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Manufacture of a large-sized flat panel airlift photobioreactor (FPA PBR) case with characteristic shapes using a thermoforming process [†]

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Abstract

The objective of this paper is to manufacture a large-sized Flat panel airlift photobioreactor (FPA PBR) case with characteristic shape using thermoforming process. Two distinguished characteristic shapes, including a blade and a stiffener, are designed to improve mixing characteristics and light utilization of the FPA PBR case. Structural analyses are carried out to obtain a proper design of the large-sized FPA PBR case. The design of the thermoforming mould is created using the proper design of the FPA PBR case. Proper conditions of the thermoforming process are estimated via a thermoforming analysis. The desired FPA PBR case with characteristic shapes is fabricated via thermoforming and bonding processes. Through durability and culture experiments, the applicability and the efficiency of the fabricated FPA PBR case have been investigated. From the results of the experiments, it has been shown that the designed FPA PBR case can significantly improve the productivity of the microalgae and the efficiency of the FPA PBR case.

Keywords: Large-sized flat panel photobioreactor; Characteristic shapes; Thermoforming process; Thermoforming mould; Microalgae; Mass cultivation

1. Introduction

Recent important environmental and industrial issues are the development of clean, renewable and sustainable energy sources to cope with global warming [1, 2]. Interest in bio-fuels has remarkably increased due to the necessity of renewable and sustainable energy sources [3]. Bio-fuels can be produced from lipids of microalgae [3, 4]. The amount of the produced bio-fuels is significantly influenced by the amount of microalgae [3, 4]. Hence, the development of the effective mass cultivation system for microalgae is one of hot issues in the research field related to bio-energy [5-8]. The Flat panel airlift photobioreactor (FPA PBR) has been proposed as a viable mass-production system of microalgae [5-8]. The performance and culture characteristics of the FPA PBR are dependent on design and manufacturing technologies of the FPA PBR cases [3]. Zittelli et al. have proposed a modular FP PBR with six removable alveolar panels for indoor mass cultivation of *Nanochloropsis sp.* [6]. Cheng-Wu et al. have developed an industrial-sized FP glass PBR for the mass production of *Nanochloropsis sp.* [7]. Degen et al. have proposed a FPA PBR with baffles to improve light utilization using a flashing-light effect [5, 8]. The objective of the present paper is to manufacture a large-sized FPA PBR case with characteristic shapes using a thermoforming process. The design and manufacturing methodologies of the large-sized FPA PBR case with characteristic shapes are investigated via analyses and experiments. Finally, the applicability and the efficiency of the fabricated FPA PBR case are discussed.

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2. Design of large-sized FPA PBR case

Fig. 1 illustrates the reference design of a large-sized FPA PBR case with characteristic shapes. The reference design of the FPA PBR case consists of two culture rooms and nine connecting parts. A connector is inserted into each connecting part. The exterior dimensions of the large sized FPA PBR case are 1400 mm × 1260 mm × 110 mm.

The culture room has two distinguished characteristic shapes, including a blade and a stiffener, as shown in Fig. 1. A blade with an arc shape is designed to improve mixing characteristics and flash-light-effects via self-circulation of microalgae, gas, and media. The arc-shaped blade reduces the flow resistance and the shear stress of the microalgae in the vicinity of the wall of the designed FPA PBR case. The concave shape of the blade enhances the light utilization of the designed FPA PBR case by multiple reflections of light on the blade. Because the concave shape of the blade increases the second moment of inertia, the blade also enhances the structural stiffness of the FPA PBR case. Dimensions of the blade are 240 mm × 383 mm × 75 mm except for the smallest blade in the

Table 1. Material properties of polycarbonate (PC) plate.

