to standardise the results for location affects caused by fixed non-uniformity of the flume tank flow. Each model was therefore tested at the top and bottom of the TER as shown in Fig. 6, and in a sequence as specified in Table 2. The last test-combination shown in Table 2 involved a modified version of model TA, namely MTA, which had bracing-ropes sown from the tongues down the centre lines at the hanging ratio E=0.71 for 29 meshes (as shown in Fig. 7) to investigate the potential to increase the stain transfer within the trawl to the tongues.

Table 2. Testing sequence of the model trawls on the Trawl Evaluation Rig. For each combination, every model was tested in the top and bottom locations of the Trawl Evaluation Rig.

Test run	Top net	Bottom net
1a	A	B
1b	B	A
2a	B	C
2b	C	B
3a	A	C
3b	C	A
4a	TA	TC
4b	TC	TA
5a	A	TA
5b	TA	A
6a	C	TC
6b	TC	C
7a	MTA	TC
7b	TC	MTA

For each trawl-net scenario the flume tank impellers were set sequentially to four operating conditions as shown in Table 3. The flow speed was measured with an electro-magnetic probe located upstream of the model, 1.25 m below the free surface on the centre line of the test section.

Table 3. Tested flow speed conditions.

Impellers rotation [rmp]	Approximate flow speed [m s^{-1}]
125	1.0
150	1.2
175	1.4
200	1.6

Generalised Linear Models (GLM) of the log-transformed data were statistically analysed using SPSS (predictive analysis software from IBM) to estimate the effects of trawl position (top vs. bottom), speed setting in the tank, and trawl type on drag-loading and in-pull of the trawls.

The sum of the two measured tensions for each wing-end give T_1 (starboard wing tension) and T_2 (port wing tension), and are composed of vector contributions from the in-pull force of the trawl F_{in} (this force must be overcome by the otter boards to maintain the open trawl) and drag force. The sum of the drag components from the combined tensions in each wing (plus the two tensions measured at the tongues in the case of the 'W' trawls) is the total drag of the trawl, F_d. As shown for the conventional trawls in Fig. 8, the relationship between the force contributions and the sum of tensions is determined by an angle θ between the frame line and flow direction at the wing end. The drag force F_d and the in-pull force F_{in} were derived as shown in eqs. (2) and (3) respectively for the conventional trawl. The angle of the frame-lines (at the connection points) relative to the flow direction was measured with a bevel gauge referenced to an unsubmerged beam on the TER that was transverse to the flow direction.

$$F_d = (T_1 + T_2)cos\theta \qquad (2)$$

$$F_{in} = \frac{(T_1+T_2)}{2} sin\theta \qquad (3)$$

From these performance indicators of the trawl models the total drag of the trawl system (including predictions of otter board drag) can be estimated from eq. (4).

$$Total\ Drag = F_d + 2\frac{F_{in}}{L/D} \qquad (4)$$

where, F_d is netting drag, F_{in} is in-pull of the net, L/D is a lift-to-drag ratio of the otter board (assumed to be 1).

All reported data is at model scale and where appropriate the results are expressed in relative, non-dimensional, terms.

Results

Fig. 9 shows the estimated effect of mesh orientation, as set in models A, B and C, on trawl drag along with 95% confidence intervals from the GLM analysis of paired-comparisons (test runs 1 through 3 in Table 2). For each speed case the drag of model C is set as the reference (with a value of 1). The percentage drag difference between model B and model C is consistently 0.5% less, although it is shown not to be statistically significant. There was no statistical difference in drag between models A, B and C at the slowest speeds while model A exhibited 3.5% less drag than model B and C at the highest speed.

