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RESEARCH ARTICLE

Experimental Study of the Effect of a Solid Wing Conveyor on Marine Debris Collection

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Abstract

Marine debris is a global problem that has not been resolved. This has encouraged the emergence of marine debris cleaning technologies, one of which is a conveyor ship. However, how effective conveyors are in collecting waste has not been studied. In this paper, experimental research on conveyors as marine debris collectors is investigated. The capability of catamarans with or without solid wing conveyors to collect marine debris is explored. Three kinds of marine debris collection models are used: no-wing conveyor, a 12.5-cm-long wing conveyor, and an 18.75-cm-long wing conveyor. Artificial marine debris (AMD) is spread on the water surface in a static tank. Then, a marine debris collector model is pulled using threads tied to the ship's body. This is done several times starting from a low speed and progressing to a high speed. After the experiment, the effectiveness of marine debris collection from these three models is analysed. In addition, the cause of marine debris not being caught by the model is investigated. This work proposes a new approach to evaluate the effectiveness of conveyer wings in marine debris collection. Based on AMD movement pattern analysis, it is suggested to operate the device at a low speed because the collected AMD ratio is high and the lost AMD ratio is small.

Keywords: Solid wing, Conveyor, Catamaran, Collection, Marine debris

1. Introduction

Marine debris is a problem for all countries and it must be addressed immediately [1]. Many countries try to figure out the best solution to this issue by meetings, conferences, and forum group discussions. Marine debris can be found in several different locations such as ecosystems [2], inhabited coastal areas and islands [3], rivers [4], and deep oceans [5]. Borrelle et al. [6] estimate that 19−23 million metric tons, or 11% of plastic debris generated globally in 2016, entered marine areas, including marine ecosystems. Every year about 8 million metric tons of plastic debris ended up in the ocean and degraded the Ocean Health Index [7−9]. There are 275 million metric tons of debris dumped into the sea from 192 coastal countries [10], and 86% of this pollution comes from Asian rivers [11].

Coastal areas are the first marine systems impacted by anthropogenic pollution, which poses a particularly negative impact on the environment [12]. Other marine debris is also found on the beach and at sea, namely heavy metals that are harmful to the environment [13]. In addition, research on the effects of marine pollution due to port activities on public health shows that this pollution poses a serious threat to human health [14]. This situation has spurred the governments of many countries and international organisations to make ambitious commitments to reduce marine debris. Several countries have made regional as well as national action plans to control debris from terrestrial areas. This also includes enhancing technology and systems.

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Researchers have reviewed technologies to prevent and collect plastic pollution [15]. They reported 52 technologies focussing on plastic pollution prevention and collection methods. Technologies are classified based on their functions: they are targeted to collect macroplastics, microplastics, or other plastics. Few technologies attempt to prevent leakage of plastic pollution, and technologies that have done so are limited in scope. A review of technologies to prevent or reduce marine plastic litter in developing countries has also been carried out [16]. The authors used a platform called 'GreenHouse' that was set up by Ubuntoo. The was authors reported the majority of currently available technologies for collection.

