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ANALYSIS OF GEOMETRIC AND DRAG–RELATED CHARACTERISTICS OF PELAGIC TRAWLS WITH COMPONENTS MADE OF DYNEEMA POLYETHYLENE FIBRES

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ABSTRACT

The performance of modern towing gear depends greatly on materials used in the manufacture of various gear components. The paper discusses basic characteristics of the Dyneema polyethylene fibres and products. The Dyneema fibres are characterised by their exceptional tenacity, 3 to 4 times that of PA fibres most commonly used in net manufacture. The high tenacity is particularly evident in Dyneema SK75, the newest generation product. New pelagic trawls described were constructed using components made of Dyneema products. Effects of Dyneema on the performance of large–mesh pelagic trawls were analysed, based on data obtained from tests

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on trawl models as well as from observations on a giant trawl operating in the Bering Sea beyond the EEZs and a trawl operated from a small fishing boat in the Baltic. The trawls incorporating Dyneema products showed excellent geometric characteristics and a considerably reduced hydrodynamic drag. The Dyneema ropes proved applicable as warps, successfully replacing the hitherto used warps made of steel.

Key words: Dyneema netting materials, trawling system, trawl warps, pelagic trawl, model research, trawl drag

INTRODUCTION

The recent decade witnessed further, important developments in methods for harvesting living resources of the sea. The developments have stemmed largely from a wide application of hydroacoustic techniques and novel materials. This has been particularly visible in trawl fisheries, especially in the manufacture and operation of pelagic trawls. Hydroacoustic techniques are widely applied to assess fish resources and to study the nature of their concentrations as well as to monitor gear performance.

Novel material technologies in fisheries involve primarily the application of new generation synthetic fibres to the gear (mainly trawl) manufacture. Properties of those fibres, their high breaking strength in particular, allow to greatly reduce the towed gear drag and to increase the gear size [9]. The new generation polyethylene (PE) Dyneema fibres were first applied in fisheries in the early 1990s.

Since 1994, the Department of Fishing Techniques, Agricultural University of Szczecin has been pursuing research focusing on application of Dyneema products to manufacture and rigging of trawls [10].

The aim of the present paper is to:

- describe the basic mechanical properties of the PE Dyneema fibres and to discuss a potential for their application in manufacture of netting materials as a replacement for the hitherto used fibres;
- present results of research on application of Dyneema ropes and cordage in the manufacture of large–size pelagic trawl and small boat pelagic trawls;
- compare geometric and drag–related characteristics of pelagic trawls rigged with steel and Dyneema ropes.

MATERIALS AND METHODS

The basic mechanical properties of the new generation fibre, Dyneema, and cordage products made of it are presented, based on manufacturers' information and on data obtained during tests, run at the Department of Fishing Techniques, on Dyneema cordage used in pelagic trawls.

Due to differences in mechanical properties, including a different coefficient of friction, of the Dyneema cordage and twines and ropes made of other materials, it is important to develop appropriate connecting techniques for links, slings, and strops. To elucidate this, strops made of 12–strand braided 2.5 and 10 mm diameter Dyneema SK 60 cordage were tested for breaking strength. The tests were run on a 0 – 100 kN range ZD 10/90 tensile testing machine (Fritz Heckert, Germany).

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To reduce trawl drag, the Dyneema SK 60 netting was used in the manufacture of the front part of the newly designed pelagic trawl. Two versions of the 2520 m mouth circumference trawl were manufactured:

- version *a*, with the entire trawl body made of steelon (PA) netting;
- version *b*, with the front part made of Dyneema products.

The trawl, to be operated by 3600 kW engine trawlers, was intended for harvesting scattered fish shoals in the blue waters.

The study was divided into the following two stages:

Stage I: testing trawl models;
Stage II: testing actual trawls at sea.

The 1:10 models were tested at the Model Research Station (MRS) at Ińsko, using methods developed at the Department of Fishing Techniques [3]. The monitoring and measuring facilities of MRS were used throughout [9]. Identical rigging was used on the two models.

At the second stage, the large–size ("giant") pelagic trawls were tested during commercial fishing cruises to the Okhotsk and Bering Seas (beyond the EEZs) on board MT Acamar.