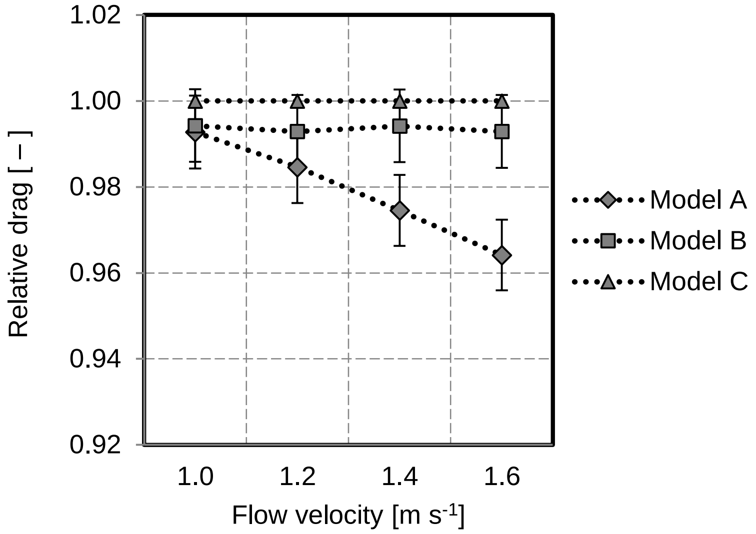


Fig. 9. Relative drag for model trawls with 95% confidence intervals and model C being the benchmark [Model A: T0 body and T45 sides; Model B: T0 body and T0 side panels; Model C: T45 body and T0 sides].

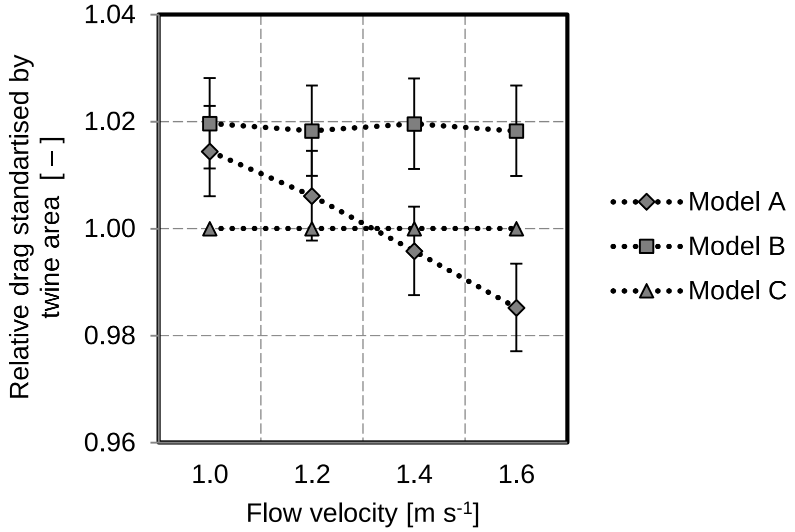
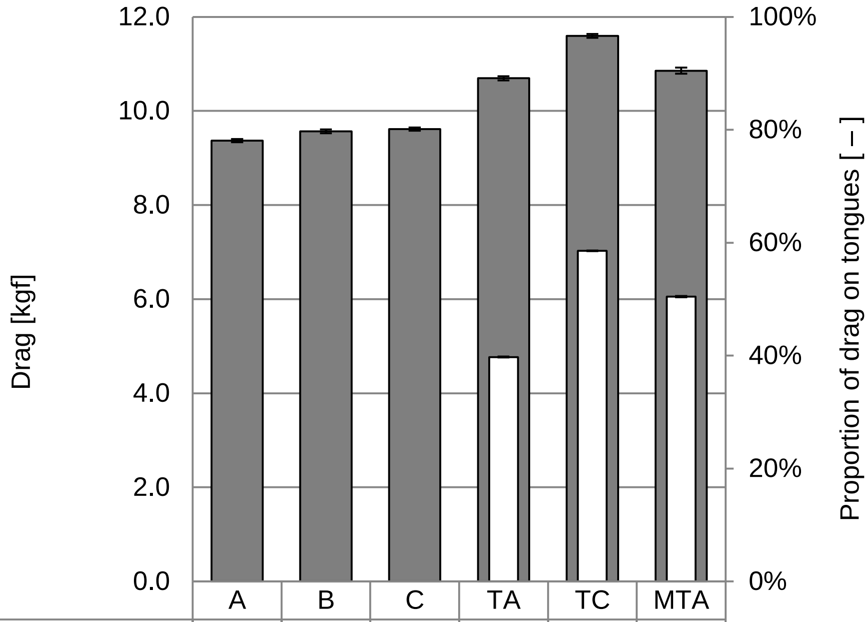
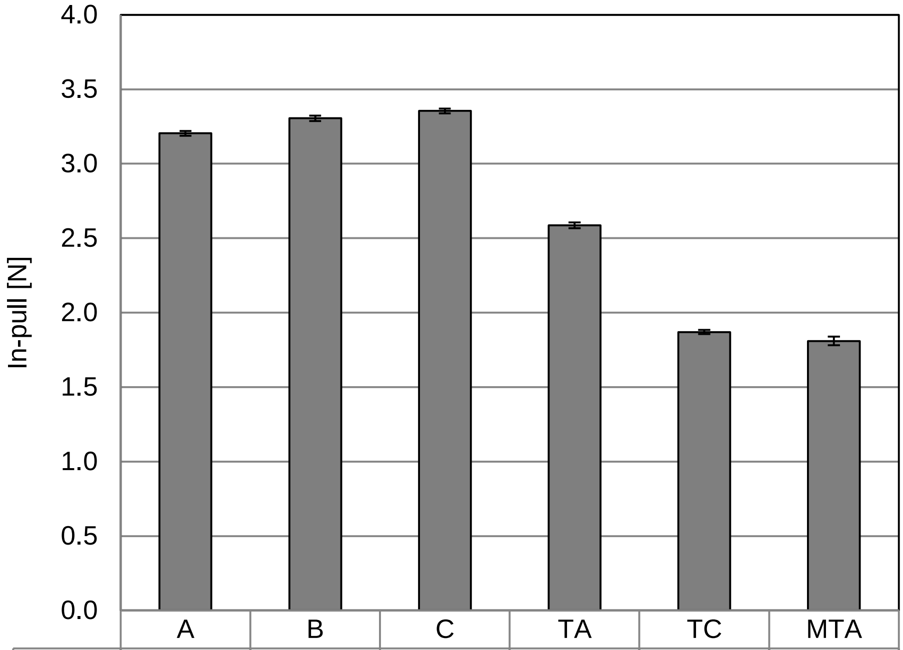