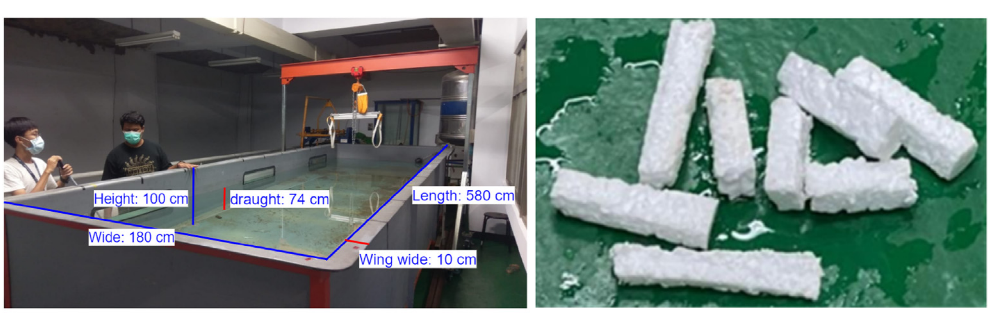
The marine debris clean-up concept of 'why move through the ocean if the ocean can move through you?' was proposed by Boyan Slat, CEO of the Ocean Cleanup Foundation. It developed a floating device to collect marine debris in the Great Pacific garbage patch [17]. Similarly, researchers have discussed passive ocean plastic collection under rough sea conditions, considering the ocean current speed, wave height, wave length, and plastic density. The results indicate that the wave length and plastic density have a negligible effect on the capture rate. In contrast, the effects of the other two parameters are significant [18]. Ji et al. [19] investigated ocean surface cleaning systems using a mooring system and motion gauges, an approach that is applicable in various marine locations. Their results denote that the system's motion response in the vertical plane is small, indicating that marine debris is unable to escape from the top and bottom of the system [19]. However, these previous studies can only be applied in locations that have large currents and waves; the idea is not applicable to locations without currents and waves such as lakes, sedentary rivers, and other calm waters. Consistently, this research does not relate to ships and conveyors or to the effects that appear due to changes in wing dimensions. Hence, experimental research on conveyors as marine debris collectors is rare. In addition, no researchers have discussed the effectiveness of a wing conveyor in marine debris collection. So, in this work experimental research has been conducted to investigate the effectiveness of catamarans with or without solid wing conveyors to collect marine debris. Furthermore, the analysis has been carried out to determine why marine debris is not caught by the wing conveyor, and future directions are proposed to improve this research.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

The experiments were carried out in a static tank at the Department of Systems and Naval Mechatronic Engineering, National Cheng Kung University; The dimensions are a total length of 5.8 m, a width of 1.8 m, a height of 1 m, and a water depth of 0.7 m (Fig. 1a). The standard size of a water bottle is 500 ml and measures 60 mm in diameter and 200 mm tall. However, the volume can range from 237 ml all the way up to 1 l [20]. Plastic bottles are the most abundant type of marine debris and are found throughout the world's oceans. This is a major concern because plastic stays in the oceans for a long time [21]. Plastic bottle waste found in waste disposal has a length from 75 to 200 mm, while the diameter ranges from 200 to 500 cm [22]. The size of marine debris varies from micrometres to tens of metres. The size distribution of floating plastic waste found in calm sea conditions is 0.25–1000 mm in length [23]. So, the average size of marine debris used for this experiment was 300 mm tall and 90 mm wide. To replace the original marine debris, artificial marine debris (AMD) was used; it was spread over the water surface in static tanks. The AMD to marine debris scale is 1:8. The AMD was about 3–5 cm long and 1–1.5 cm wide (Fig. 1b).

Eighty pieces of AMD were spread on the water surface of the static tank. AMD deployment was



(a) (b)

Fig. 1. Experimental apparatus: (a) static tank and (b) artificial marine debris.

done freely, with no rules. This was done to resemble the real conditions of marine debris in the sea. The water in the tank was calm. At the beginning of the experiment, there were no waves at all due to wind and current. After beginning the experiment, small waves were formed on the water surface as a result of each model's movement.

2.2. Experiment

Three models were used in this experiment. They are catamarans with conveyors without wings, catamarans with 12.5-cm-long wing conveyors, and catamarans with 18.75-cm-long wing conveyors (Fig. 2). The catamaran has an inner flat hull with a static conveyor between the two hulls. The angle between the wing and the conveyor is 45°. The cross-section area of the wing is 37.7 cm^2 for the 12.5-cm-long wings and 55.5 cm^2 for the 18.75-cm-long wings. The detailed specifications of the instruments used are given in Table 1. The conveyor and wing were constructed at a 1:8 scale. The catamaran model is made of wood, while the conveyor is made of Styrofoam, and the solid wing is made of plastic.

2.3. Experimental procedures

The procedures were carried out on the three models. As shown in experimental setup in Fig. 3a, the catamaran model and the wing conveyor were pulled manually using a thread fixed in the centre of the model. In addition, two other threads were attached to each sides of the model to ensure a straight screening path. AMD deployment was done freely, with no rules (Fig. 3b). This research was conducted in calm water conditions before the model was pulled. The force used to pull each model was not same; thus, each model had a different speed. A limitation of this study is that while each model moved the same distance, each one took a different amount of time to move that distance. Each model was pulled with five speed variations ranging from low to high. The velocity was determined by dividing the time during which the model moves by the path length.