Effects of Dyneema products on the geometric and drag–related characteristics (termed operation parameters) of small boat pelagic trawls used in the Baltic were studied during operations of a 220 kW DZI–102 fishing boat owned by Mr. B.Waniewski. The measuring devices used were those applied in trawl model tests, but modified to meet the conditions of operating a trawl from a small boat at sea [9].

Operation parameters of trawls towed with steel and Dyneema warps were compared, based on tests run both on models at MRS and on trawls operated at sea. The sea trials were conducted on board the 66 kW SNB–AR 1 research boat owned by the Agricultural University of Szczecin and on board the 162 kW KOŁ–41 fishing boat owned by Mr R.Klimczak.

RESULTS AND DISCUSSION

Basic mechanical properties of the Dyneema ropes and cordage

In 1979, the DuPont (DSM) company patented a gel–spinning technology for polyethylene (PE) fibre manufacture. The basic material is ultra high molecular weight PE. The manufacturing process involves extrusion of gel fibres through spinnerets. The fibres are subsequently drawn, at the polymer melting temperature (about 145°C), to several hundred times their initial length. As the fibre is drawn, the linear orientation of molecules higher than 95% and the crystallinity level of up to 85% is achieved [1]. This creates the excellent and unique physical and mechanical properties of the fibres, manufactured under a trade name of Dyneema.

The fibres found commercial applications in 1990. They were at that time manufactured in three grades:

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- Dyneema SK60,
- Dyneema SK65,
- Dyneema SK66.

The fisheries applications rely on Dyneema SK60, and – since 1997 – on its improved version, Dyneema SK75.

The main mechanical properties of major technical fibres used in the manufacture of netting materials are presented in Table 1. The Dyneema fibres are characterised by their exceptional tenacity, 3 to 4 times that of PA fibres most commonly used in net manufacture. The high tenacity is particularly evident in Dyneema SK75, the newest generation product. From the fishery application standpoint, it is particularly important that the fibre breaking strength does not depend on whether the fibre is dry or wet. Also important in this context is the low density of the fibres, lower than that of water. The manufacture technology, particularly the high extension, prevents any substantial elongation of the fibres under a load. The Dyneema product elongation under a breaking load does not exceed 5% [1].

Table 1. Mechanical properties of synthetic fibres used in fishing gear manufacture (after Anon. 2000)

Fibre	Density g·cm^{-3}	Tenacity				Elongation %
		N·tex^{-1}	g·den^{-1}	GPa	kG·mm^{-2}	
Dyneema SK60	0.97	2.80	32	2.7	275.4	3.5
Dyneema SK75	0.97	3.50	40	3.4	346.8	3.7
Aramid – regular	1.44	2.05	23	2.9	295.8	3.6
Polyamide	1.14	0.80	9	0.9	91.8	20
Polyester	1.38	0.80	9	1.1	112.2	13
Polypropylene	0.90	0.60	7	0.6	61.2	20
Steel	7.86	0.20	2	1.77	180.54	1.1

For fishery applications, the following Dyneema fibre grades are manufactured:

- 55 dtex,
- 110 dtex,
- 165 dtex,
- 220 dtex,
- 440 dtex,
- 880 dtex,
- 1320 dtex,
- 1760 dtex.

Table 2 summarises characteristics of netting materials manufactured from Dyneema fibres and cordage. The breaking strength of knotted Dyneema products is 35–55% of the knotless ones, the knotted PA products having a corresponding breaking strength of 60–65% of that typical of knotless ones.

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Table 2. Properties of netting made of Dyneema yarns and cordage used in netting manufacture (after Anon., 2000)

Dyneema SK 65 netting										
Twine size	Twisted		Braided [mm]							
	210/23	210/46	1.5	2.5	3.0	4.0	5.0	6.0	7.0	9.0
Approx. [m·kg^{-1}]	1680	835	480	320	240	140	95	65	44	27
Approx. breaking strength [KG]	106	190	300	570	840	1080	1680	2440	3290	5400

Dyneema SK 75 netting									
Twine size	Twisted		Braided [mm]						
	210/23	210/46	1.3	1.5	2.0	2.5	3.0	4.0	5.0	6.0
Approx. [m·kg^{-1}]	680	835	800	480	400	320	240	140	95	65
Approx. breaking strength [KG]	138	246	280	370	560	740	1080	1400	2180	3170

For fishery applications, the following four types of Dyneema ropes are manufactured:

- 12–strand braided ropes,
- braided ropes with a core,
- ropes with a braided cover,
- cable ropes.