Trans-mittance (%)	Reflec-tion index	Density (kg/m^3)	Elastic modulus (GPa)	Pois-son's ratio	Yield strength (MPa)
85 - 91	1.5 - 1.6	1,250	2.0	0.38	58.8

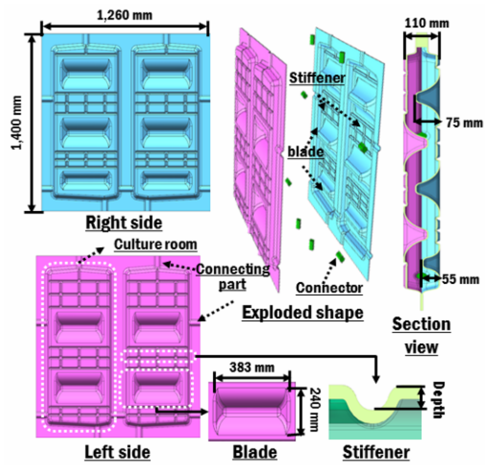


Fig. 1. Reference design (Design 1) of large-sized FPA PBR cases.

bottom region of the right side. Considering the pressure distribution and the microalgae accumulation in the FPA PBR case, the smallest blade is added to the bottom region of the right side. A stiffener with a semicircular shape is designed to increase the stiffness of the cultivation room. In addition, the stiffener improves the light utilization of the FPA PBR case through multiple reflections of the light on the stiffener. Reference depths of the stiffener for left and right sides are 8 mm and 9 mm, respectively.

The FPA PBR case is manufactured from a thermoforming process. Due to strain hardening phenomenon of the large deformed plastic material, the strength and the rigidity of the blades and the stiffeners are additionally augmented. Polycarbonate (PC) is chosen as the material of the FPA PBR case. Table 1 shows the material properties of the PC plate.

3. Analyses

In order to obtain a proper design of a large-sized FPA PBR case, the influence of the formation of the stiffeners on the rigidity of the FPA PBR case is investigated via structural analyses. The measure of the rigidity is chosen as the maximum bulging distance of the FPA PBR case. Five design alternatives of the FPA PBR case are chosen, as shown in Fig. 2. A structural analysis is performed using ABAQUS V6.11. The FPA PBR case is represented by tetrahedral solid elements. A linear hydrostatic pressure distribution is applied to the inside of the case. The safety factor and the maximum height are set to be 2.0 and 1.089 m, respectively. The reference thickness of the PC plate is set to be 4.0 mm.

In order to estimate the thermoforming conditions and the

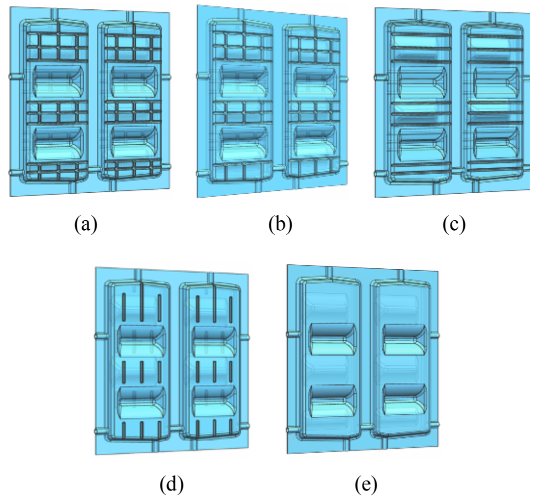


Fig. 2. Design alternatives of the FPA PBR case: (a) design 1; (b) design 2; (c) design 3; (d) design 4; (e) design 5.