Table 1. Detailed specifications of the model.

Parameter	Model
Length between perpendicular (cm)	50
Breath (cm)	37
Draft (cm)	2.5
Separation ratio S/L	18/50
Conveyor wide (cm)	18
Conveyor length (cm)	10
Conveyor thickness (cm)	1.5
Wing length (cm)	12.5, 18.5
Wing height (cm)	3
Wing thickness (cm)	0.4
Wing angle (degree)	45
Cross section area of wing (cm^2)	37.7, 55.5

3. Experimental results and discussion

This section describes the recorded (observed and measured) results for pieces of AMD collected, pieces of AMD in the sail zone, the collected AMD ratio, the pieces of collected AMD in the sail zone area, the pieces of AMD collected relative to all pieces of AMD in the static tank, and the AMD lost ratio. In addition, an analysis has been conducted to

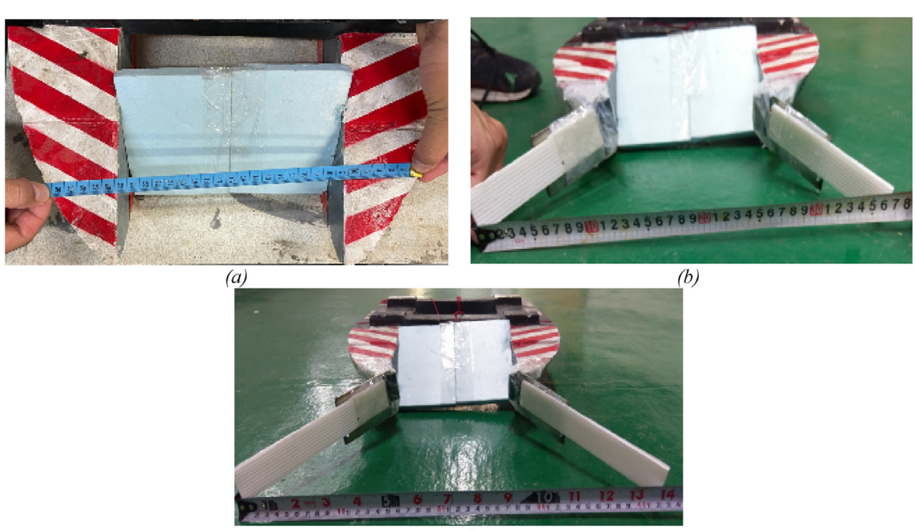


Fig. 2. Ship and conveyor model: (a) no-wing conveyor, (b) 12.5-cm-long wing conveyer, (c) and 18.75-cm-long wing conveyer.

(a) (b)

Fig. 3. Experimental procedures: (a) experiment setup and (b) initial conditions.

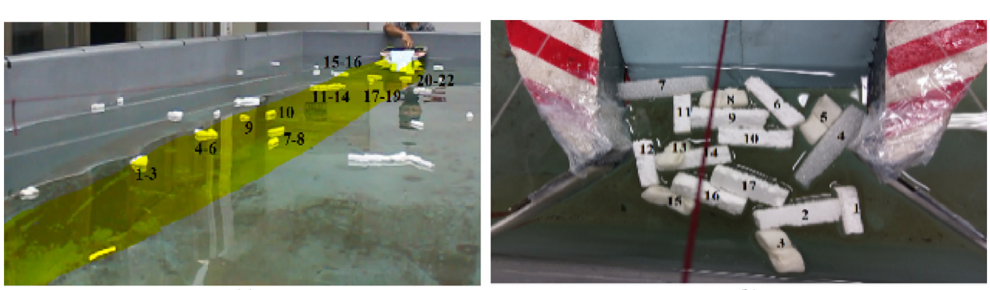
determine why AMD was not caught by the catamaran with or without a wing conveyor.

3.1. AMD collected

The data obtained were the pieces of AMD collected at each speed and the pieces of AMD in the sail zone. The sail zone is area where the model moves (yellow area in Fig. 4a); this area is the water surface area swept by the wing conveyor. Before pulling the model and commencing the experiment, water in the sail zone is calm and it contains many pieces of AMD. There were five speed variations – from low to high – for the no-wing conveyor model and the 12.5-cm-long wing conveyor model when collecting AMD. However, the 18.75-cm-long wing conveyor model had six different speeds (from low to high) when collecting AMD. Figure 4b shows an example of pieces of AMD collected by the model.

