Thesis for the Degree of Master of Fisheries Science

DESIGN AND TEST OF AN ENERGY-EFFICIENT MIDWATER TRAWL BY SIMULATION AND FLUME TANK

by

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KOICA-PKNU International Graduate Program of Fisheries Science

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시뮬레이션과 수조실험을 통한 에너지 절감형 중층 트롤의 설계 및 실험

Advisor: Prof. Chun-Woo LEE

by

Charles TEYE

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Abstract

In this study, we designed a suitable energy-efficient midwater trawl to harvest small pelagic fishes in the Ghanaian waters. A mass spring-model was used to describe and calculate the shape and movement of a midwater trawl system. Two different gears were simulated by the dynamic simulation software, SimuTrawl, developed in Pukyong National University, Korea by Marine Production System Laboratory (MPSL). One gear was made up of polyetylene (PE) netting while the other gear was PE in the first six panels and the rest of the fourteen panels were replaced with "Dyneema", half the diameter of the PE netting twine. To check on the accuracy of the mathematical calculation of the simulated gear, we constructed a small scale model midwater trawl net based on the normal scaling rules and tested it in a 3D water circulating flume tank (10.2 m long x 3.2 m high x 2.8 m wide). The height of the net mouth of the simulation of PE and "Dyneema" netting (PE+DY) had higher opening between 19% and 25% than the height of PE

netting. The net drag of PE+DY was reduced by 16% to 31% compared to the drag of PE. The model test likewise recorded a reduction in the drag of the PE+DY between 20% and 23% compared to the drag of PE. These results confirm the hypothesis that replacing a polyethylene midwater trawl gear with “Dyneema” netting material, half the diameter of polyethylene netting twine, from the 7th panel to the 20th panel (codend) will yield a higher height of net mouth opening and lower drag. This type of gear should be highly useful for the Ghanaian small pelagic fisheries.

1. INTRODUCTION

A basic tenet of the ecosystem approach to fisheries management is that harvesting should be conducted with minimal impact on juvenile fish, non-target species, and marine habitats. A range of technical modifications of fishing gears aimed at improving their selective properties is available to help achieve these goals, but their effectiveness varies.

Fishing technology has been developed in the 20th century, mostly by Russian and Japanese scientists (Baranov, 1969). It represents a generalization of practical experience accumulated by many generations of fishermen all over the world. Procedures have been worked out for objectively comparing fishing methods and gears to help select the most suitable ones and to permit a preliminary evaluation of the technical and economic feasibility of technological improvements and innovations.

Opportunities for innovation have been especially good in the recent decades with advances in fibre technology, mechanization of gear handling, an improved performance of vessels, computer processing for gear design, navigation aids, and fish detection. Dynamic changes have occurred in recent years in the world fisheries: improving the selection of fishing grounds, gears and methods. It also involves sophisticated equipments such as monitoring instruments, large and powerful fishing gear and automatic machines. Fishermen who are able to blend practical experience with technical knowledge are highly needed (Fridman, 1986).

1.1 Trawl gears

Trawl fishing is a controversial subject worldwide, attributed with low intra- and inter-specific catch selectivity (Madsen *et al*., 2002; King *et al*., 2004; Broadhurst *et al*., 2006). Behavior of a fishing gear during a haul may be affected by multiple time-dependent and often by unpredictable factors such as seabed irregularities, waves and currents. Thus a trawl gear design is a scientific field which involves several basic calculations, formulas, tests and knowledge on the size and shape of the target species. It is a process of preparing technical specifications and drawings for a fishing gear, which has to satisfy the gear handling, the technical, the operational, the economic and the social requirements (Fridman, 1986).

Traditionally, netting materials were directly used for net construction without knowing much about its geometry in the water. Recently, flume tanks were introduced to judge the working shape and position on a model of each gear, the speed, the magnitude and the direction of forces. Currently, other methods also exist such as underwater cameras to monitor the real shape of the net *in situ* and computer software for visualising the shape of the net at different design parameters. Each design has its own specifications and there are certain rules to draw the net plans in accordance with international standards.

Net designing has undergone technical changes in the past decades with modernization of fishing techniques, methodology and invention of different software. The basic principles of the designing are still the same with a few additional techniques. The ideal process for designing a trawling system is using both tools in a complementary manner and in a logical sequence of work, using the dynamic simulation for progress in the definition of a design, and then it is recommended to evaluate the prototype in a flume tank to refine their correct performance and potential defects.

During the 1960s, pelagic trawling has been developed as a capture technique for shoaling species. The trawls which are used to catch these resources are cone-shaped nets which are towed in midwater. They are normally made of four panels, ending in codends, and the nets have lateral wings extending forward from the opening. The horizontal openings are maintained by otter boards. Floats and/or sailkites on the head line and weights on the ground line provide for the vertical opening. Until 1962, the two panel net type prevailed. This type has been described in detail by Scharfe (1960) and later it was replaced by the rectangular four panel type.

1.2 Fisheries in Ghana

In Ghana, fishing is a significant economic activity in the entire coastal zone of the country. The fisheries sector supports more than 2 million of the 24 million people in the country and contributes 5% to GDP. The coastline of Ghana is about 550 km in length with a narrow continental shelf varying in width from a minimum of 20 km off Cape St. Paul to 100 km between Takoradi and Cape Coast (Bernacsek, 1986), and a total EEZ of 24,300 km^2. The sea bed is a mixture of soft (i.e., muddy to sandy mud), hard and rocky bottoms in the inshore areas at depths between 10 and 50 m (Buchanan, 1957).

The shelf is traversed by a belt of dead madreporarian corals beginning at 75 m, beyond which the bottom falls off sharply suggesting that this marks the approximate transition between the continental shelf and the slope. Soft sediments predominate along the coastline and coral belt, while hard bottoms are largely and centrally located between Takoradi and Tema. The coastal belt of Ghana is part of a central upwelling zone extending from Cape Palmas to about 2°E (Longhurst, 1962; Williams, 1968). This occurs as a result of the southern edge of the Guinean current, which flows along the coast in an eastward direction at the surface, encountering the westward flowing south equatorial current. From July to September each year, a major upwelling occurs on the continental shelf with a minor upwelling occurring in December-January. This period is characterized by low temperature on sea surface (< 23℃), high salinities (>35 psu), and the upwelling of cold, nutrient-rich waters to replace the warm surface layers (Ofori-Adu, 1978).

The marine fishing industry in Ghana has three sectors: inshore fishing by small-scale artisanal fishing using traditional wooden dugout canoes; the semi-industrial small-sized inshore trawlers; the deep-sea industrial fleet made up of large trawlers, purse seiners and pole and liners. The small-scale, traditional sub-sector represents over 60% of marine total catch annually (Mensah and Koranteng, 1988), and it employs large numbers of men in fishing and women in post-harvest activities such as processing and marketing of fish. Gear types used in the artisanal fishery include: a wide variety of gilling and entangling nets, seine nets, hook & line and cast nets. The semi-industrial (inshore) fleets consist of locally built wooden vessels of 8-37 m in length with in-board engines of 400 hp. They operate only two types of gears; trawl gears and purse seines and they contribute nearly 5% of the total fish catch. Industrial fleets are large steel-hulled foreign built trawlers of about 35 m in length with engines of over 600 hp, shrimpers, tuna pole and liners, and purse seiners. They contribute 32% of the total catch.

1.3 Justification

The negative impacts of the fishing industry in the 200 nm Exclusive Economic Zone (EEZ) of Ghana include the direct consequences on the marine environment of over-fishing and harmful fishing techniques. Important problems in industrial fishery are catchability and selectivity of fishing gears. With more and more boats searching for fewer and fewer fish, there has been a dramatic increase in the use of destructive, habitat-destroying fishing techniques like dynamites, beach seining and bottom trawling in Ghanaian waters. Bottom trawling is the most destructive fishing gear in use, with the capacity to greatly disrupt benthic ecosystems in shallow as well as in deep sea waters. It also mechanically disturbs the sea bottom and destroys a wide variety of marine benthic creatures (Knieb, 1991).

The increased fishing has also led to increased capture of endangered marine turtles and juvenile fish. This could be reduced by the use of more selective fishing techniques to avoid catching immature fish and/or species of lower economic value that are then discarded. Technological development of fishing gears and methods in the past was aimed to increase production but currently many stocks are overfished. The possibilities to expand fishing on underexploited resources are limited and there are also concerns about the environmental impacts of fishing operation. Gear development is now very much focused on selective fishing and gears with less impact on the environment through modifications of existing gears or new gear designs. To overcome these problems, there is urgent need to reduce the pressure on demersal resources by diversifying to resource specific trawls, i.e. midwater trawls. Therefore, designing an energy-efficient midwater trawl which has less adverse effect on the marine environment has become a necessity for the Ghanaian fisheries.

1.4 Trawl gear energy efficiency

The recent rise in oil prices has brought renewed attention to energy savings in the fishing industry, and particularly in trawling. Coastal trawlers spend most of their time on fishing grounds near the coast. In such cases, the most successful energy-saving medications ought to result from changes in the fishing gear and towing conditions. Fuel consumption and ecosystem impacts can be reduced through changes in operational techniques and gear design without drastic changes in gear behavior. Reducing the towing drag or resistance of trawl nets is a very effective approach to improving fuel efficiency in this type of fishing method. One method for achieving such reduced drag is by using smaller diameter twines in the trawl netting (Ward *et al*., 2005).

Drag of a gear can be reduced by making the trawl smaller, reducing the opening (wing end spread and net mouth height), reducing the twine surface area of netting, reducing the ground contact friction or using lower drag trawl doors and components. Twine surface area can be reduced either by using larger mesh sizes or reduced twine diameters. If the same design of trawl is used but constructed with smaller diameter twines the drag of the trawl will reduce when compared with the conventional trawl with larger diameter twines.

A trawl gear is part of a dynamic system therefore a decrease in the drag of the trawl will cause other parts of the trawl gear to change shape. When the drag of a trawl is decreased, there will usually be big changes in the door spread, the wing end spread and the net mouth height. One or all of these parameters will usually increase. To maximize the benefits from the use of smaller diameter twines and large mesh, it is necessary to make other alterations to the gear to optimize the catching potential and fuel savings.

"Dyneema", a High Modulus Polyethylene fiber, is an advanced form of knotless netting that has superior strength and performance over conventional netting. This netting reduces the drag of the trawl on two separate dimensions. First, the trawl can be constructed with a twine of 50% of the diameter. Second, the drag will be reduced further by using knotless netting material. Taking into account that the drag of a trawl is directly related to the twine surface area of its netting, the over-all drag of the gear will reduce considerably. "Dyneema" has high-strength but low-weight. Stretching the fiber introduces molecular alignment and a high level of crystallinity. It has a density of less than 1, and this provides the basis for the fiber's light weight and high strength, as well as for its low elongation. The strength and elongation of products made with "Dyneema" are comparable to steel, with only 15% of the weight of steel.