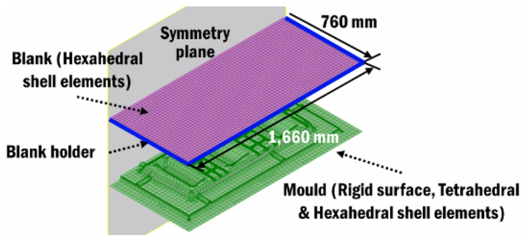


Fig. 3. Model of thermoforming analysis for the FPA PBR case.

formability, a thermoforming analysis is performed using PAMFORM-2G. Fig. 3 shows the simulation model. Using symmetric characteristics of the PBR case and the mould, a symmetric model is adopted. The PC plate is represented by hexahedral shell elements. The mould is assumed as a rigid surface. The initial temperature of the PC plate, the stamping speed, the mould temperature, the vacuum pressure, the friction coefficient, and the thermal conductivity coefficient are set to be 175°C, 54 mm/seconds, 60°C, 0.1 MPa, 0.35 and 0.5, respectively. In the preliminary formability analysis, the average thickness reduction rate of the reference design is estimated to be nearly 0.8. Hence, in order to manufacture the FPA PBR case with the reference thickness except for large deformed regions, the initial thickness of the PC plate is chosen as 4.5 mm. Considering the viscoelastic-plastic behavior of the PC plate during the thermoforming process, the G'sell and Jonas model is adopted as the stress-strain relationship of the PC plate. The coefficient of the G'sell and Jonas model for the thermoforming analysis is estimated via tensile tests at elevated temperatures.

4. Experiments

Fig. 4 illustrates the manufacturing procedure of the FPA PBR case. The thermoforming process is used to fabricate both sides of the FPA PBR case. The thermoforming process

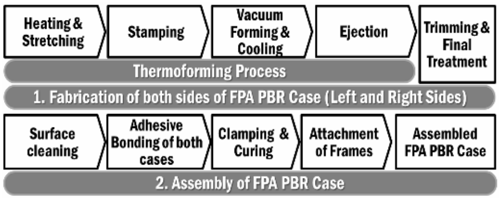
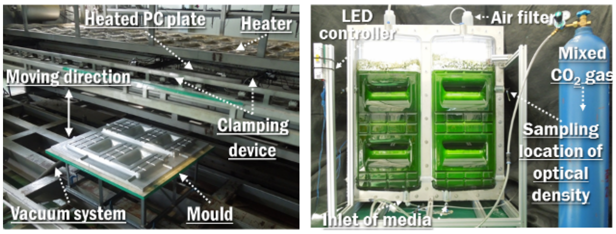
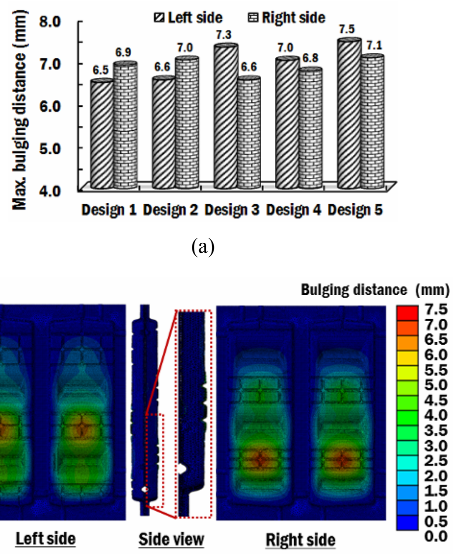


Fig. 4. Manufacturing procedure of FPA PBR cases.



(a) (b)

Fig. 5. Experimental setups: (a) theromforming experiments; (b) culture experiments.



(a)

(b)

Fig. 6. Results of rigidity analyses: (a) maximum bulging distances for different designs; (b) distribution of bulging distance (Design 1).

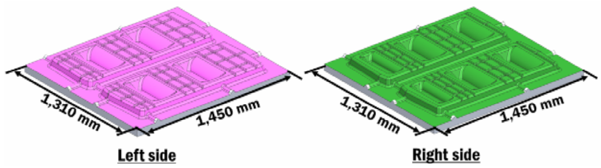


Fig. 7. Design of thermoforming mould for a proper case design.

consists of heating, stamping, vacuum, and ejection steps. Thermoforming conditions are estimated via thermoforming analyses. A pair of thermoformed cases is joined by a bonding process. Two types of adhesive, including two phase epoxy and acrylic adhesives, are used to join both sides of the case. The two phase epoxy adhesive is applied to symmetric regions. The acrylic adhesive is used to join exterior regions of the FPA PBR case.