A comparison graph of the number of AMD collected at low to high speed is shown in Fig. 5a. AMD collected by the three models does not have the same pattern. For the no-wing conveyor and 12.5-cm-long wing conveyor models, the higher the speed, the less AMD is collected. Meanwhile, for the 18.75-cm-long wing conveyor model, the amount of collected AMD does not show a linear pattern relative to speed. The 18.75-cm-long wing conveyor model collects the least AMD, while the 12.5-cm-long wing conveyor and no-wing conveyor models collect the most AMD.

The faster the speed, the less debris is collected, but it takes less time to collect the debris, and multiple collections can be carried out over a fixed time. So, it is better to compare the amount of garbage collected quickly and slowly over a certain period of time or at the same speed, because the sail distance of all models is the same. By comparing the amount of AMD collected at 0.3 and 0.4 m/s, the 18.75-cm-long wing conveyor model collects the most AMD, followed by the 12.5-cm-long wing conveyor and no-wing conveyor models (Fig. 5a). However, at 0.4 m/s, the 12.5-cm-long wing model and the no-wing model collect almost the same amount of AMD. At 0.4 m/s, the AMD in the sail zone is also almost the same for the 12.5-cm-long wing conveyer and no-wing conveyer models. This corresponds to the AMD in the sail zone before the model moves (Fig. 5b). At 0.3 and 0.4 m/s, the 18.75-cm-long wing conveyor model collects the most



(a) (b)

Fig. 4. AMD position: (a) in the sail zone and (b) collected AMD.