In marine and industrial applications, "Dyneema" has the highest strength-to-weight ratio. The low-friction properties of the fiber protect it from internal abrasion, resulting in long service lives in rope tensile and bending fatigue testing. "Dyneema" fiber has a melting point between 144ºC and 152ºC. The tenacity and modulus decrease at higher temperatures but increase at sub-zero temperatures.

There is no brittle point found as low as -150ºC, therefore the fiber can be used between this temperature and 70ºC. Brief exposure to higher temperatures will not cause any serious loss of properties. "Dyneema" fiber elongates irreversibly with increasing static load and temperature. This is known as creep, and "Dyneema" shows the lowest creep with the longest creep life.

It is, however, hypothesized that replacing a polyethylene midwater trawl gear with "Dyneema" netting material, half the diameter of polyethylene netting twine, from the 7th panel to the 20th panel (codend) will result in a higher height of net mouth opening and lower drag.

1.5 Objectives

This study aims at designing a suitable energy-efficient midwater trawl gear to harvest small pelagic fishes in Ghanaian waters.

Specifically:

1. To design a prototype pelagic trawl gear, and improve the performance or higher probability of catching of the gear by simulation
2. To reduce the net drag and increase the net mouth opening
3. To confirm the validity of the computer simulation by flume tank test.

2. MATERIALS AND METHODS

2.1 Mathematical model

2.1.1 Equation of motion

A midwater trawl system is a structure in which a rigid body and flexible structures are connected to each other, therefore the shape of this system is easily changed with external forces. It moves in a three-dimensional space, X, Y and Z planes. That is, the XY plane is parallel to the surface of the sea, and the Z-axis is the depth of the fishing gear (Fig. 1.).

In this study, a mass spring-model (Lee, 2002) was used to describe and calculate the shape and movement of a midwater trawl system. This mathematical model theorizes that the factors constituting the system are the material points and the

Fig. 1. The coordinate system of a trawl gear: A, XY plane; B, XZ plane.

external forces such as the hydrodynamic load, gravity and buoyancy act on these material points. The material points were connected to each other by springs, but the springs do not have any mass and the internal force acted on these springs. The non-linear differential equations were implicitly integrated with time for guaranteeing a stable solution. The equation of motion for each mass point can be described as follows:

$$(\mathrm{m} + \Delta\mathrm{m})\ddot{\mathbf{q}} = \mathbf{F}_{\mathrm{int}} + \mathbf{F}_{\mathrm{ext}} \tag{1}$$

m: mass of the material points

Δm: added mass

$\ddot{\mathbf{q}}$: acceleration vector

$\mathbf{F}_{int}$: internal forces applied between the material points

$\mathbf{F}_{ext}$: external forces applied to the material points.

The internal force is derived from the elasticity of the lines, which connect the points, and the external forces represent the drag, sheering force, gravity, buoyancy, which act on each of the points. The added mass of the material points is given as follows:

$$\Delta\mathrm{m} = \rho_{\mathrm{w}}\,\mathrm{V}_{\mathrm{n}}\,\mathrm{C}_{\mathrm{m}} \tag{2}$$

$\rho_{w:}$ density of seawater

$V_{n:}$ volume of the material points

$C_{m:}$ added mass coefficient.

C_m is calculated as follows:

$$C_m = 1 + \sin\alpha \qquad (3)$$

α: angle of attack.

The internal force is the force that is applied to the springs connecting each material point. All the lines and the twines are a kind of spring, the force, which acts on that spring, is considered proportional to a degree of displacement. It is given as:

$$\mathbf{F}_{int} = -\sum_{i=1}^{n} k_i \ \mathbf{n}_i \left[|r_i| - l_i^o\right] \qquad (4)$$

$k_{i:}$ stiffness of the springs comprising the structure

$\mathbf{n}_{i:}$ unit vector along the line of the spring

$|r_i|$: magnitude of the position vector between the neighboring material points

l_i^o: initial length of the spring

n: numbers of adjacent material points i.

The stiffness is the equivalent value of each material. It is calculated by the following formula:

$$k = \frac{EA}{l^o} \tag{5}$$

E: Young Modulus

A: Effective Area of the material.

The external force ($\mathbf{F}_{ext}$) is the force that is applied to each material point from the outside environment, and it consists of the drag force ($\mathbf{F_D}$), lift force ($\mathbf{F_L}$), and buoyancy and sinking force ($\mathbf{F_B}$), as follows (Fig. 2):

$$\mathbf{F}_{ext} = \mathbf{F_D} + \mathbf{F_L} + \mathbf{F_B} \tag{6}$$

The drag and lift forces are as follows (Fig. 3):

$$\mathbf{F_D} = -\frac{1}{2} C_D \rho_w S \mathbf{V}|\mathbf{V}| \tag{7}$$

$$\mathbf{F_L} = \frac{1}{2} C_L \rho_w S\, V^2 \mathbf{n_L} \tag{8}$$

C_D: drag force coefficient

S: projected area of the material point

V: magnitude of the resultant velocity vector

C_L: lift force coefficient

$\mathbf{n_L}$: unit vector of the lift force.

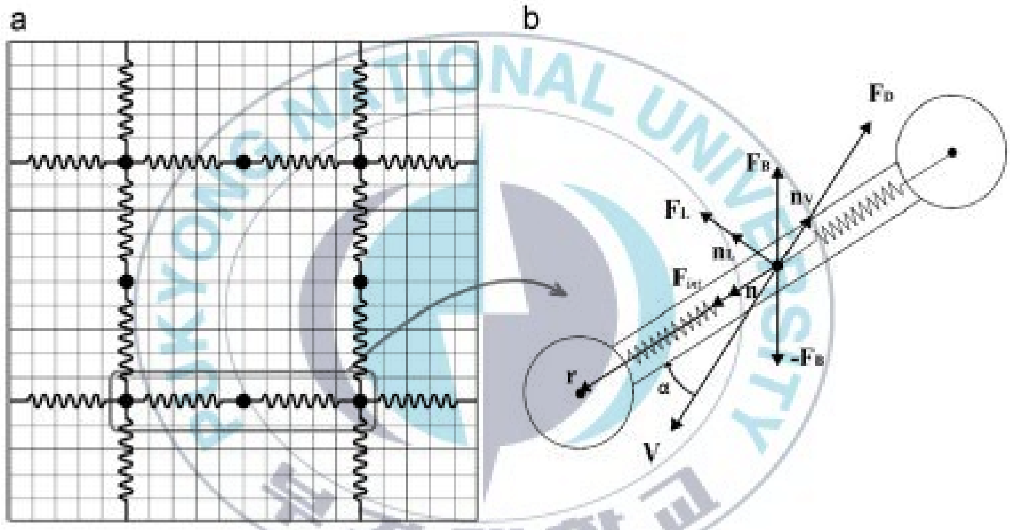


Fig. 2. Placement of virtual mathematical mesh by grouping method (a) and vector notation of the element (b).

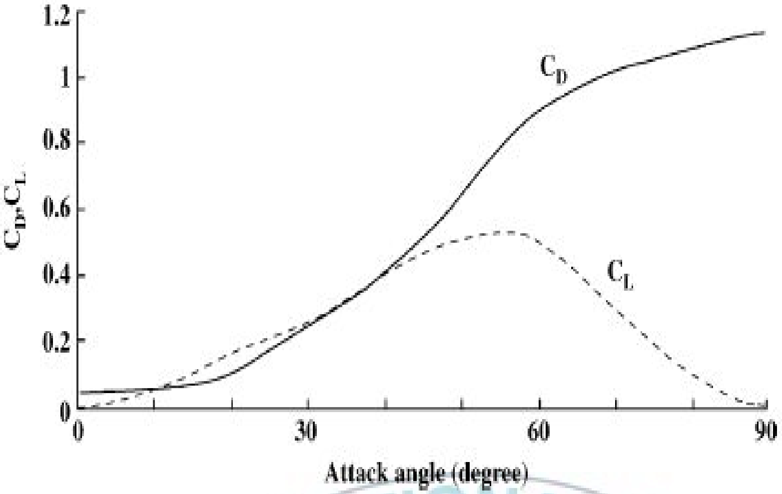


Fig. 3. The drag and sheering force coefficients for a specific netting as a function of angle of attack.

The $\mathbf{n_L}$ is calculated as follows:

$$\mathbf{n_L} = \frac{(\mathbf{V} \times \mathbf{r}) \times \mathbf{V}}{(\mathbf{V} \times \mathbf{r}) \times \mathbf{V}} \tag{9}$$

V: resultant velocity vector.

The resultant velocity vector **V** is composed of the motion velocity vector of the material point $\mathbf{V_m}$ and the current velocity vector $\mathbf{V_c}$ as follows:

$$\mathbf{V} = \mathbf{V_m} - \mathbf{V_c} \tag{10}$$

The hydrodynamic coefficients of the mesh bar are the function of the attack angle (Fig. 4) formed by the bar and the velocity vector and the attack angle is obtained as follows:

$$\alpha = \cos^{-1}\left[\frac{V.\ r}{|V||r|}\right] \tag{11}$$

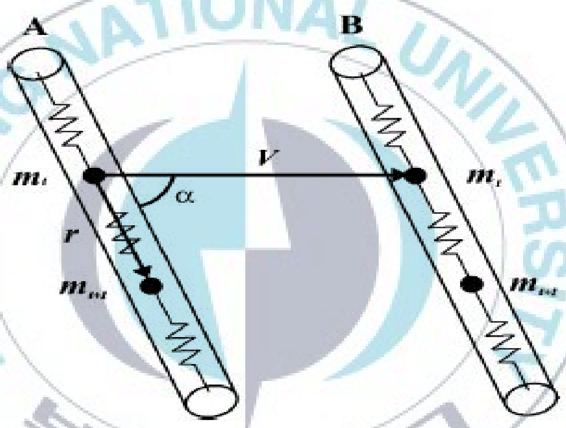


Fig. 4. Schematic representation of the displacement and definition of the vectors for a mesh bar.

The buoyancy and sinking force, $\mathbf{F_B}$, can be written as follows:

$$\mathbf{F_B} = (\rho_i - \rho_w)V_n\mathbf{g} \tag{12}$$

ρ_i: density of the structure

$\mathbf{g}$: gravity acceleration.

V_n: Volume of the material point.