Fig. 10. Relative drag standardised by twine area, with 95% confidence intervals and model C being the benchmark [Model A: T0 body and T45 sides; Model B: T0 body and T0 side panels; Model C: T45 body and T0 sides].



	A	B	C	TA	TC	MTA
Drag	9.4	9.6	9.6	10.7	11.6	10.9
Tongue loading				40%	59%	50%

Fig.11. Estimated marginal mean drag from GLM and proportion of total drag transferred to tongues for each trawl, with 95% confidence intervals.



	A	B	C	TA	TC	MTA
In-pull	3.2	3.3	3.4	2.6	1.9	1.8

Fig. 12. Expected in-pull (otter board loading) for all models, with 95% confidence intervals.

Fig 9 shows the effects of twine orientation on the drag for models A, B, and C as it could be practically implemented in trawls. However, as shown in Table 1, the twine area for the models slightly varied, and in order to evaluate the effects of mesh orientation on the netting drag from a general perspective, the drag values were also standardised by twine area (Fig. 10). The drag standardised by twine area (drag twine-area^{-1}) for model B was consistently estimated to be significantly higher than for model C by about 2.0%. There was no statistical difference in standardised drag between models A and B at the slowest speeds while model A produced less standardised drag than model B at the higher speeds; by about 3.5%. It appears that model A produced progressively less standardised drag compared to models B and C. Model A had 1.5% higher drag twine-area^{-1} than model C at the lowest speed and 1.5% lower drag twine-area^{-1} at the highest speed.