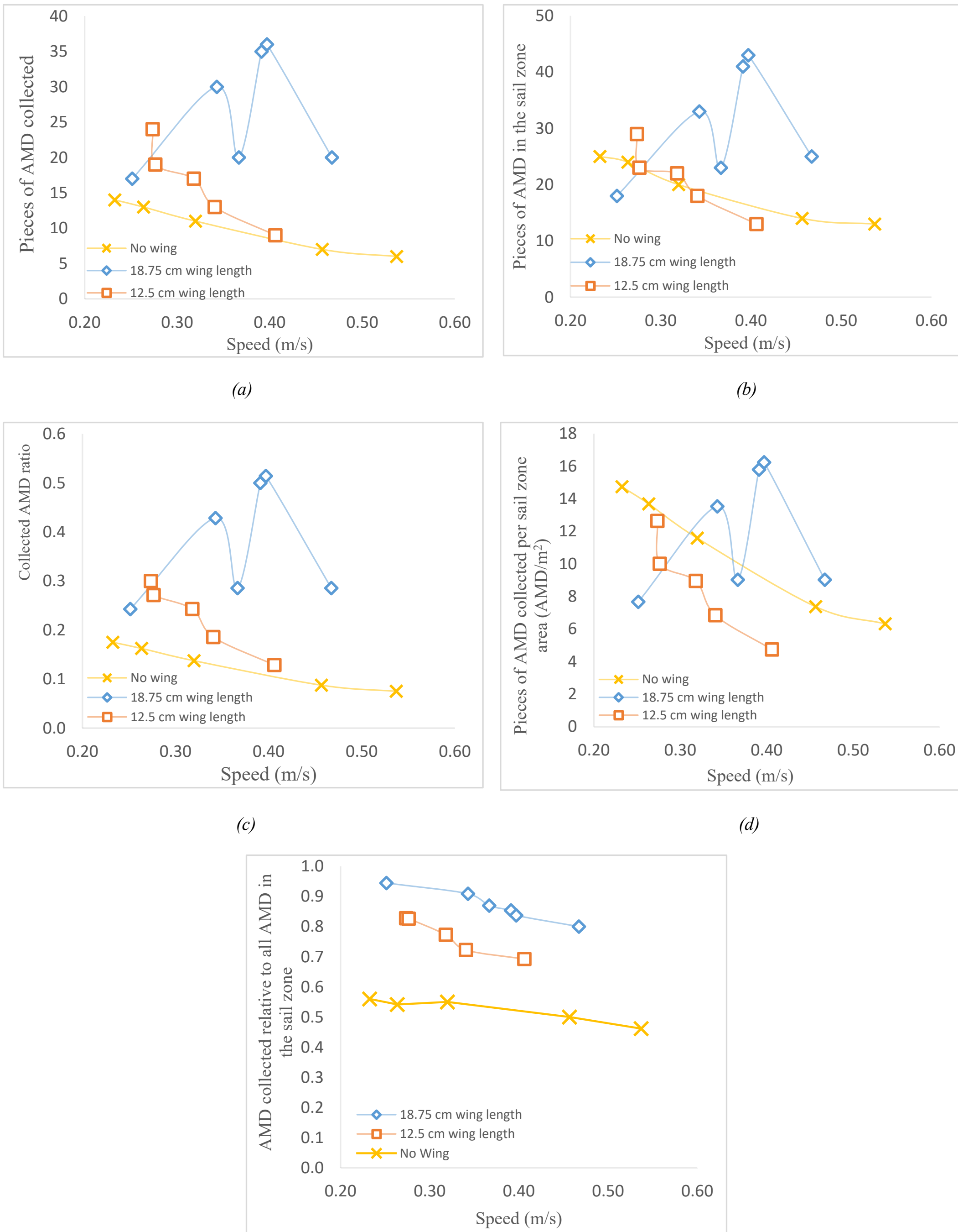


Fig. 5. Comparison of AMD collected in some experimental conditions: (a) pieces of AMD collected vs speed, (b) pieces of AMD in the sail zone vs speed, (c) collected AMD ratio (pieces of AMD collected relative to all AMD in the static tank) vs speed, (d) pieces of AMD collected per the sail zone area vs speed, and (e) AMD collected relative to all AMD in the sail zone vs speed.

AMD in the sail zone, followed by the 12.5-cm-long wing conveyor and no-wing conveyor models.

The AMD in the sail zone varies across all model speeds. For the no-wing conveyor and 12.5-cm-long wing conveyor models, the higher the speed, the less AMD in the sail zone (Fig. 5b). On the other hand, for the 18.75-cm-long wing conveyor model, the AMD in the sail zone changes depending on the speed. Hence, the AMD in the sail zone in the three models is different because the sail zone width is different. The longer the wing conveyor, the wider the sail zone. However, because AMD spreads freely, a wider the sailing zone does not necessarily mean there is more AMD in the sail zone.

Figure 5c shows the collected AMD ratio: the AMD collected relative to all AMD in the static tank. For the no-wing conveyor and the 12.5-cm-long wing conveyer models, the higher the speed, the lower the AMD collected ratio. On the contrary, for the 18.75-cm-long wing conveyor model, the AMD collected ratio goes up and down as the speed changes. On average, this model has the highest AMD collected ratio compared with the other two models. Note that the graphs in Fig. 5a and 5c shows the same pattern, because the AMD in the static tank is the same for all conditions.

Figure 5d presents the ratio of the pieces of AMD collected to the sail zone area (AMD/m^2). At low speeds, the no-wing conveyor model has the highest ratio, but the higher the speed, the lower the ratio. Likewise, the 12.5-cm-long wing conveyor model has a high ratio at low speeds, but the higher the speed the lower the ratio. On the other hand, the 18.75-cm-long wing conveyor model shows no pattern in this ratio. When the speed is less than 0.4 m/s, the average ratio of the three models is almost the same. However, after 0.4 m/s, the 18.75-cm-long wing conveyor model has the highest ratio, followed by no-wing conveyor and 12.5-cm-long wing conveyor models. The sail zone area is different for all models: the longer the wing conveyor, the wider the sail zone, and the larger the angle of the wing conveyor, the wider the sail zone. So, the fairest way to judge how effective the tool is to compare between the AMD collected and the total AMD before collection only in the sail zone.