The trawl fisheries rely mostly on 12–strand braided ropes, impregnated with a coating material to increase resistance against abrasion. Cable ropes are used as head– and groundropes of the trawls. Table 3 summarises the most important technical characteristics of 12–strand braided ropes.

Table 3. Breaking strength of Dyneema 12-strand braided ropes (after Anon. 2000)

Diameter [mm]	Weight [kg·100 m]	Breaking strength [t]	
		SK 60	SK 75
10	5.7	7.2	9.1
11	7	8.6	10.8
12	8	10.4	13.0
14	11	14.1	17.6
16	14	17.8	22.2

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18	18	22.4	28.0
20	22	27.7	34.6
22	26	33.6	42.0
24	31	39.8	49.8
26	36	47.0	58.8
28	42	54.4	68.1
30	48	62.5	78.1
40	86	108.0	136.0
50	138	168.0	203.0

Strop resistance

When putting together a fishing gear, the components are often connected with eyes, particularly when making strops to rig the trawl. When using novel materials, it is necesssary to apply techniques which render the strops resistant to forces occurring during operations at sea. The resistance of strops the eyes of which were made by plaiting strands in various ways and those with eyes additionally protected with bands and seams was tested. The tests showed the most resistant strops to be those made with eyes plaited 6 times, with strand ends hidden inside, protected with a band, and with the plaiting additionally sewn through. The least time consuming, and only slightly less resistant, were those eyes made by a single intertwining, double twining of the free end, and hiding the free end inside. Intertwining resulted also in maintaining a stable length of the strop. For a 2.5 mm diameter braided twine, breaking strength of 3.15 to 3.72 kN was obtained, a 10 mm rope producing a corresponding breaking strength range of 52.6 – 68.8 kN. Photographs in Figs 1, 2, and 3 show the strop tensile testing machine and a result of breaking the strop.

Fig. 1. A 10 mm diameter Dyneema SK60 strop, ready for tensile testing and a set of needles for intertwining

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Fig. 2. Testing a 10 mm diameter Dyneema strop in the ZD 10/90 tensile testing device

Fig. 3. The result of breaking a 10 mm Dyneema strop

Geometric and drag–related characteristics of a trawling system involving a giant 2530 m mouth circumference pelagic trawl

In pelagic trawl fisheries, the catch size is a function of the amount of water filtered by a trawl per unit time [11]. For this reason, maximisation of the trawl mouth area, with a simultaneous reduction of energy expenditure on trawling, is aimed at. This can be achieved by minimising the resistance (drag) of a trawling system. One of approaches towards that end is to reduce the drag of the trawl itself, which is attainable by using Dyneema netting and cordage. Thanks to their breaking strength 3–4 times that of polyamide materials used so far, the Dyneema products make it possible to use netting and ropes of much smaller diameters, and hence of a much smaller drag area. Therefore, when designing giant–size trawls for harvesting scattered fish shoals in the blue waters, application of Dyneema products was foreseen. Due to the relatively high prices of those products (in 1994–1995), Dyneema ropes were used in the front (mouth) part of the trawl only. The much lower diameters of the Dyneema ropes used in the front part of the trawl, compared to the diameters of the commonly used PA ropes, resulted in a much smaller drag area of the trawl body.

Table 4 summarises data on the drag areas of the two 2520 m trawl versions studied. The two trawls differed in having their surrounding ropes and the front part made either of steelon (PA) or Dyneema [11]. The largest differences were visible when the front parts made of both types of products were compared. The drag area of the Dyneema–containing trawl was 64% of that shown by the trawl made entirely of PA. When comparing the ropes surrounding the trawl mouth, the difference was lower and resulted from small differences in the diameters of the ropes. The drag area in trawl version *b* was by 11% smaller than that in version *a*. Table 4 shows also drag areas of entire trawls, without codends. The version *b* drag area was 78% of that shown by the all–PA trawl. Application of the Dyneema products resulted in a substantial (by more than 1/5) reduction of the trawl body drag area. The table disregards the codend drag areas on purpose, because, firstly, they were identical in both versions, and secondly, in spite of its magnitude, the codend drag area contributed very little to the total trawl body drag due to the fact that the angle of attack of netting in that part of the trawl was zero [5].