In order to investigate the reliability of the fabricated FPA PBR case, a full-scale durability experiment is performed using the assembled FPA PBR case during 30 days in an outdoor environment. Culture experiments are carried out to examine the applicability and the efficiency of the fabricated FPA PBR case. The intensity of illumination, the acidity of media, the media, the gas flow, and the temperature of the culture room are 860 Lux, 8 P.H., Castenholz D, 120 cc/min, and 24°C, respectively. The supplied gas consists of air of 95 % and CO_2 of 5 %. LEDs and light guide plates are used to supply light with a uniform intensity to the FPA PBR case [3]. *Dunaliella salina* DCCBC2 is chosen as the cultured microalgae. In order to quantitatively investigate culture characteristics of the designed case, the density of microalgae in the culture room is estimated by the optical density [3]. The optical density is measured by a spectrophotometer [3]. Fig. 5 shows setups of thermoforming and culture experiments.

5. Results and discussion

5.1 Proper design of FPA PBR case and mould

Fig. 6 shows the results of structural analyses. The bulging distance decreases when the stiffener is applied to the culture room. The bulging distance of the FPA PBR case with stiffeners in both longitudinal and width directions are smaller than that of the FPA PBR cases with stiffeners in the single direction, as shown in Fig. 6(a). The maximum bulged region is changed from the left side to the right side when stiffeners are created in the longitudinal and width directions together. The maximum bulging distance of design 2 is slightly greater than that of design 1. From these results, design 1 is selected as a proper design for the FPA PBR case.

Fundamental surface geometries of thermoforming moulds are created from inside surfaces of the FPA PBR case with the proper design. The draft angle is added to the fundamental surface geometries. In order to consider the shrinkage and the trim of the thermoformed part, external surfaces of the mould are offset from fundamental surfaces of the moulds in the normal direction. The draft angle and the offset length are set to be 5 ^{o} and 7.0 mm, respectively. Fig. 7 shows the design of the thermoforming moulds. The dimensions of thermoforming moulds are 1450 mm × 1310 mm × 95 mm. The diameter of the vacuum hole is set to be 3 mm.

5.2 Formability and thermoforming conditions

Figs. 8 and 9 show results of the thermoforming analysis for the proper design of the FPA PBR case. Through the repeated analysis of heating and stamping steps, it is noted that the minimum stretching depth is nearly 175 mm to fully cover the mould with the stretched PC plate after the stamping step, as

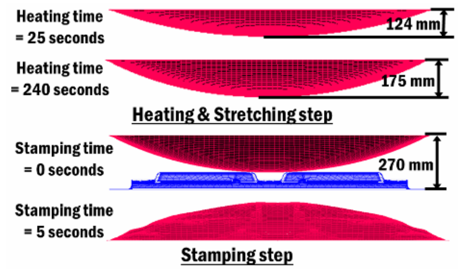
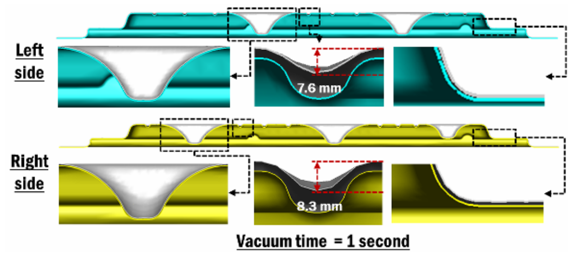
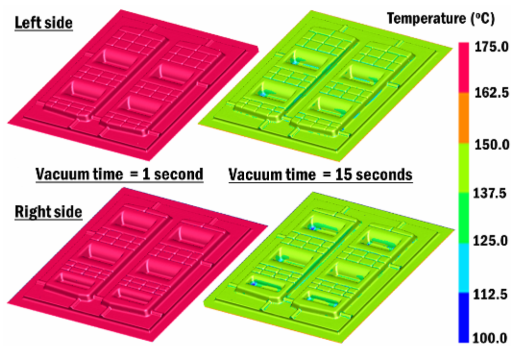


Fig. 8. Results of thermoforming analyses (heating and stamping steps).