Figure 5e shows a comparison of the AMD collecting capabilities of the three models: AMD collected relative to all AMD in the sail zone. This is the fairest comparison to judge how effectively models collect AMD. Because if it only compares the AMD collected from the three models (Fig. 5a), there may be differences in the AMD collected before the model moves or the AMD in the sail zone (Fig. 5b), and the comparison would not be fair. The results show that the lower the speed, the higher the collected AMD ratio. In addition, the longer the wing, the higher the collected AMD ratio, and the longer the front view, the higher the collected AMD ratio, because longer wings produce a longer front view. Hence, more AMD can be collected as the wing length increases and the speed decreases. Overall, the 18.75-cm-long wing conveyor model has the highest collected AMD ratio, followed by the 12.5-cm-long wing conveyor model and the no-wing conveyor model.

3.2. Analysis of why AMD is not caught by the model

There are three hypotheses as to why AMD is not captured by the model. First, AMD is not caught because the space in front of the conveyor is already full of AMD. This happens because after AMD is collected, as it will stay in front of a static conveyor. So, when there is not enough space in front of the conveyor, other garbage cannot be collected. The model dimensions that influence this hypothesis are the wing length and the front view length. Second, AMD is not caught because the AMD moves sideways to avoid the conveyor wing when the conveyor wing wants to catch it. This phenomenon can happen because of waves and currents caused by the model's movement. The variables that influence this hypothesis are speed, the wing length, and the front view length. Third, there is movement of AMD while the model runs because of waves and currents that are generated by the model's movement. So, AMD moves away from the model. This relates to the AMD calculations in the sail zone, because no AMD in the sail zone is counted before the model moves to collect AMD. The above hypotheses were tested by observing video clips or images in several locations while each model is running collecting AMD.

The causes of AMD not being caught by the model were determined in five stages. First, experimental video recordings of each model were examined. Second, two videos for each model, one at low speed and one at high speed, were viewed in detail. Third, 3–5 consecutive pictures were taken from each video. Fourth, AMD movement was observed, especially movement away from the wing. Fifth, the observations were used to test the hypotheses.

Table 2 presents the patterns of AMD movement of the three models at low and high speeds. At a low speed of 0.26 m/s, the no-wing model collected 13 pieces of AMD. At a high speed of 0.46 m/s, the no-wing model gathered 7 pieces of AMD. The trend of AMD collection for this model shows that the faster the model moves, the less AMD collected. This trend also occurs for the 12.5-cm-long wing conveyor model, but not for the 18.75-cm-long wing conveyor model. At a low speed of 0.25 m/s, the 18.75-cm-long wing conveyor model captured 17 pieces of AMD, while at a high speed of 0.40 m/s, this model captured 36 pieces of AMD. However, selecting the best model to collect AMD from this point of view would be unfair: the total AMD in the sail zone must be considered. Hence, comparison of the AMD collected and AMD in the sail zone can be

Table 2. AMD movement pattern.

Pattern	Model					
	No-wing conveyor		12.5 cm wing length		18.75 cm wing length	
	Low speed (0.26 m/s)	High speed (0.46 m/s)	Low speed (0.27 m/s)	High speed (0.41 m/s)	Low speed (0.25 m/s)	High speed (0.40 m/s)
AMD collected	13	7	24	9	17	36
AMD in the sail zone	24	14	29	13	18	43
AMD collected per AMD in the sail zone	0.542	0.500	0.828	0.692	0.945	0.837
Wave generated by ship motion	Small	High	Small	High	Small	High
Pieces of AMD that move to the side	11	7	5	2	1	4
Pieces of AMD that pass over the wing	No	No	No	2	No	3
Total AMD lost	11	7	5	4	1	7
AMD lost ratio	0.458	0.5	0.172	0.308	0.055	0.163
Space in front of ship	Available	None	Available	None	Available	None

used to determine the best model for collecting AMD. For low and high speeds in the three models, this comparison shows the same trend, namely the faster the speed, the smaller the collected AMD ratio (Table 2).