Table 4. Drag area of polyamide and Dyneema versions of the 2520 m circumference giant trawl

Item	Polyamide (version *a*)		Dyneema (version *b*)	
	[m^2]	[%]	[m^2]	[%]
Surrounding ropes	28	100	25	88
Front part	165	100	105	64
Total drag area	295	100	232	78

The 2520 m mouth circumference trawl model drag as well as the calculated real drag are plotted in Fig. 4 as a function of towing speed. Within the towing speed range analysed, the trawl drag increased in a similar way in the two trawl versions. However, the drag produced by version *b* was clearly, by 10–16%, lower than that of version *a*. This is a very substantial reduction which will make it possible either to save energy needed to tow the trawl, to increase the trawl dimensions, or to increase towing speed [7]. Such capabilities are very advantageous from the standpoint of fishing operation tactics. Incorporating Dyneema

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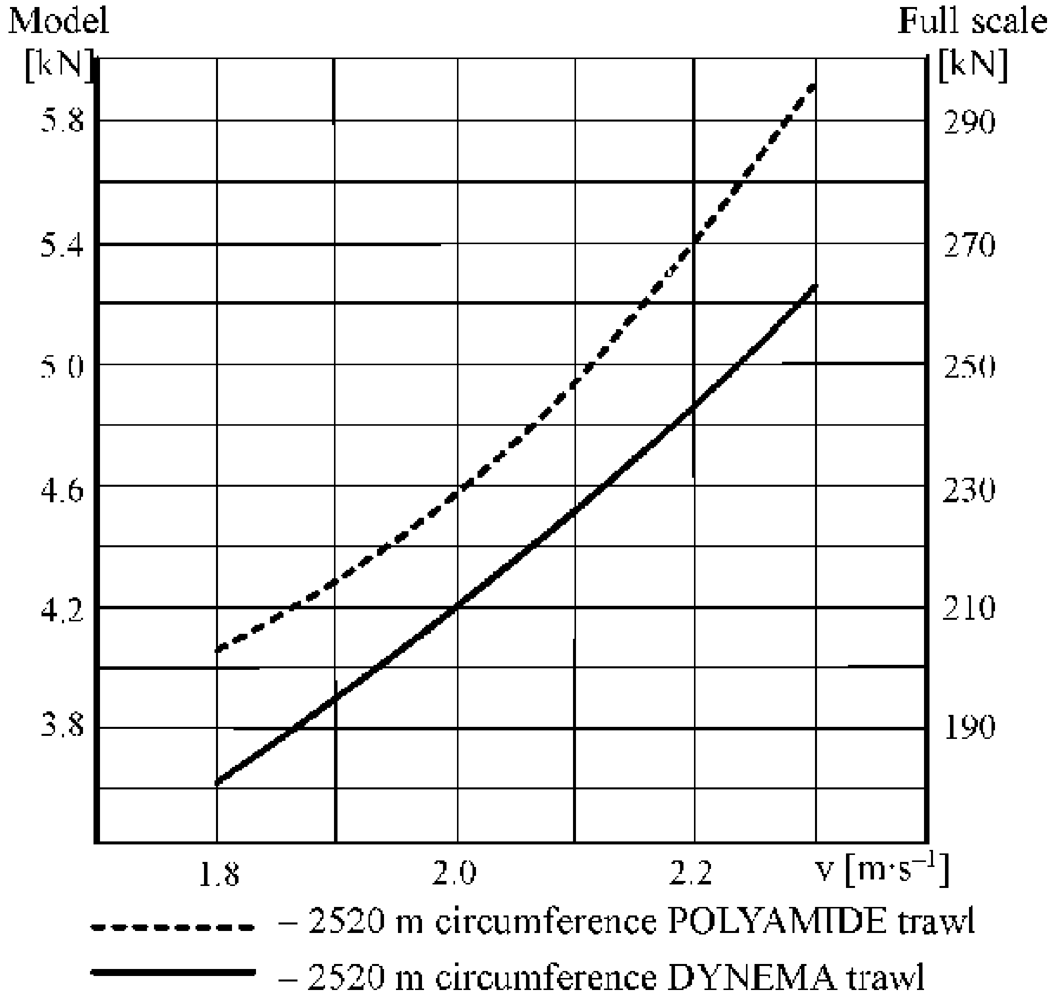
products, smaller in diameter and more resistant, in the front part of the trawl allows to reduce the drag area of the trawl body, excluding the codend, by 22%.