After substituting the internal and external forces in Eq. (1), the equation of motion governing the motion of the midwater trawl system is given as:

$$M\ddot{\mathbf{q}}\,(t) = \mathbf{F}_{int} + \mathbf{F}_{\mathbf{D}}\,(t) + \mathbf{F}_{\mathbf{L}}\,(t) + \mathbf{F}_{\mathbf{B}}\,(t) \qquad (13)$$

M: mass including added masses

$\ddot{\mathbf{q}}$: acceleration.

Equation (13) can be transformed into two first-order differential equations:

$$\ddot{\mathbf{q}} = \mathbf{V}_m\,(t) \qquad (14)$$

$$\mathbf{V}_m\,(t) = M^{-1}[\mathbf{F}_{int}\,(t) + \mathbf{F}_{\mathbf{D}}\,(t) + \mathbf{F}_{\mathbf{L}}\,(t) + \mathbf{F}_{\mathbf{B}}\,(t)] \qquad (15)$$

2.2 Dynamic simulation

The dynamic simulation software, SimuTrawl, developed in Pukyong National University, Korea by Marine Production System Laboratory (MPSL), was employed to simulate the mechanical behavior of the prototype trawl. It is based on solving the momentum equations and taking into account the hydrodynamic forces applied to each part of the gear (Vincent, 1999). Two different gears were simulated. One was made up of polyetylene (PE) netting (Fig. 5), whereas the second one was PE in the first six panels and the rest of the fourteen panels were replaced with “Dyneema”, half the diameter of the PE netting twine (Fig. 6).

The simulations were performed for the full scale trawl under similar operational conditions, with 250 m, 300 m and 350 m of warp lengths with a time step of 0.0001 s, recorded data at 390, input depth of 150 m and water depth of 300 m. For comparison of this study, we used only the simulation outputs that may be comparable with the data obtained in the flume tank. The towing speeds used for the simulation were in the range of 3 to 5 knots, with increments of 1 knot. During each towing speed, the following data were collected: Distance of doors, Depth of doors, Width of net mouth, Height of net mouth and Drag.

Fig. 5. The design of the gear.

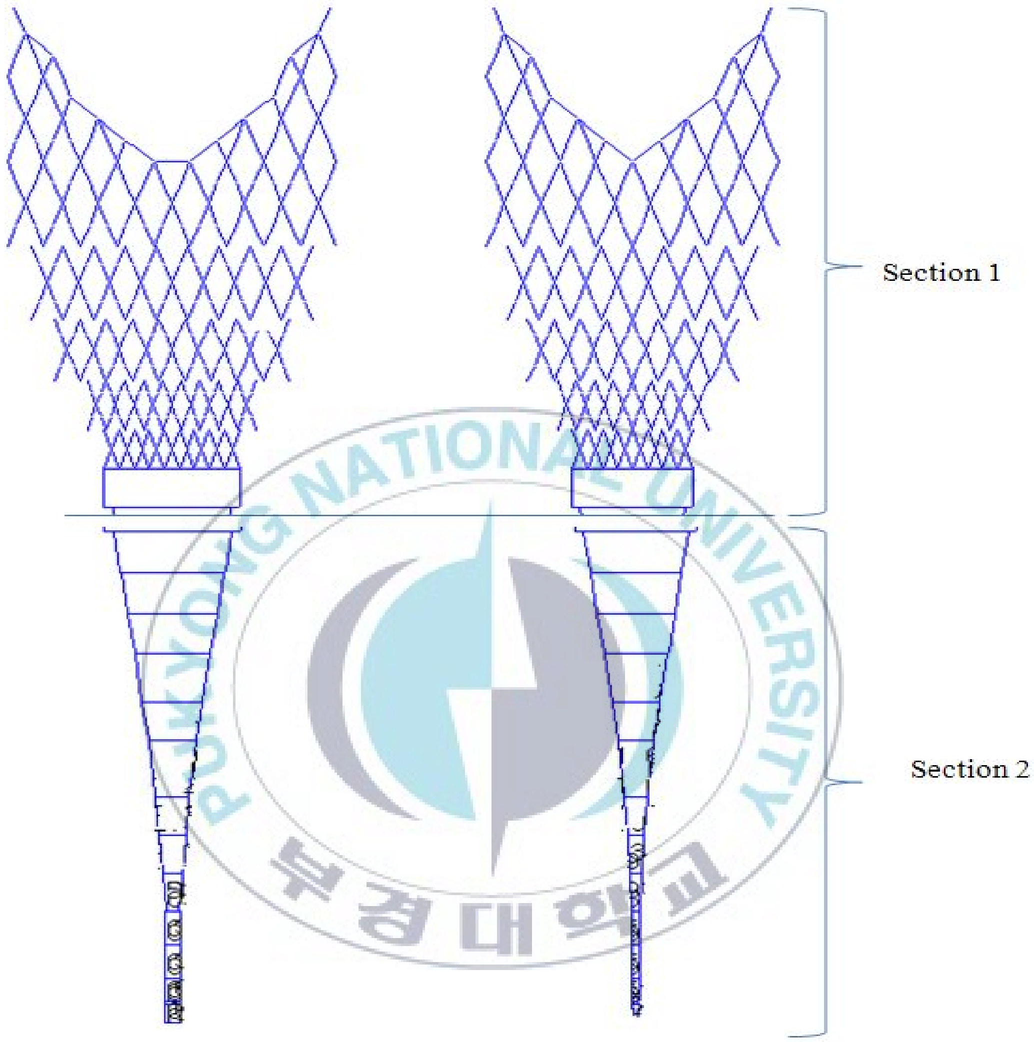


Fig. 6. Designed gear divided into two sections.

2.3 Trawl gear properties

An accurate simulation is based on the precise information of each part of the fishing gear (Fig. 7; Table 1). The properties of the designed trawl gear are listed below:

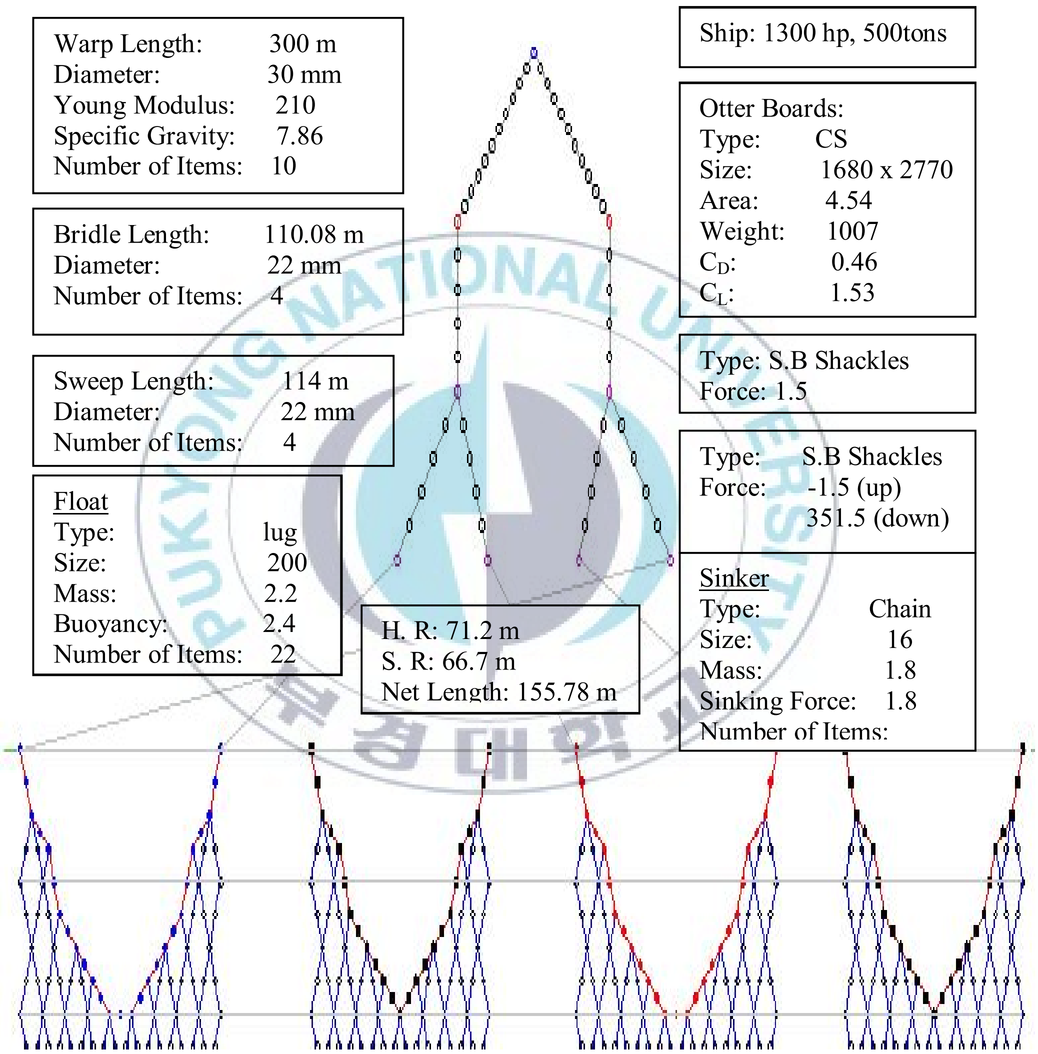


Fig. 7. Trawl accessories.

Table 1. Full scale trawl panel properties

Nets		Knots	M.S (mm)	Head Panel		Side Panel		M.D	Diameter	Hanging Ratio
				Upper	Lower	Upper	Lower			
PE	Rope θ12	Knot	14,000	10	10	9	9	3	12	95
PE	Rope θ10	knot	12,000	10	10	9	9	1	10	95
PE	Rope θ8	knot	10,000	10	10	9	9	1	8	95
PE	Rope θ7	knot	8,000	10	10	9	9	1	7	96
PE	Rope θ7	knot	6,400	10	10	9	9	1	7	96
PE	Net θ6	knot	3,200	18	18	16	16	2	6	96
PE	Net θ5	knotless	1,600	36	32	32	28	4	5	97
PE	Net180ply	knotless	800	63	55	55	47	8	4.68	97
PE	Net 90ply	knotless	400	109	93	94	79	16	3.31	97
PE	Net 50ply	knotless	150	248	198	208	158	50	2.47	97
PE	Net 50ply	knotless	120	247	197	197	147	50	2.47	97
PE	Net 40ply	knotless	90	262	182	196	120	100	2.21	97
PE	Net 40ply	knotless	60	273	213	180	131	100	2.21	97
PE	Net 40ply	knotless	60	213	153	131	91	100	2.21	97
PE	Net 40ply	knotless	60	153	103	91	51	100	2.21	97
PE	Net 40ply	knotless	60	103	103	51	51	90	4.28	95
PE	Net 40ply	knotless	60	103	103	51	51	90	4.28	95
PE	Net 40ply	knotless	60	103	103	51	51	60	4.28	95
PE	Net 40ply	knotless	60	103	103	51	51	10	4.28	95
PE	Net 40ply	knotless	60	103	103	51	4	50	4.28	95

2.4 Midwater trawl system model

The scaling of the physical model was based on the normal scaling rules (Tauti, 1934; Christensen, 1973; Hu *et al.,* 2001). The linear scale factor, λ, is defined as the quantity in the full-scale trawl divided by the corresponding quantity in the model. In general terms, reductions to dimensions of a linear nature were made throughout the model by the amount of the basic factor (Fiorentini *et al.,* 2004). The factor concerning drag resistance, which is dependent on surface area for its value, varies proportionally with the square of the velocity of water flow (Tauti, 1934). Weight and buoyancy forces that rely on volume for their value are reduced by the cube of the basic scale. The fundamental modeling rules may be summarized as follows:

$$L_m = \frac{L_f}{\lambda} \tag{16}$$

$$A_m = \frac{A_f}{\lambda^2} \tag{17}$$

$$F_m = \frac{F_f}{\lambda^3}\frac{\rho_m}{\rho_f} \tag{18}$$

λ, Linear scale factor; L, Length; A, Area; F, Force; ρ, Density; m, model; f, full-scale.