The results for the 'W' trawl implementation of models A and C, namely TA and TC, are shown in Fig. 11. Model TA showed a 8.4% lower drag compared to TC, which is mainly due to twine area difference. However, TA produced significantly less drag transfer through the tongues, which implies higher strain on the otter boards – TA and TC exhibited 40% and 59% drag transfer to the tongues respectively. The introduction of the bracing-ropes to model TA, shown as MTA, lead to a significant increase in drag-loading of the tongues, from 40% to 50%, though the model's drag slightly increased due to the additional drag of the ropes. Model MTA had 6% less drag than TC.

Fig. 12 contains predicted in-pull force for all trawl models, and it shows that models MTA and TC would require similar size otter boards that would be approximately half the size of those required by models A and C.

Discussion

Models B and C comprise main body sections (nearly parallel to the flow) that have T0 and T45 netting orientation respectively, while the side sections for both models are of T0 orientation. Given that Model B exhibited 2% higher drag twine-area^{-1} than model C, it suggests that T0 in the upper and lower sections had slightly more drag than T45 mesh. Alternatively, the explanation could be that model B produced a higher drag due to the four side-seams that connected the main body sections to side panels of the trawl; and additionally, the seams for model B are bar-to-mesh joins and bulky compared to the two mesh-to-mesh joins for model C.

Model A is fundamentally different to models B and C in respect to the orientation of meshes in the side sections of the trawl (T45 vs. T0), and identical to model B in respect to the configuration of the upper and lower body panels, so it appears that T45 mesh in side sections at 45° to the flow produces progressively lower drag compared to T0 with speed. The reduction in T45 drag relative to T0 as flow speed (and corresponding Reynolds number) increased is consistent with the general understanding that higher Reynolds number can ameliorate the separation of flow around an object and lower its drag coefficient. This effect might be more significant for T45 netting, which contains twine elements that are normal to the flow, compared to T0 where all twine elements are oblique to the flow and therefore more streamlined in cross-section. It could be that the drag for both orientations is similar at certain speeds; however, it is evident that the drag coefficient for T45 at 45° reduces as water speed increases relative to the drag coefficient for T0 netting at 45°.

Analytical predictions of netting drag based on equations and methodology taken from Zhan et al (2006) and illustrated in Fig. 2, suggest a substantial increase in drag for T45 panels at 0° – 45° compared to T0 (~20% increase). In contrast to this, the observed drag difference for the two types of mesh in the present experiments was very subtle and consequently there seems to be no strong advantage of using any particular type of mesh in a prawn trawl from a netting-drag perspective.

Table 4 presents the estimated total drag loadings from the trawl and otter boards combined for all models as per eq. 4.

Table 4. Estimated total drag (trawl and otter boards) for all trawl model cases including 95% confidence intervals.

Trawl	A	B	C	TA	TC	MTA
Predicted total drag [kgf]	15.8 ± 0.05	16.2 ± 0.06	16.3 ± 0.05	15.9 ± 0.06	15.3 ± 0.05	14.5 ± 0.09

Model A exhibited 3.0% (± 0.4%, p=0.05) less drag than the other standard trawls on average, and had similar drag to its 'W' counterpart, model TA. For the model TA implementation of the 'W' trawl concept, the drag penalty of the extra twine area in the tongues cancelled the rather moderate drag benefits associated with the transference of netting drag through the tongues and away from the wings and otter boards.

For the 'W' trawl, model TC, there was 4% less total drag than for the TA trawl system. This improvement was caused by the way that model TC had much higher transfer of netting drag to the tongues than model TA. However, the introduction of the bracing ropes along the centre lines of the T0 body panels of model TA (presented as MTA) led to (1) an increase of the strain transfer to the tongues: from 40% to 50%, and (2) a decrease of the trawl's wing-end angle, and made model MTA the best performer of all trawls tested.