Fig. 4. Plots of 2520 m circumference trawl model drag and calculated real drag of full scale trawl versus towing speed



The giant trawl at–sea trials were conducted in the international waters of the Bering Sea in 1995 and 1996 during routine fishing reconnaissance cruises [11]. Rigging of the trawl was guided by the model test results. A number of trials involving alteration of various rigging components were run at sea. The basic operation parameters of the Dyneema–containing trawl, obtained during the trials at sea with different lengths of warps paid out and at comparable towing speeds are summarised in Table 5.

Table 5. Operation parameters of the giant trawl tested at sea on board MT Acamar

Warp length Ltr [m]	Vertical opening AB [m]	Horizontal opening CD [m]	Door spread Y [m]	Trawl depth Z [m]
500	135	140	233	200
600	140	142	237	230
700	145	152	252	270

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800	145	140	232	280
900	145	141	234	320
1000	145	137	227	400

The trawling system tested, rigged in a standard way and equipped with warps of changeable length, performed satisfactorily and achieved advantageous operation parameters. The results obtained fully met the design objectives and supported conclusions drawn from the research on models.

Operation parameters of a small boat trawling system involving a 420 m mouth circumference Dyneema–containing pelagic trawl

A new large–mesh pelagic trawl intended for the 220 kW DZI 102 fishing boat (owned by Mr. B. Waniewski) was designed. The trawl body consisted in 65% of Dyneema, PA components contributing 35%. The drag area of the identical trawl made entirely of PA was by 25% larger than that of the Dyneema–containing trawl. It should be mentioned that, in addition to the reduced drag area, introduction of Dyneema increased the trawl component resistance to mechanical damage by a factor of 3, which would doubtless extend the trawl's durability.

The Dyneema ropes were also used for rigging. The trawl is usually towed on 8 Hercules–type rope legs, 12 mm in diameter and 80 m long. The new rigging included 6 legs made of 6 mm Dyneema ropes, the remaining two bottom legs being standard 12 mm Hercules ropes. That resulted in a reduction, by half, of the leg drag area. It should be mentioned that the 6 mm Dyneema legs are by about 50% more resistant than the standard 12 mm Hercules legs used so far.

Results of at–sea trials conducted in September 2000 on board the DZI 102 are summarised in Table 6. Application of the Dyneema products resulted in a reduced drag of the trawling system and made it possible to increase the towing speed to 2.0 m·s^{-1}. The trawl opening parameters were very advantageous, particularly with respect to the horizontal opening of the belly, which reached 50 m, and to the trawl door spread exceeding 100 m at 2.0 m·s^{-1} trawling speed.

Table 6. Operation parameters of a trawling system with a 420 m circumference pelagic trawl, recorded during trials on board the DZI 102 boat

Towing speed [m·s^{-1}]	Headline depth [m]	Vertical opening [m]	Horizontal opening [m]	Door spread [m]	Drag [kN]
1.7	57.8	15.5	42.4	88.1	28.8
1.8	52.1	13.3	43.6	90.8	31.0
1.9	44.2	11.9	45.4	94.7	33.8
2.0	34.0	11.1	47.9	99.7	37.2
2.1	21.7	11.2	50.9	105.9	41.1

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Geometric and drag–related characteristics of a 1400 m mouth circumference pelagic trawl towed with steel and Dyneema warps