The velocity scale is given by:

$$V_m = \frac{V_f}{\lambda^{1/2}} \tag{19}$$

V: towing speed in m/s.

For a panel of netting to be a true scale model, both the mesh size and twine diameter should be scaled down by the scale factor (Tables 2 and 3). The number of meshes along and across each panel should be the same in the model as in the full scale (Fig. 8). The important parameters to scale correctly are twine surface area and panel length and width due to their effect on model drag and geometry. A model must therefore be used to select an appropriate model mesh size and twine diameter and correct the number of meshes.

In order to model twine surface correctly the ratio of twine diameter/mesh size must be the same in the model panel as found in the full scale panel:

$$\frac{D}{2A}(\text{fullscale}) = \frac{d}{2a}(\text{model}) \tag{20}$$

After the model twine diameter has been chosen from the options available, the appropriate model mesh size can be calculated.

$$2a = (2A \times d)/D \tag{21}$$

The number of mesh across and along each model panel can be calculated to ensure that the twine surface area and linear dimensions are modeled accurately.

$$n = (2A \times N)/(2a \times S) \tag{22}$$

n: number of meshes across or along the model panel

N: number of meshes across or along the full scale panel

2A: full mesh size in full scale net panel (knot center to knot center)

2a: full mesh size in model net panel (knot center to knot center)

S: scale factor (e.g., S= 80 for a scale of 1: 80).

Table 2. Full scale trawl properties scaled down by a factor for model

Properties	Scaling factor	Full gear	Model
Head Rope (m)	80 : 1	71.2	0.890
Side Rope (m)	80 : 1	66.7	0.834
Length of Bar (m)	80 : 1	7	0.0875
Net Length (m)	80 : 1	155.78	1.947
Mesh Size (m)	80 : 1	14	0.175
Twine Diameter (m)	80 : 1	0.012	0.00015
Area of Net (m^2):	64 : 1		
PE		268	4.19
PE+DY		161	2.5
Velocity (m/s)	9 : 1	1.5	0.17
		2.0	0.22
		2.5	0.28

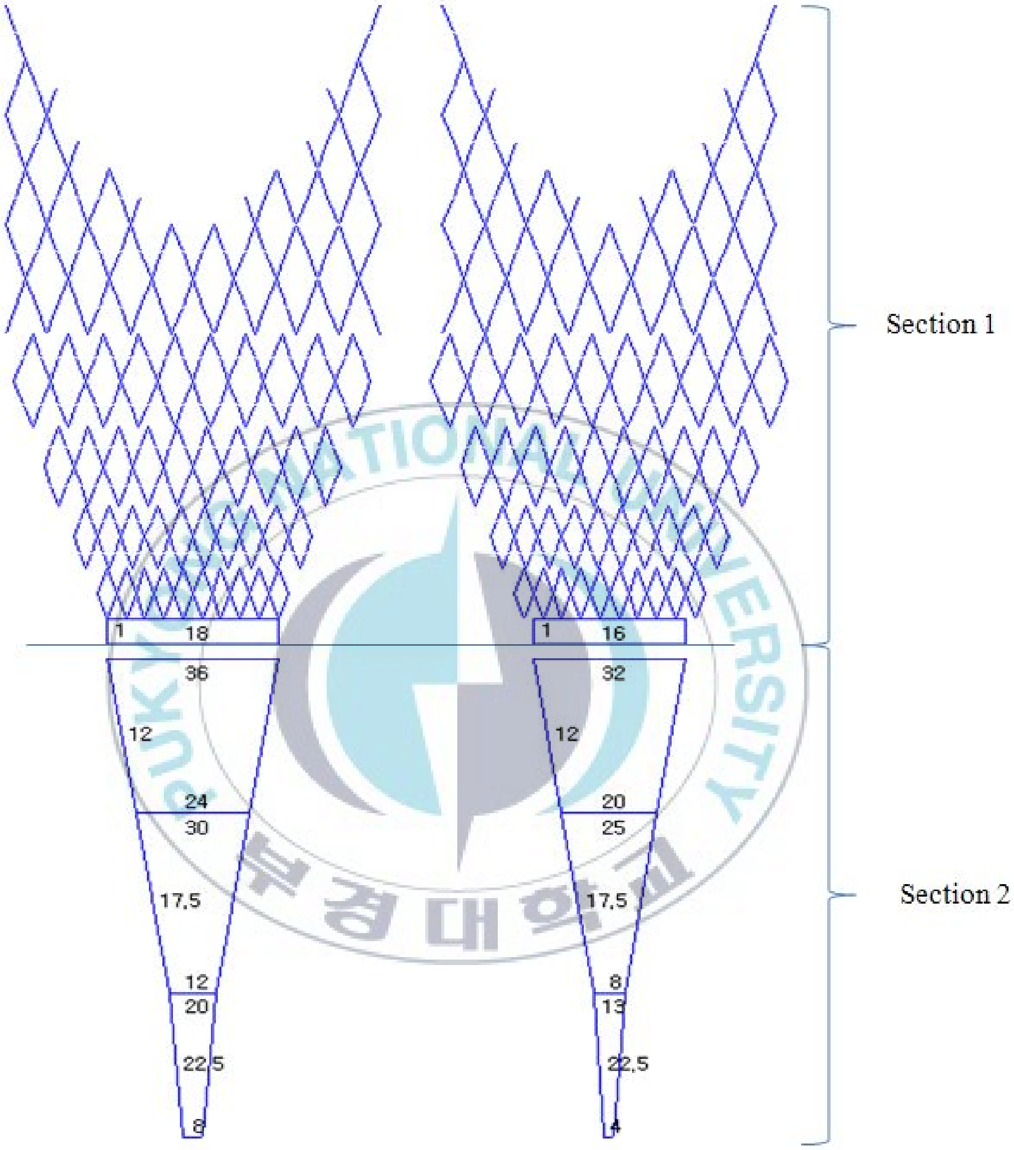


Fig. 8. Model gear divided into two sections.

Table 3. Model trawl panel properties

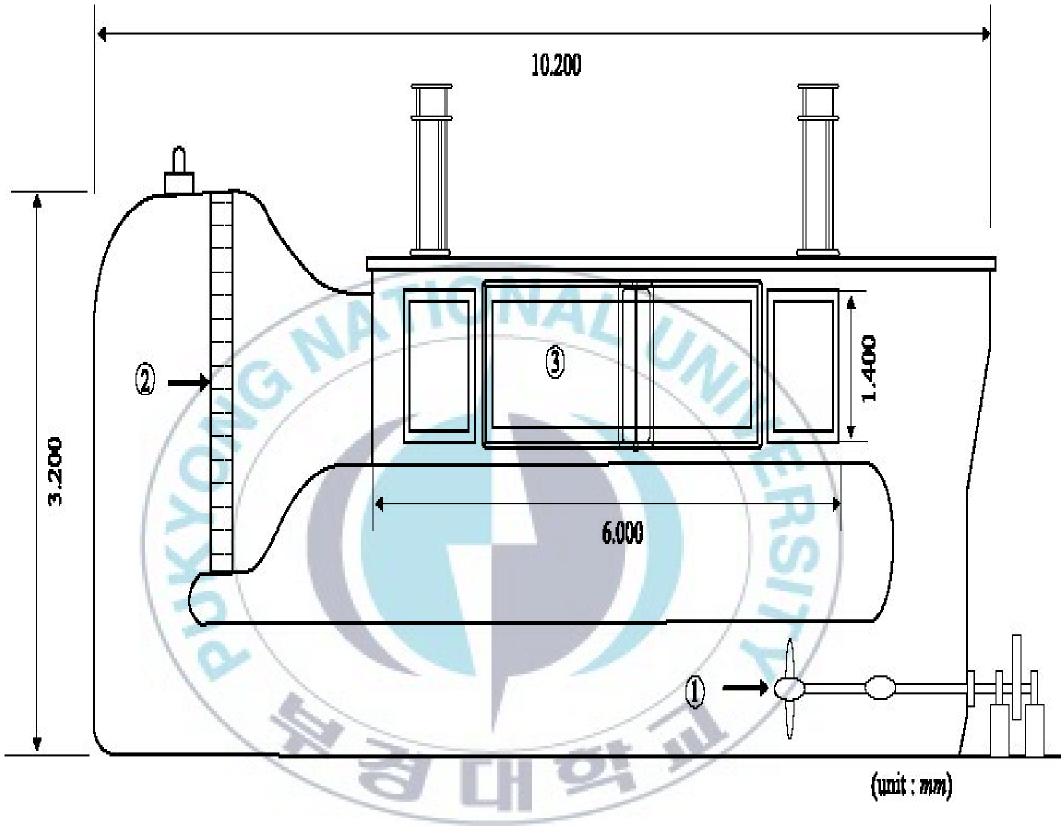
Nets		Knots	M.S (mm)	Head Panel		Side Panel		M.D	Diameter	Hanging Ratio
				Upper	Lower	Upper	Lower			
PE	Rope θ 0.14	knot	175	10	10	9	9	3	0.14	95
PE	Rope θ 0.12	knot	150	10	10	9	9	1	0.12	95
PE	Rope θ 0.12	knot	125	10	10	9	9	1	0.12	95
PE	Rope θ 0.12	knot	100	10	10	9	9	1	0.12	95
PE	Rope θ 0.12	knot	80	10	10	9	9	1	0.12	95
PE	Net θ 0.12	knot	40	18	18	16	16	1	0.12	95
PE	Net θ 0.12	knotless	20	36	24	32	20	12	0.12	95
PE	Net θ 0.23	knotless	16	30	12	25	8	17.5	0.23	95
PE	Net θ 0.28	knotless	10	20	8	13	4	22.5	0.28	95

2.5 Flume tank test

To check on the accuracy of the mathematical calculation of the simulated gear, we constructed a model midwater trawl and tested it in a 3D water circulating flume tank (10.2 m long x 3.2 m high x 2.8 m wide) equipped with a uniform current producing system at Pukyong National University, Busan, Korea (Fig. 9). The current producing capability ranges from 0.1 m/s to 1.2 m/s and flows along horizontal direction using circulating water channel system.