(a)



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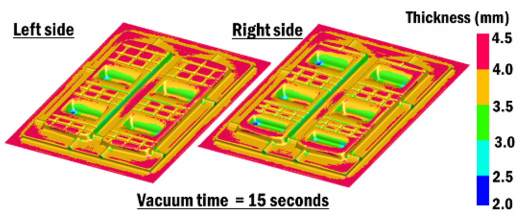


(c)

Fig. 9. Results of thermoforming analyses (vacuum step): (a) deformed shape; (b) temperature distribution; (c) thickness distribution.

shown in Fig. 8. Considering the stretching depth of the PC plate and the height of the mould, the required stamping stroke is nearly 270 mm. From these results, heating and stamping times of the FPA PBR case are determined to be 240 seconds and 5 seconds, respectively, as shown in Fig. 8 and Table 2.

In the vacuum step, most of detail shapes of the FPA PBR case are formed within the vacuum time of 1 second except for the stiffeners, as shown in Fig. 9(a). Through the investigation of the deformed shape of the FPA PBR case during the vacuum step, it is noted vacuum time is greater than 10 seconds to create stable stiffener shapes without variation of the

Table 2. Thermoforming conditions of the designed FPA PBR case.

Steps	Heating	Stamping	Vacuum	Cooling
Time (Seconds)	240	5	15	30

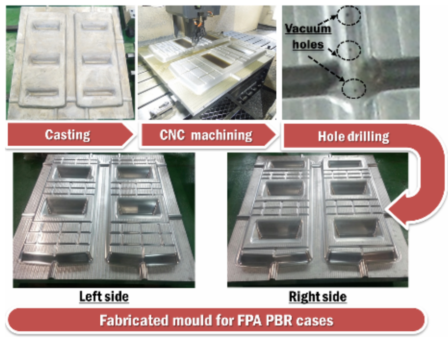


Fig. 10. Fabrication procedure of thermoforming moulds.

detailed stiffener shape according to the vacuum time. The temperature distribution of the thermoformed FPA PBR case is less than 150°C when the vacuum time is 15 seconds, as shown in Fig. 9(b). The glass transition temperature of the PC plate is nearly 150°C. In order to prevent spring-back, shrinkage, deformation of the thermoformed case after ejection, the thermoformed part must be cooled below the glass transition temperature of the PC plate. From these results, the vacuum time is determined to be 15 seconds, as shown in Table 2. Through the investigation of the temperature variation of the thermoformed case in the vacuum step, the cooling time is determined to be 30 seconds. The thickness of the FPA PBR case ranges from 3.6 mm to 4.4 mm except for inside regions of the blades, as shown in Fig. 9(c). The thickness of the interior regions of blades lies in the range of 2.3-2.8 mm.

An excessively thinned region, where the thickness is less than 1 mm, does not appear in thermoformed cases. From these results, it is revealed that the proposed thermoforming process can thermoform the desired FPA PBR case with characteristic shapes.

5.3 Fabrication of FPA PBR case

Thermoforming moulds of the FPA PBR case are manufactured from casting, CNC machining and hole drilling processes, as shown in Fig. 10. Aluminum is chosen as the casting material. Manufacturing time of the moulds is nearly 10 days.