The tests, carried out at MRS Ińsko, involved a model of a trawling system with a 1400 m belly mouth circumference and 3–part doors (7.9 m^2 surface area and 1900 kg weight) [4]. The model test results were converted to data pertaining to a system towed with 550 m long 30 mm diameter Dyneema warps and 26 mm steel ones. The results are summarised in Tables 7 and 8. Within the towing speed range used, both sets produced a similar hydrodynamic drag, in spite of a larger diameter of the Dyneema warps. The opening parameters showed the Dyneema warps–equipped trawling system to achieve a slightly smaller vertical and a larger horizontal opening. On the other hand, the door spread was clearly larger in the Dyneema ropes–equipped trawl. Such a trend is particularly advantageous for harvesting success of a trawl. In addition, it is more difficult to open the trawl horizontally than vertically. Moreover, as shown by the data, the most significant differences in favour of the Dyneema warps–equipped trawl are those pertaining to the trawl depth, which is illustrated by Table 9. The results allow to conclude that replacing steel warps with those made of Dyneema ropes allows to operate the trawl at a shallower depth as the Dyneema products have a higher buoyancy than that of steel ropes. It should be also mentioned that, in spite of similar diameters of both warp types, their tensile strengths are not comparable. The steel rope require a breaking load of 35 t, while 80 t, i.e., more than twice as much is needed to break the Dyneema ropes. For this reason, the diameter of the Dyneema ropes used can be smaller to further reduce the hydrodynamic drag of the trawl set.

Table 7. Operation parameters of a trawling system model corresponding to a 1400 m circumference trawl, towed with 550 m long, 30 mm dia, Dyneema warps

Towing speed [$m\cdot s^{-1}$]	Groundrope depth [m]	Vertical opening [m]	Horizontal opening [m]	Trawl door spread [m]	Hydrodynamic drag [kN]
2.1	211.8	80.8	87.9	165.3	213.6
2.2	189.0	81.3	87.2	164.9	235.0
2.3	170.0	81.3	87.3	164.7	255.1
2.4	155.0	81.0	88.2	164.7	274.1
2.5	143.8	80.4	89.9	164.8	291.8
2.6	136.6	79.3	92.4	165.1	308.2

Table 8. Operation parameters of a trawling system model corresponding to a 1400 m circumference trawl, towed with 550 m long, 26 mm dia, steel warps

Towing speed [$m\cdot s^{-1}$]	Groundrope depth [m]	Vertical opening [m]	Horizontal opening [m]	Trawl door spread [m]	Hydrodynamic drag [kN]
2.1	246.5	86.6	85.6	147.8	224.8
2.2	232.5	87.3	85.4	154.8	233.7
2.3	217.3	87.3	85.8	159.4	246.0
2.4	200.9	86.4	86.7	161.7	261.8
2.5	183.2	84.7	88.1	161.5	280.9
2.6	164.4	82.2	90.1	159.0	303.4

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Table 9. Groundrope depth of a 1400 m circumference trawl towed with Dyneema and steel warps

Towing speed [m·s^{-1}]	Dyneema warps	Steel warps	Difference [%]
	groundrope depth [m]		
2.1	211.8	246.5	86
2.2	189.0	232.5	81
2.3	170.0	217.3	78
2.4	155.0	200.9	77
2.5	143.8	183.2	78
2.6	136.6	164.4	83

CONCLUSIONS

1. Compared to other synthetic fibre types used in manufacture of fishing gear, the polyethylene Dyneema fibres have very advantageous properties, including a high breaking strength. This makes it possible to use smaller–diameter products in gear manufacture, which results in a greatly reduced hydrodynamic drag of the towed gear and a lower energy expenditure on towing.
2. When putting a trawl together, especially when making strops, a particularly good connection of 12–strand coreless braided ropes can be obtained by intertwining them once, twining of the free ends twice, and hiding the free end inside. Trials showed such connections to perform faultlessly at sea.
3. Replacing polyamide ropes in the front part of the large–size trawls with the Dyneema ropes makes it possible to reduce the drag area by 22%. The hydrodynamic drag of a Dyneema ropes–containing trawling system is by 10–16% lower than that produced by a system including a trawl made entirely of polyamide.
4. Studies on a small boat trawling system involving a 420 m trawl showed the replacement of 65% of the polyamide products with the new generation fibres to reduce the drag area by 21%, with a simultaneous increase, by a factor as high as 3, of the resistance to mechanical damage.
5. Results of testing trawl models showed the replacement of steel warps with those made of Dyneema ropes of identical length and diameter to allow towing the trawl at a shallower depth.

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