At a low speed for the no-wing conveyor model, only AMD at the catamaran bow tip were not caught. AMD moves sideways because of the waves generated by the model's movement. AMD also did not move too much from the initial position at this low speed. At 0.26 m/s, 11 out of 24 pieces of AMD in the sail zone moved to the side; at 0.46 m/s, 7 of 14 pieces of AMD in the sail zone moved to the side. It appears that the faster the speed, the more AMD moves to the side. However, the AMD that moves to the side is also influenced by the AMD in the sail zone or the AMD in the initial conditions before the model moves. So, more AMD moves sideways at a low speed because there is more AMD in the sail zone at low speeds. In the no-wing conveyor model at a low speed, AMD cannot be collected, but this is not because the space in front of the ship is full. At high speed, many pieces of AMD were not caught by the no-wing conveyor model. The waves generated by model movement are sufficient to move some AMD away from the model. Moreover, the high speed also makes the model unstable: it tilts forward and there is no space available in front of the ship.

At a low speeds, the 12.5-cm-long wing conveyor model did not catch AMD at the sail zone edge or wingtip. These pieces of AMD moves sideways because of the waves generated by the model movement (Fig. 6a). Overall, AMD did not move too much:

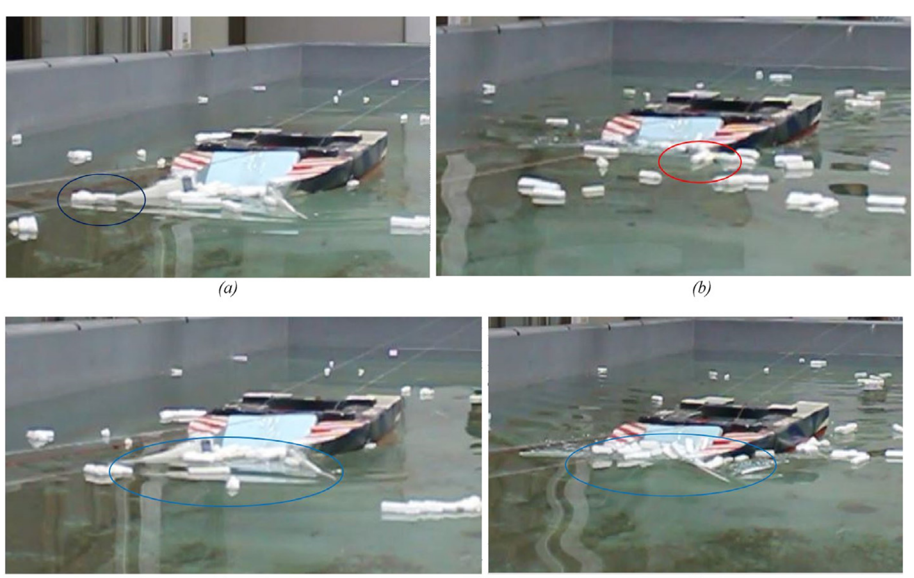


Fig. 6. Comparison of AMD collected in some conditions: (a) AMD moving to the side, (b) AMD passing over the wing, (c) space in front of the conveyor is still available, and (d) space in front of the conveyor is not available.

at 0.27 m/s, 5 out of 29 pieces of AMD in the sail zone moved to the side, and at 0.41 m/s, 2 out of 13 pieces of AMD in the sail zone moved to the side. This trend is the same as in the no-wing conveyor model, because there is an influence from the number of AMD in the sail zone or the number of AMD in the initial conditions before the model moves. So, more AMD move sideways when the model moves at a low speed because there is more AMD in the sail zone. The space in front of the conveyor is still available (Fig. 6c). Furthermore, AMD was not captured at the high speed because the waves generated by the model's movement were too large, allowing water to pass over the wing (Fig. 6b). AMD also goes over the wings and is not caught. Indeed, 2 pieces of AMD passed over the wings. This also resulted in not catching 2 pieces of AMD at the edge of the screening zone because they moved to the side. In addition, the space in front of the conveyor was full, hampering the ability to collect AMD (Fig. 6d). This happens because the space becomes smaller due to the water-covered wings.

At the low speed, the AMD that was not caught by the 18.75-cm-long wing conveyer model was located at the wingtip or at the edge of the sail zone. These pieces of AMD move sideways because of the waves generated by the model's movement. At 0.25 m/s, 1 out of 18 pieces of AMD in the sail zone moved sideways; at 0.40 m/s, 4 out of 43 pieces of AMD in the sail zone moved sideways. This trend differs from the no-wing conveyor and 12.5-cm-long wing conveyor models. The trend is that the greater the speed, the more AMD moves to the side; this is also in accordance with the effect of the number of AMD in the sail zone or the number of AMD in the initial conditions before the model moves. AMD also do not move too much from the initial position because the waves generated are not too big. Moreover, space in front of the conveyor is still available at the low speed.