Several thermoforming experiments are performed using the proposed thermoforming process, as shown in Fig. 11. Plastic FPA PBR cases with characteristic shapes are successfully manufactured when the estimated thermoforming conditions are applied to sub-steps of the thermoforming process, as shown in Figs. 12 and 13. The total thermoforming time is nearly 290 seconds. The thermoformed case is trimmed by a CNC milling machine. Overall and sectional shapes of the thermoformed FPA PBR case are fairly similar to those of the

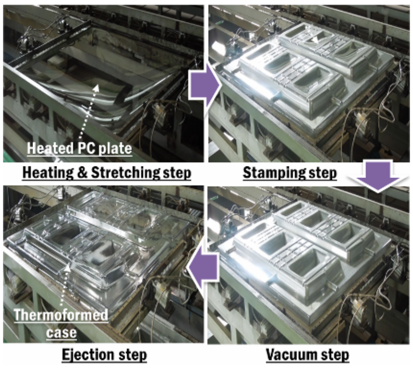
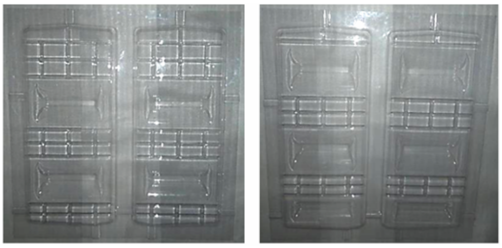
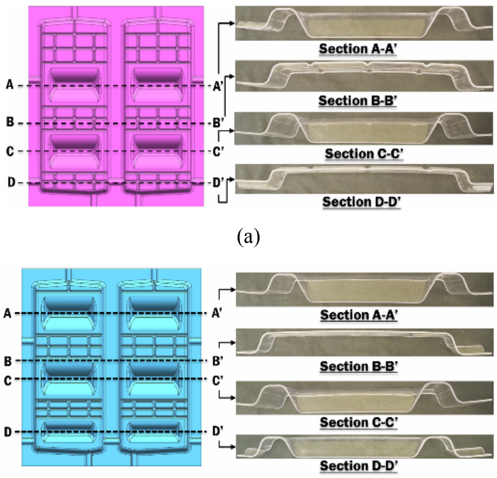


Fig. 11. Thermoforming procedure of the FPA PBR cases.



(a) (b)

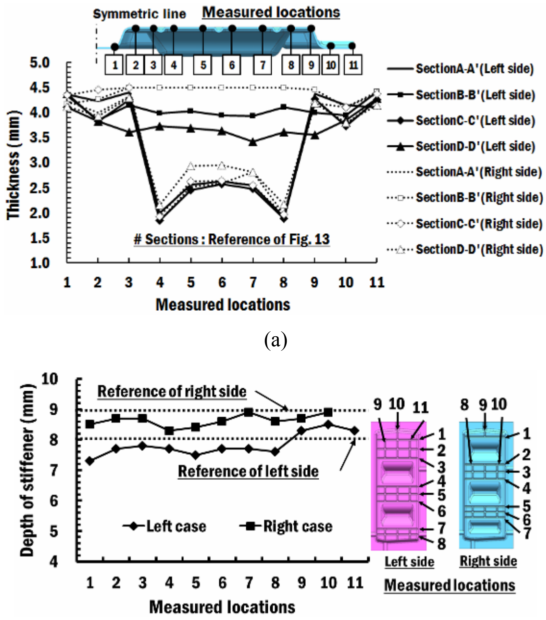
Fig. 12. Thermoformed FPA PBR case: (a) left side; (b) right side.



(b)

Fig. 13. Sectional shapes of the thermoformed FPA PBR case: (a) left side; (b) right side.

thermoforming analysis. The thickness of the FPA PBR case ranges from 3.6 mm to 4.4 mm except for the inside regions of the blades, as shown in Fig. 14(a). The thickness of the inside regions of the blades lies in the range of 1.8 mm - 2.9 mm, as shown in Fig. 14(a). These results are almost identical to the thickness distributions of the thermoforming analysis. From these results, it is noted that the desired FPA PBR case can be manufactured when the estimated thermoforming conditions via the thermoforming analysis are applied to the proposed thermoforming process. The depth of the stiffener for the left side ranges from 7.3 mm to 8.5 mm, as shown in Fig. 14(b). The depth of the stiffener for the right side lies in the range of 8.3 mm - 8.9 mm, as shown in Fig. 14(b). Considering conventional thermoformed products with a dimensional tolerance of 10% [9], it is noted that a reasonable FPA PBR case is fabricated from the proposed thermoforming process.