Model TC, which has bars hung on the bosum, requires the use of more expensive knotless netting (Ultracross) to avoid distortion of the trawl that occurs with conventional knotted netting, due to its difference in stretched length in the lateral and longitudinal directions. Ultracross knotless netting also provides the advantage that it will sustain much higher loads along the line of the bars without local distortion of the mesh shape (Sterling & Eayrs, 2010). Models TA and MTA have T0 mesh orientation in the main body of the trawl and as a result conventional knotted netting can be used without causing distortion of the trawl, but it has been demonstrated that the T0 'W' trawl (model TA) requires bracing ropes attached down the centrelines of the top and bottom sections to improve strain transfer within the trawl to the tongues and to achieve any overall drag-benefit. The implementation of bracing ropes adds cost to the construction of the trawl, but results in a trawl with superior performance to model TC.

The comparison of drag performance between the conventional trawls (models A and C) and 'W' trawls (models TA and TC) (Fig. 11) shows that the total netting drag is not proportional to twine area. This is because the additional twine area in models TA and TC is exposed to the flow at a low angle. The double tongue and conventional trawls comprise equal side-panels (for A and TA, and C and TC), while the overall trawl twine area is greater for the 'W' trawls due to the addition of the two tongues to the main body (54.0% greater for TA compared to A; and 60.6% greater for TC compared to C). Despite the significant addition of twine area in the 'W' models, the overall drag only increased by 14.1% and 20.6% for TA and TC respectively. The low effect on total drag of a relatively large increase in netting at a low angle of attack is consistent with the hypothesis of the twine 'shadow' effect suggested by Goudey (1992) and illustrated by Enerhaug et al. (2012).

In the present work, the conventional trawl models were designed to have a low amount of twine in the main body compared to industry practice in order to accentuate the effect of mesh orientation in the side sections on drag, if any existed. In practice, substantially longer trawls than the tested models would be required. Models of such trawls would have significantly more twine area generally and the difference in twine area, and associated drag, between the conventional trawls and the 'W' trawls would be much less significant in percentage terms.

Overall, 7.6 – 8.9% ($p=0.05$) less drag is estimated for a trawl system based on 'W' trawl, model MTA, compared to conventional trawl, model A. This represents the demonstrated benefits of the 'W' trawl concept as tested in the present study. In the field, higher relative drag benefits can be expected for commercial trawl gear because the detrimental drag effect of adding tongues will be subdued by the generally higher twine area of the commercial trawls.

Conclusions and recommendations

The study investigated a novel design concept for prawn trawls called the 'W' trawl. The innovation is characterised by the redirection of drag loading from the wings to the centreline connection points of the 'W' trawl in order to reduce the amount of in-pull force applied to the otter boards and give an overall drag reduction of the system, because smaller otter boards can be used. The work also investigated the drag implications of using T45 vs. T0 netting orientation in various sections of a prawn trawl to identify low-drag cases. Below are the main conclusions:

(i) At a very low angle of attack (where netting is near parallel to the flow), T0 mesh may produce a slightly higher drag compared to T45. At higher angle of attack (where the netting was subjected to the flow at an angle of about 45°), T45 mesh exhibited a progressively reducing drag compared to T0 as flow speed increased.

(ii) In the 'W' trawl design, drag was better redirected through the centreline to the tongues for T45 mesh body sections compared to T0: 59% and 40% of the total drag was transferred respectively.

(iii) The introduction of bracing ropes along the upper and lower centrelines of the T0 mesh body sections at the hanging coefficient $E=0.71$ improved the strain transfer to the tongues from 40% to 50% of the total drag, and reduced the trawls dynamic wing-end angle. Potential exists to enhance strain transfer to the tongues and achieve further performance improvement of the 'W' trawl through optimising of the hanging ratio used to attach the bracing ropes.

(iv) The best 'W' trawl design tested to date indicated a 8.3% (± 0.6%, $p=0.05$) drag benefit for industry compared to a conventional trawl. In the field, higher drag benefits for commercial trawl gear can be expected because the measured detrimental drag effect of adding tongues to the model trawls will be subdued by the general increase in twine area of the commercial trawls.

(v) Further work is required to investigate the application of 'W' trawl technology to specific commercial prawn-trawling contexts and its associated drag saving potential.

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