The flow velocities for the experiment were 0.17 m/s, 0.22 m/s and 0.28 m/s corresponding to respective full scale simulation towing speeds of 1.5 m/s, 2 m/s and 2.5 m/s. The water is circulated around the tank by a propeller driven by an electro-hydraulic system. The model trawls remained stationary when under test with the water flowing through and around them. They were worked from a platform above the tank, the warps being attached to towing points, adjustable in height and width, upstream of the working section.

Observation of the models in the tank was made through large glass windows in one side of the tank and from a motorized trolley which runs on rails along the top of the tank. Accurate measurement of vertical net dimensions was taken with a digitizer attached to the observation window. A digital camera was placed in front of the observable glass window to snap shots of the model trawls at different flow velocities. The flume tank was connected to a computer to analyze and record the drag.



①, Impeller; ②, Honey comb; ③, Observation window

Fig. 9. Schematic drawing of the flume tank.

3. RESULTS

3.1 Simulation

3.1.1 Otter board opening

The distance between the pair of otter boards increased gradually from 85 m at 1.5 m/s to 115 m (35%) at 2 m/s and 128 m (11%) at 2.5 m/s for PE+Dy netting. For PE netting, the distance rose from 70 m to 94 m (34%) but reduced slightly to 91 m (-3%) at towing speeds of 1.5 m/s, 2 m/s and 2.5 m/s, respectively. Comparing PE and PE+DY, the distance increased from 70 m to 85 m (22%) at 1.5 m/s, 94 m to 115 m (23%) at 2 m/s and 91 m to 128 m (41%) at 2.5 m/s (Fig. 10).

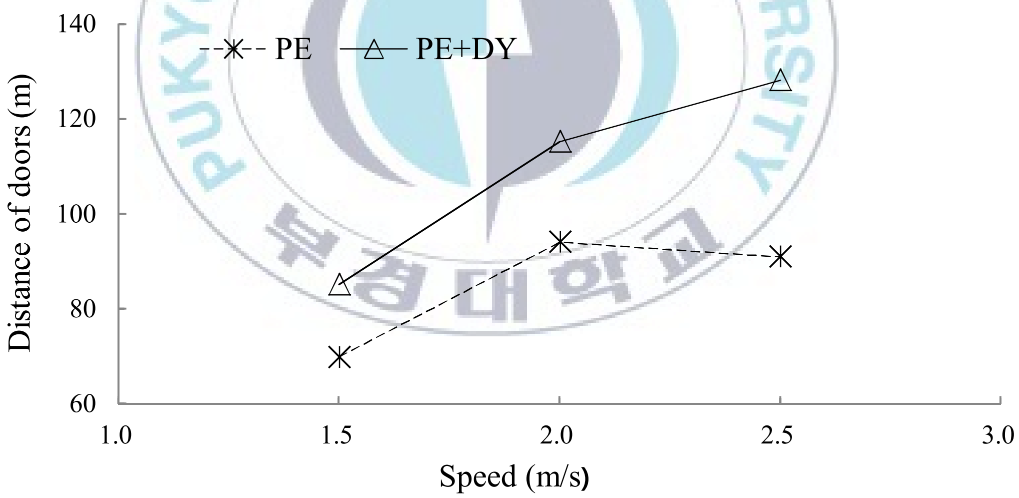
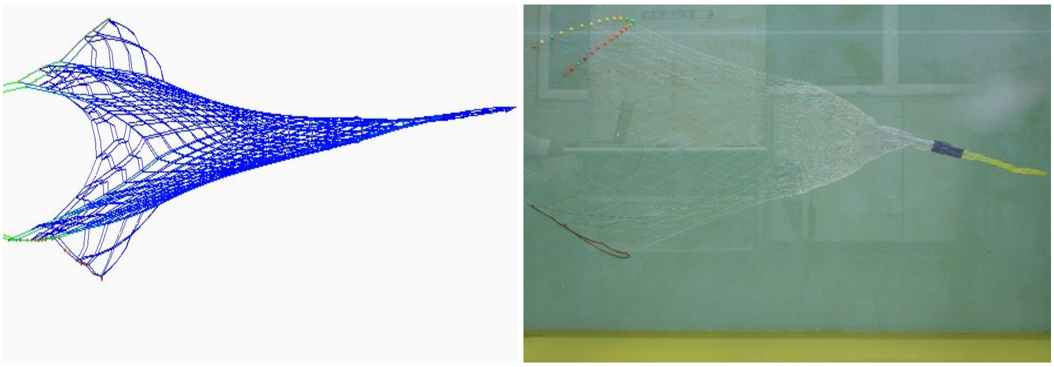
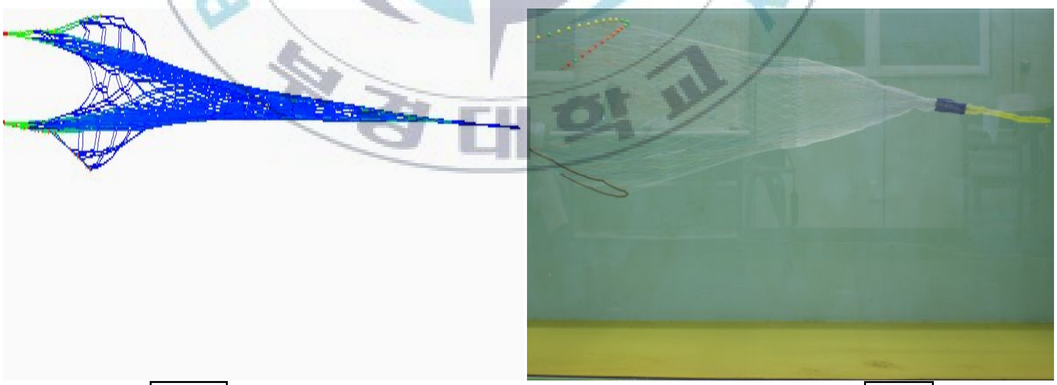


Fig. 10. Relationship between otter board openings and towing speed of PE and PE+DY with a 300 m warp length.



Speed: 1.5 m/s

Speed: 2.0 m/s



A Speed: 2.5 m/s B

Fig. 11. The Simulation shapes of PE (A) and Model tests of PE (B).

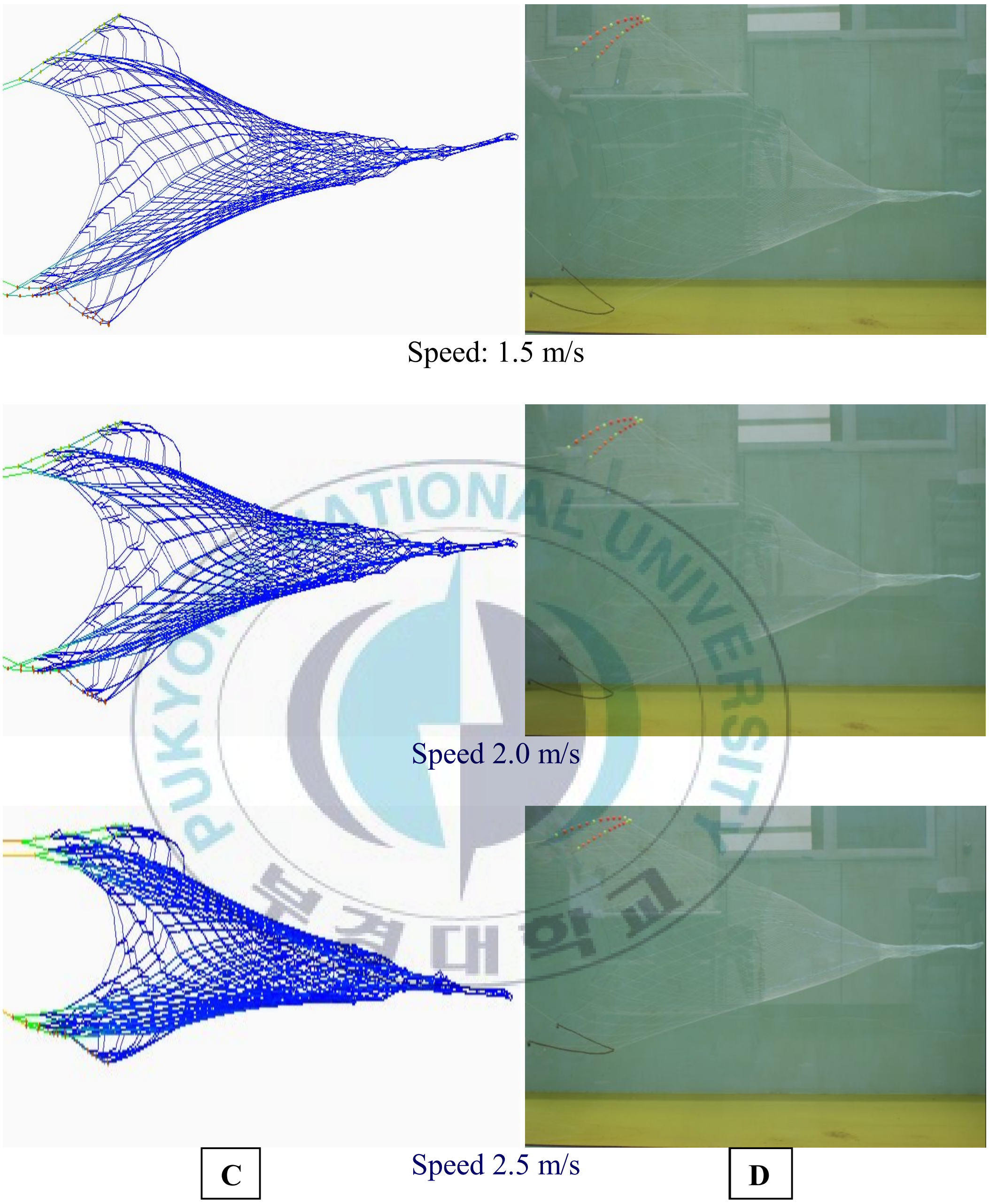


Fig. 12. The Simulation shapes of PE+DY (C) and Model tests of PE+DY (D).