(b)

Fig. 14. Distributions of thickness and stiffener depth for the thermoformed FPA PBR case: (a) thickness; (b) depth of stiffener.

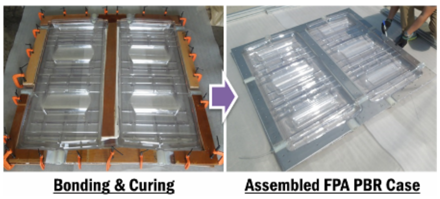


Fig. 15. Bonding process and assembly of the designed FPA PBR case.

Both sides of the thermoformed FPA PBR case are joined by a bonding process, as shown in Fig. 15. The curing time is nearly 24 hours. In order to install the FPA PBR case in the setup of durability and culture experiments, aluminum frames are assembled to the bonded cases, as shown in Fig. 15.

5.4 Durability and culture characteristics

Figs. 16 and 17 show the results of full-scale durability and culture experiments. During the full-scale durability experiment, the defects and the failure do not appear in the assembled FPA PBR case. The maximum bulging appears at the bottom region of the right side case, as shown in Fig. 16. The maximum bulging distance is less than 7 mm. From these results, it is noted that the designed FPA PBR case has a sufficient rigidity to continuously culture the microalgae.

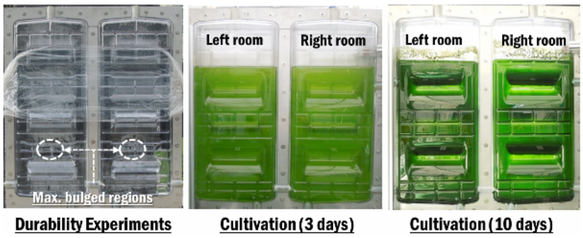


Fig. 16. Results of full-scale durability and culture experiments.

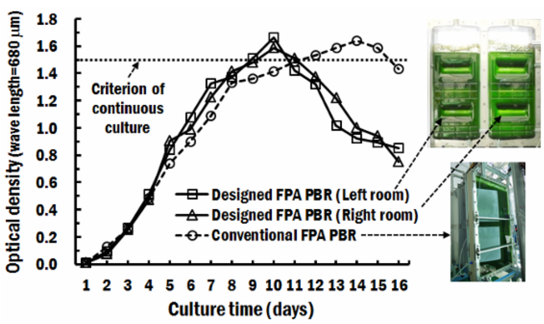


Fig. 17. Culture characteristics and the efficiency of the designed case.

Dunaliella salina DCCBC2 is successfully cultivated by the designed FPA PBR case, as shown in Figs. 16 and 17. The maximum concentration is observed when the *Dunaliella salina* DCCBC2 is cultured for nearly 10 days. The maximum optical density ranges from 1.6 to 1.7, as shown in Fig. 17. The optical density of the designed FPA PBR case reaches the criterion of a continuous culture after 9 days of cultivation of *Dunaliella salina* DCCBC2, as shown in Fig. 17. From this result, it is noted that *Dunaliella salina* DCCBC2 can be continuously cultured after 9 days of cultivation when the designed FPA PBR case is used. In order to investigate the efficiency of the designed FPA PBR case, culture characteristics of the designed FPA PBR case are compared to those of the conventional FPA PBR without characteristic shapes, as shown in Fig. 17. The maximum culture time and the continuous culture time of the designed case are shorter than those of the conventional case by nearly 29 % and 19 %, respectively. The growth rate of the designed FPA PBR case is higher than that of the conventional FPA PBR case before the maximum culture time. These results are ascribed to the fact that the blade with the arc shape improves mixing characteristics and flash-light-effects, and the concave shape of the blade and the stiffener increases the light utilization. Based on the above results, it is shown that the designed FPA PBR case can significantly improve the productivity of microalgae and the efficiency of FPA PBR case.