Many of the pieces of AMD were not caught by the 18.75-cm-long wing conveyor model at the high speed. As the model began moving, there were 4 pieces of AMD at the sail zone edge that were not caught because they moved away from the wing. This happened because of the waves generated by the model's movement. After the model started moving more quickly, the waves generated by ship movement were big, so water passed over the wings. Three pieces of AMD also passed over the wings and were not caught. Big waves also make the space in front of the conveyor smaller. This makes AMD harder to collect.

Pieces of AMD lost are those in the sail zone that are not caught by the wing conveyor. So, AMD lost is the difference between the pieces of AMD in the sail zone and the pieces of AMD caught. Table 2 also shows the total pieces of AMD lost for the three models at different speeds. For the no-wing model at 0.25 m/s, 11 out of 18 pieces of AMD in the sail zone were lost; at 0.46 m/s, 7 out of 14 pieces of AMD in the sail zone were lost. For the 12.5-cm-long wing conveyor model at 0.27 m/s, 5 out of 29 pieces of AMD in the sail zone were lost; at 0.41 m/s, 4 out of 13 pieces of AMD in the sail zone were lost. For the 18.75-cm-long wing conveyor model at 0.25 m/s, 1 out of 18 pieces of AMD in the sail zone were lost; at 0.40 m/s, 7 out of 43 pieces of AMD in the sail zone were lost.

Comparing the pieces of AMD lost cannot reveal which model loses the most AMD, because each model travels at a different speed. At the low speed, the no-wing model and 12.5-cm-long wing conveyor model lose more AMD than at the high speed. The 18.75-cm-long wing conveyor model loses more AMD at the high speed than the low speed. The AMD lost ratio can be used to determine which model loses the most AMD; it is the ratio of the pieces of AMD lost to the pieces of AMD in the sail zone. Of note, this measure considers the initial pieces of AMD in the sail zone. The no-wing conveyor model has the highest AMD lost ratio, followed by the 12.5-cm-long and 18.75-cm-long wing conveyor models (Table 2). Hence, the 18.75-cm-long wing conveyor is the best model to collect AMD because it has the lowest AMD lost ratio.

4. Conclusions

Marine debris can be found throughout the world and remains a huge problem. In this paper, an approach to assess the effectiveness of the use of solid wings in marine debris collection has been proposed. Three kinds of marine debris collection models were built and then pulled in a static tank to collect AMD. The 18.75-cm-long wing conveyer model had the highest collected AMD ratio, followed by the 12.5-cm-long wing conveyer model and the no-wind conveyer model. Thus, the longer the front view, the higher of collected AMD ratio, because longer wings produce a longer front view. So, this means that more AMD can be collected as the wing length increases and the speed decreases.

The cause of AMD not being caught has also been investigated. At the low speed of each model, only AMD at the edge of the display zone or the wingtip were not captured. AMD moves sideways because of the waves generated by the model's motion. This movement becomes more pronounced as the speed increases. The waves lead to capturing fewer pieces of AMD, and water passes over the wings. Besides, the AMD in the sail zone needs to be considered when assessing AMD that moves to the side of the ship. At the low speed, AMD does not move much and space in front of the conveyor is still available. At the high speed of the three models, however, the waves generated by the model's movement are too large and water and AMD pass over the wings. The waves also prevent AMD at the sail zone edge from being caught because they move away from the wing. Other than that, AMD is not caught because the space in front of the conveyor is full. This happens because the space gets smaller due to the wings being covered in water. The high speed also makes the model unstable and it tilts forward.

Based on AMD movement pattern analysis, it is suggested to operate at a low speed because the collected AMD ratio is high and the resulting resistance force is also small. Three things can be considered when designing the wing conveyor in the future: first, make sure the wing sits higher above the water, especially if it operates at a high speed. Second, ship resistance force must be considered because this will affect the selection of ship's engine, fuel consumption, and operating costs. Third, to reduce drag force, a perforated conveyor wing design can be considered.

Declaration of competing interest

There is no conflict of interest.

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