3.1.2 Otter board depth

The depth of the otter boards declined sharply with an increasing towing speed from 1.5 m/s to 2.5 m/s for both PE and PE+DY. PE reduced by 27% (181 m to 133 m) from 1.5 m/s to 2 m/s and 23% (133 m to 103 m) from 2 m/s to 2.5 m/s. PE+DY also decreased by 23% (196 m to 150 m) from 1.5 m/s to 2 m/s and 2% (150 m to 119 m) from 2 m/s to 2.5 m/s. PE+DY, however, sank 15 m (9%) deeper than PE at 1.5 m/s, 17 m (13%) at 2 m/s and 16 m (16%) at 2.5 m/s (Fig. 13).

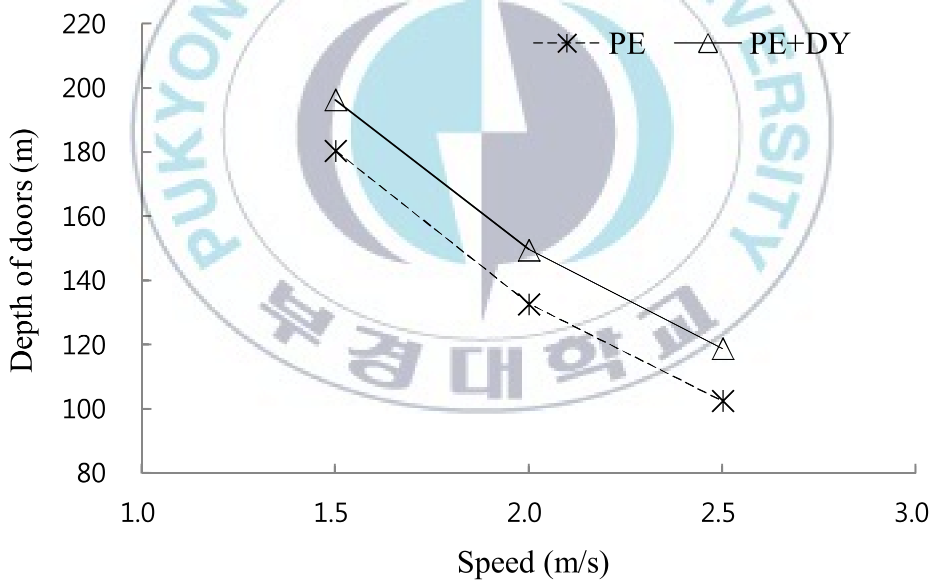


Fig. 13. Relationship between otter board depths and towing speed of PE and PE+DY with a 300 m warp length.

3.1.3 Width of net mouth

The width of the net mouth, which is directly related to the otter board opening, increased as the towing speed increased. For the PE net, the width opened from 20 m at 1.5 m/s to 28 m (40%) at 2 m/s and then leveled at 28 m for 2.5 m/s as well. PE+DY net rose from 28 m to 36 m (29%) when towing speed was increased from 1.5 m/s to 2 m/s and further increased to 40 m (11%) at 2.5 m/s. Comparatively, the width of PE+DY net opened 37% (20 m to 28 m), 29% (28 m to 36 m) and continued to increase by 43% from (28 m to 40 m) at 1.5 m/s, 2 m/s and 2.5 m/s respective towing speeds (Fig. 14).

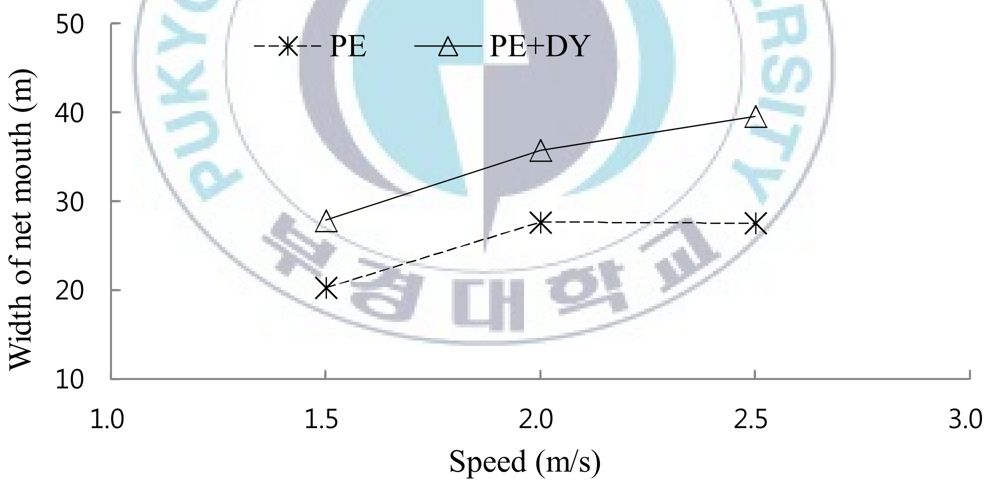


Fig. 14. Relationship between width of net mouth and towing speed of PE and PE+DY with a 300 m warp length.

3.1.4 Height of net mouth

The height of net mouth drastically reduced as the towing speed increased for both nettings. The PE net height, 44 m at 1.5 m/s, decreased to 31 m (30%) at 2 m/s and subsequently declined to 23 m (26%) at 2.5 m/s. PE+DY equally dropped from 53 m at 1.5 m/s to 38 m (28%) at 2 m/s and again went down to 28 m (26%) at 2.5 m/s. PE+DY net, however, showed a slight increase in the height of net mouth by 19% (44 m to 53 m), 25% (31 m to 38 m), and further rose by 24% (23 m to 28 m) at 1.5 m/s, 2 m/s and 2.5 m/s respectively (Fig. 15).

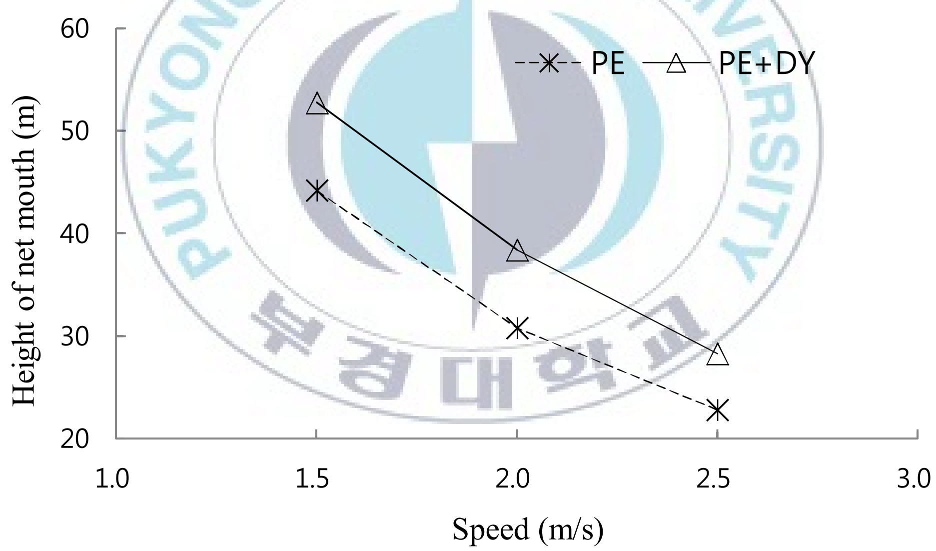


Fig. 15. Relationship between height of net mouth and towing speed of PE and PE+DY with a 300 m warp length.

3.1.5 Total drag

The drags of the gears were considered in sections. For section1, the drag of PE+DY was higher than that of PE by 14% at 1.5 m/s, 15% at 2 m/s and 44% at 2.5 m/s. Section 2, on the contrary, had the drag of PE+DY reduced compared to PE by 38%, 46% and 48% at 1.5 m/s, 2 m/s and 2.5 m/s respectively. The drag for the net plus bridle of the PE+DY net equally declined compared to PE by 20% at 1.5 m/s, 31% at 2 m/s but only 13% at 2.5 m/s. The total drag of the PE+DY trawl net compared to that of PE net also reduced by 10%, 18% and 13% at 1.5 m/s, 2 m/s and 2.5 m/s towing speeds respectively (Table 4).

Table 4. Drag at different sections of the trawl gear

Material	Speed	Section 1	Section 2	Net and bridle	Total drag
PE	1.5	1,545	3,711	6,093	9,603
PE+DY		1,758	2,290	4,878	8,632
PE	2	2,416	6,434	10,877	13,875
PE+DY		2,785	3,489	7,459	11,327
PE	2.5	3,272	9,720	14,375	18,192
PE+DY		4,722	5,043	12,078	15,756

3.1.6 Warp length

The results of the PE+DY net showed that as the length of warp gets longer, the intervals of the otter boards as well as the width of net mouth gets larger while the fishing gear gets deeper. The otter board distance increased by 12% from 250 m to 300 m and 11% from 300 m to 350 m. The depth of the doors got depeer by 15% at both 300 m and 350 m. The width of net mouth rose by 9% from 250 m to 300 m and 6% at 350 m. The net mouth height reduced by 3% at both 300 m and 350 m warp lengths. The total drag of the gear increased by 6% from 250 m to 300 m and 6% from 300 m to 350 m (Table 5).

Table 5. The results of simulation of PE+DY net in accordance with the changes in the warp length with 2 m/s towing speed

Warp length (m)	Distance of doors (m)	Depth of doors (m)	Width of net mouth (m)	Height of net mouth (m)	Total drag (kgf)
250	103	127	33	39	10,696
300	115	150	36	38	11,327
350	128	172	38	37	12,023

3.1.7 Total buoyancy

The shape of the fishing gear changes with the change in design parameters of the fishing gear. As the buoyancy increased from 1722 (N) to 2435 (N), the height of mouth elongated by 8% and then further increased by 10% with a buoyancy of 3148 (N). The width declined by 3% as the buoyancy increased to 2435 (N) and also to 3148 (N). Depth of doors equally reduced by 3% with buoyancy 2435 (N) and 2% with 3148 (N). Distance of doors decreased by 2% from 1722 (N) to 2435 (N) and by 3% with 3148 (N). Total drag increased by 4% with 2435 (N) and by 2.5% with 3148 (N) (Table 6).