6. Conclusions

In this paper, a large-sized FPA PBR case with characteristic shapes has been manufactured from a thermoforming process. Two characteristic shapes, including a blade and a stiffener, have been designed to improve mixing characteristics, flash-light-effects, light utilization, and rigidity of the FPA PBR case. A proper design of a large-sized FPA PBR case has been estimated via a structural analysis. The design of the thermoforming mould has been created using the proper design of the FPA PBR case. Appropriate thermoforming conditions, including heating, stamping, vacuum, and cooling times, have been estimated via a three-dimensional thermoforming analysis. In addition, the formability of the designed FPA PBR case has been investigated using the results of the thermoforming analysis. The thermoforming mould has been fabricated from casting, CNC machining and hole drilling processes. Both sides of the desired FPA PBR case with characteristic shapes have been successfully manufactured from the designed thermoforming process. The assembled FPA PBR case has been fabricated via a bonding process and frame attachment. Through full-scale durability experiments, it has been shown that the designed FPA PBR case has a sufficient rigidity to continuously culture microalgae. Culture experiments have been performed using the assembled FPA PBR case and *Dunaliella salina* DCCBC2. The results of the culture experiments have been shown that the designed FPA PBR case can successfully cultivate microalgae. Through the comparison of the culture characteristics of the designed FPA PBR case with those of the conventional FPA PBR case, it has been shown the maximum culture time and the continuous culture time of the designed case are shorter than those of the conventional case by nearly 29 % and 19 %, respectively. In addition, it has been demonstrated that the designed FPA PBR case with characteristic shapes can significantly improve the productivity of microalgae and the efficiency of FPA PBR case.

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References

[1] O. Kwon and Y. J. Yoon, Optimizing present power distribution system and novel renewable energy sources for Tamil Nadu in India using HOMER, *International Journal of Precision Engineering and Manufacturing*, 15 (8) (2014) 1695-1701.

[2] B. Bhandari, S. R. Poudel, K. T. Lee and S. H. Ahn, Mathematical modeling of hybrid renewable energy system: A review on small hydro-solar-wind power generation, *International Journal of Precision Engineering and Manufacturing-Green Technology*, 1 (2) (2014) 157-173.

[3] D. G. Ahn, C. G. Cho, Y. S. Ahn, S. H. Jeong and J. T. Kim, Application of rapid prototyping technology to rapid development of flat panel (FP) photobioreactor case for microalgae, *Journal of Biobased Materials Bioenergy,* 7 (1) (2013) 39-49.

[4] L. Brennan and P. Owendo, Biofuels from microalgae-A review of technologies for production, processing, and extractions of biofuels and co-products, *Renewable and Sustainable Energy Reviews,* 14 (2) (2010) 557-577.

[5] C. U. Ugwu, H. Aoyagi and H. Uchiyama, Photobioreactors for mass cultivation of algae, *Bioresource Technology,* 99 (10) (2008) 4021-4028.

[6] G. C. Zittelli, R. Pastorelli and M. R Tredici, A modular flat panel photobioreactor (MFPP) for indoor mass cultivation of Nanochloropsis sp., *Journal Applied Phycology*, 12 (3-5) (2000) 521-526.

[7] Z. Cheng-Wu, O. Zmora, R. Kopel and A. Richmond, An industrial-size flat plate glass reactor for mass production of Nanochloropsis sp., *Aquaculture*, 195 (1-2) (2001) 35-49.

[8] J. Degen, A. Uebele, A. Retze, U. Schmid-Staiger and W. Trösch, A novel airlift photobioreactor with baffles for improved light utilization through the flashing light effect, *Journal of Biotechnology*, 92 (2) (2001) 89-94.

[9] I. Adolf, *Thermoforming – A Practical Guide*, Hanser Publishers, Munich, Germany (2000).

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