Table 6. The results of simulation of PE+DY net in accordance with the changes in the total buoyancy with 2 m/s towing speed

Total bouyancy (N)	Distance of doors (m)	Depth of doors (m)	Width of net mouth (m)	Height of net mouth (m)	Total drag (kgf)
1722	115	150	36	38	11,327
2435	113	146	35	41	11,743
3148	110	143	34	45	12,034

3.1.8 Area of door

When the area of door was increased from 4.5 m^2 to 5.1 m^2, the distance of the otter board increased by 8%, and further increased to 6% at 5.7 m^2. The depth also increased by 5% and 1% with increase in area of door from 4.5 m^2 to 5.1 m^2 and then to 5.7 m^2 respectfully. Net mouth width increased by 3% for both 5.1 m^2 and 5.7 m^2. Total drag of the gear rose by 12% and 3% with 5.1 m^2 and 5.7 m^2, respectively (Table 7).

Table 7. The results of simulation of PE+DY net in accordance with the changes in the area of door with 2 m/s towing speed

Area of door (m^2)	Distance of doors (m)	Depth of doors (m)	Width of net mouth (m)	Height of net mouth (m)	Total drag (kgf)
4.5	115	150	36	38	11,327
5.1	124	157	37	38	12,642
5.7	132	159	39	37	13,030

3.2 Model test

3.2.1 Height of net mouth

The net mouth height of both PE and PE+DY models declined as current speed increased from 1.5 m/s to 2.5 m/s. Comparing the two models, height of PE+DY model opened wider than that of PE by 23%, 26% and 40% at 1.5 m/s, 2 m/s and 2.5 m/s respective speeds (Fig. 16).

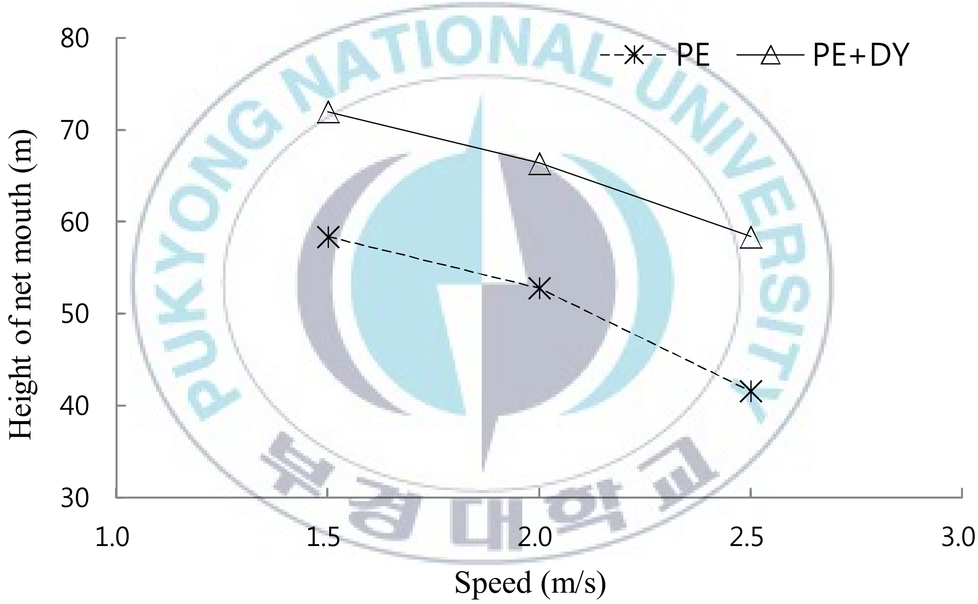


Fig. 16. Relationship between height of net mouth and towing speed of PE model and PE+DY model.

3.2.2 Drag

Model drag increased with an increasing speed for both models. The PE+DY model drag, however, reduced by 23%, 21% and 23% compared to PE model drag at speeds of 1.5 m/s, 2 m/s and 2.5 m/s, respectively (Fig. 17).

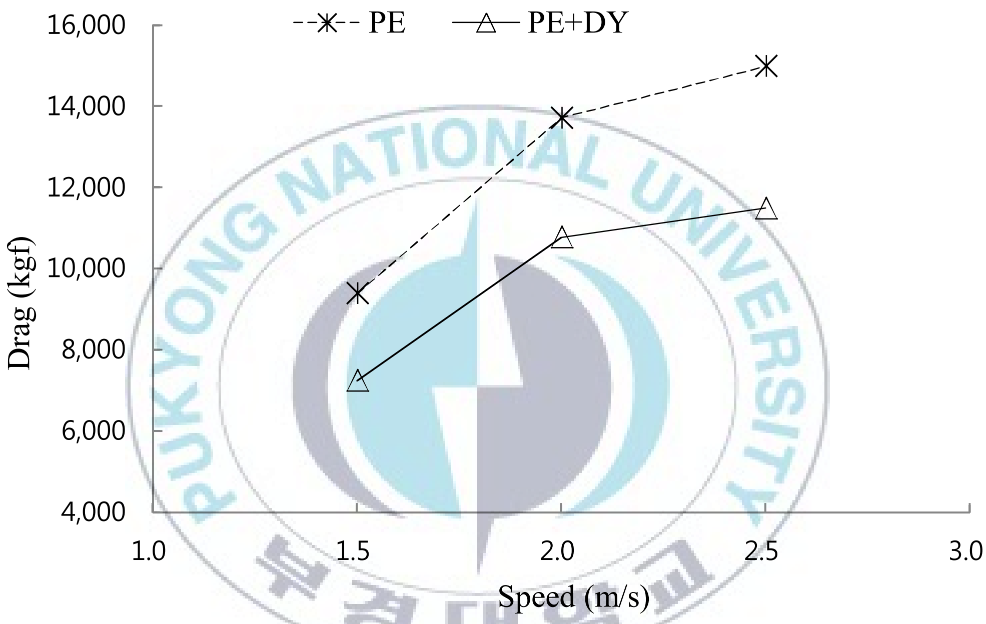


Fig. 17. Relationship between drag and towing speed of PE model and PE+DY model.

3.3 Comparison between Simulation and Flume tank models

3.3.1 Height of net mouth

The heights of PE simulation and its model reduced with increasing towing speed from 1.5 m/s to 2.5 m/s. The model height was higher than that of the simulation by 32%, 71% and 82% at towing speeds of 1.5 m/s, 2 m/s and 2.5 m/s, respectively (Fig. 18). For PE+DY, the model height equally opened higher than the simulation by 36%, 73% and 106% as speed increases from 1.5 m/s to 2.5 m/s (Fig. 19)

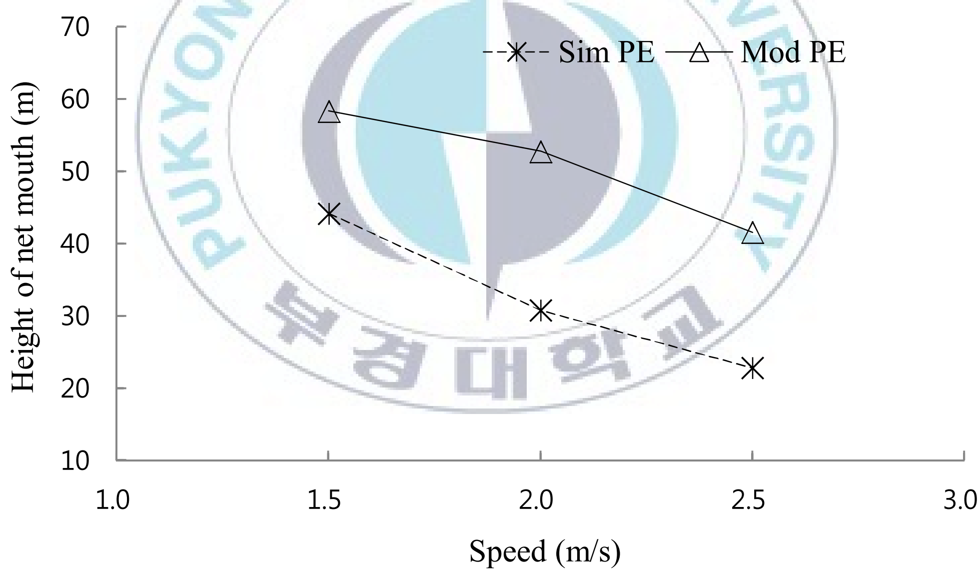


Fig. 18. Relationship between height of PE simulation and PE model and towing speed.

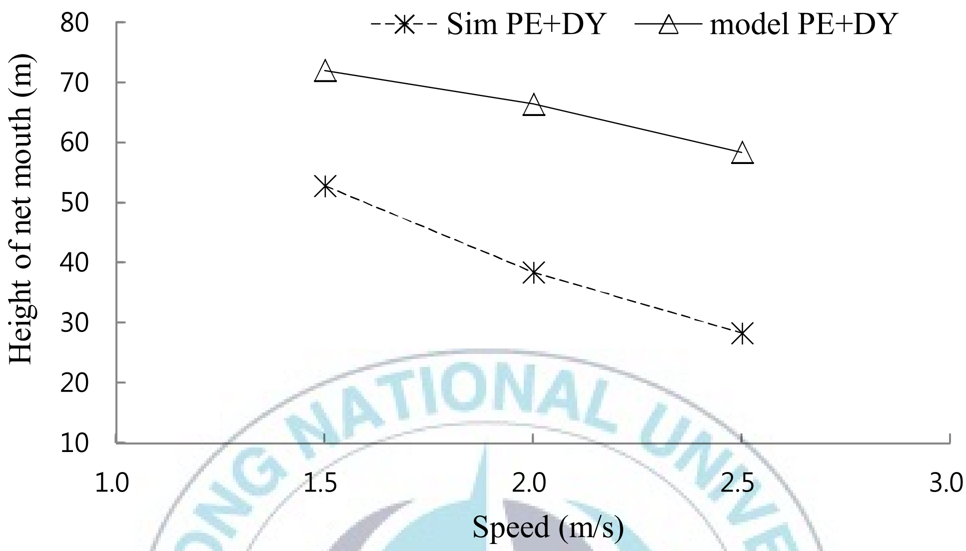


Fig. 19. Relationship between height of PE+DY simulation and PE+DY model and towing speed.

3.3.2 Drag

Drags of PE simulation and its model both increased with increasing speed but the simulation drag inclined steeper. The simulation drag reduced by 54%, 26% and 4% compared to the model drag at 1.5 m/s, 2 m/s and 2.5 m/s respectively (Fig. 20). The PE+DY simulation sharply increased while its model increased slightly with increasing speed. The model drag increased by 49%, 44% but reduced by 5% at 1.5 m/s, 2 m/s and 2.5 m/s respectively.

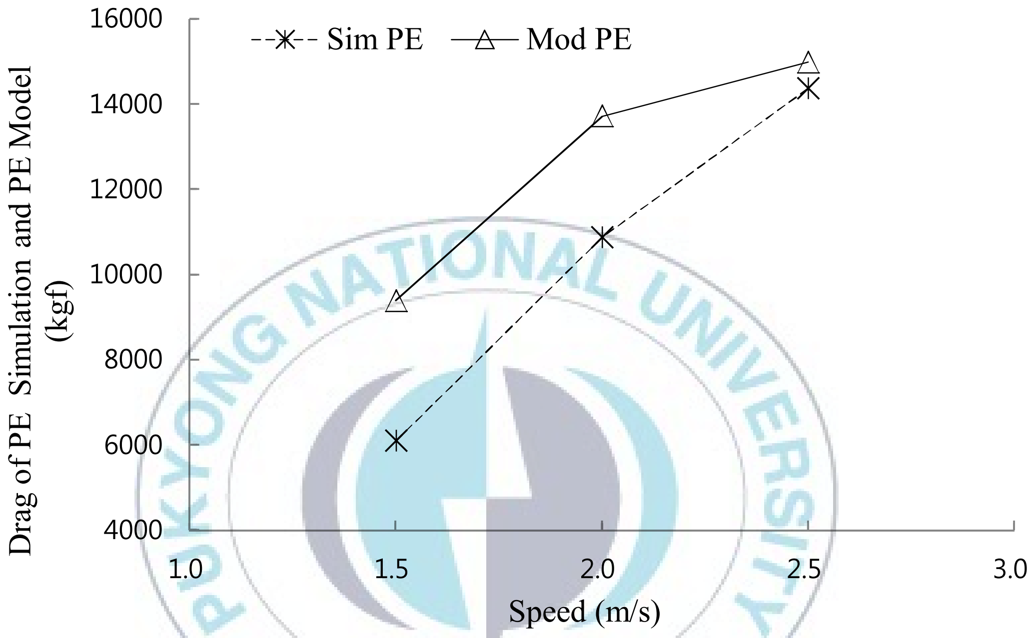


Fig. 20. Relationship between towing speed and drag of PE simulation and PE model.

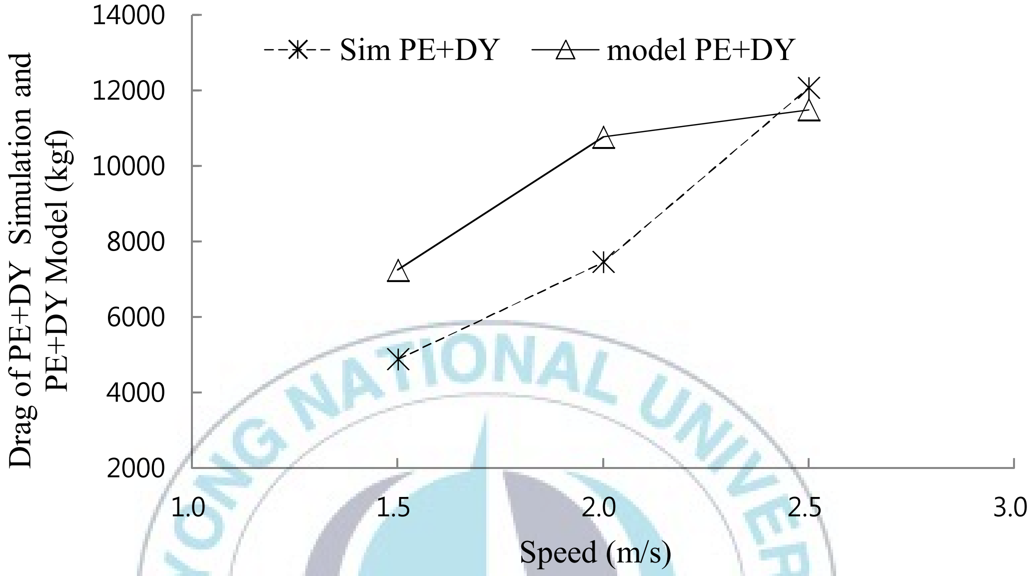


Fig. 21. Relationship between towing speed and drag of PE+DY simulation and PE+DY model.

4. DISCUSSION

The interaction between a net structure, a fishing vessel, rigging, warps and other trawl elements connected together are complex. An importance of flow velocities and pressures estimation both around and in trawl consists in an exclusive dependence of the forces acting on each part of the trawl system. The knowledge of these forces allows defining the shape, drag and behavior of the structure during a trawling process, drag and loads in its twines and ropes. Therefore, the main design requirements for the midwater trawls are high stability, large mouth opening, low turbulence and low drag (Hameed and Boopendranath, 2000).

According to Ferro (1981), incorrect weights or trawl boards used on a net can prevent the forming of a square opening of the mouth and this cause distortion of the net itself with an area of slack or strained netting causing net damage or fish escape. In this study, however, the buoyancy of the floats of the simulated gears balanced with the sinking force of the sinkers and this ensured effective opening of the net mouth. The buoyancy force was later increased to ascertain its effect on the fishing gear, because the shape of the fishing gear changes with the change in design parameters of the fishing gear. It was realized that the height of mouth elongated and the drag as well increased as a result of the increament.

The fishing gear in this study was designed with large meshes of 14,000 mm in the first panel and was reduced gradually from one panel to the other until 60 mm at the codend (the minimum mesh size for trawl gears as stipulated in the Ghanaian Fisheries Act 625, 2002). These large meshes conformed with Gabriel *et al*. (2005) who discussed the use of large mesh sizes in front parts of the trawls and concluded that increasing large meshes has a good guiding effect without losing the effectiveness of the trawl. An increase in the mesh size decreases the total trawl resistance, reduces the weight of rigging needed and possibly increases trawling speed (Fridman, 1986). The trawl netting also promotes the herding effect in fish (Glass *et al*., 1995). The fish rarely swim through the mesh located in the part of the trawl body near the opening (Gabriel *et al.,* 2005). The smaller mesh at the rear part of the trawl (codend) serves as a mechanical sieve to prevent fish of similar and larger girth from escaping.

The matching of towed net depth to fish school depth and the dynamic stability of the midwater trawl gear are the most important factors in determining catching efficiency. The depth of the midwater trawl net is fundamentally determined at the point of balance between the trawl gear's weight and resistance in water. It is a function of the trawl gear's weight, hydrodynamic resistance, the towing speed of the gear and the length of warp. The depth of the gear can be controlled by changing the warp length and sometimes by changing the towing speed. The control of depth is done by heaving in the warp when the trawl gear is below the depth of a target fish school or increasing warp when the trawl gear is above the depth of fish school.

The exact length of warp to be reduced or increased cannot, however, be determined consistently because it varies according to the surrounding circumstances, the size of the trawl gear, the amount of catch and the oceanic factors. The 300 m warp length used in this study was reduced to 250 m and also increased to 350 m to determine its effect on the drag of the fishing gear. It was realized that the total drag of the gear increased by the same percentage from 250 m to 300 m and also from 300 m to 350 m.

A single vessel midwater trawl makes it necessary to use otter boards for spreading the net horizontally (Gabriel *et al.,* 2005). Hameed and Boopendranath (2000) reported that otter boards are rigid sheer devices which are used to keep the trawl mouth, bridles and warps horizontally open. The weight on the foot rope and the sweep lines determine the vertical mouth opening while the size of the trawl boards determines the horizontal spread of the net mouth. The otter board of

PE+DY opening ranged between 22% and 41% wider than that of the PE net mouth opening as the towing speed increases. The width of the net mouth of PE+DY net equally increased by 29% to 43% compared to that of the PE net. This eventually widens the swept area of the net and therefore the net has a higher possibility of catching more fish.

One of the major factors influencing fish catch is the vertical opening of the net. Large modern midwater trawls are rigged in such a way that the weights in front and along the ground line provide for the vertical opening of the trawl (FAO, 2008). The otter board depth of PE+DY net, which has a direct relationship with the height of net mouth, increased between 9% and 16% deeper than that of PE net. The height of the net mouth of the simulation of PE+DY netting had higher opening of 19% to 25% than that of the PE netting. The same trend was recorded in the flume tank where height of PE+DY model opened wider than PE model by 23% to 40% as speed increases. By comparing simulation and model test, it was evident that the model heights in both PE and PE+DY were slightly higher than their respective simulation heights.

Fuel consumption during fishing is a primary concern due to environmental effects and operating costs. The consumption is generally related to hydrodynamic resistance on the gear. The drag in this study increased with an increase in towing speed from 1.5 m/s to 2.5 m/s and this supported Lee and Lee (2000) who indicated that the drag of a trawler changes linearly with towing speed. The drag of the simulated PE+DY gear (including bridles) was reduced by 16% to 31% of the PE drag. This results is slightly lower than 49% recorded by Lee *et al.,* (2012). The PE+DY model test likewise recorded a reduction in drag between 20% and 23% confirming that the replacement of PE netting with "Dyneema" netting has yielded in the reduction of drag resulting in cutting down of cost on fuel consumption, i.e. an energy-efficient trawl.

One advantage of the flume tank testing of a model is that the design defects are clearly visible in the flume tank and it does not require more questioning. One can clearly examine the effects of alterations to the design and rigging, effect of towing speed on geometry and orientation and measuring forces acting on the gear, and to measure motions of fishing gear. It is, however, much more complex viewing the results of the simulation.

5. CONCLUSION

The dynamic simulation by the mass-spring model showed the status of the gear such as fishing gear depth, distance of otter boards, and shape of the gear and drag of each line. It depended on the parameters such as towing force, warp length, force of a sinker, buoyancy of a float, type of otter board and netting materials. First, the development of a simulation required modeling of the system. Next, a stable and exact calculation of the nonlinear model was calculated. Finally, the validity of the mathematical model was verified via comparisons of numerical solutions derived from the mathematical model and the results of flume tank experimental models.

The heights of the net mouth of both the simulation and the model of PE+DY netting had higher openings than the heights of both simulation and the model of PE netting respectively. Also, there were reductions in the drags of both simulation and model of PE+DY netting compared to their respective drags in both simulation and the model of PE netting. These results support the hypothesis which states that replacing a polyethylene midwater trawl gear with "Dyneema" netting material, half the diameter of polyethylene netting twine, from the 7^{th}

panel to the 20th panel (codend) will yield a higher height of net mouth opening and lower drag.

If a computer simulation model is established according to this procedure, the simulation can then be used to estimate the behavior of the fishing gear and verify the performance of the fishing operation. This approach can help to reduce the expense and time required to improve existing fishing gear or develop new gear. This type of gear should be highly useful for the Ghanaian small pelagic fisheries. We, however, recommend a full scale test of the fishing gear during trawling as a further study.

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