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New results from microalgae production and techniques

Abstract
The paper deals with new technical solutions for outdoor cultivation systems for microalgae production. Various types of algae cultivation systems and materials applied for reactors are described. The characteristics and performance of a novel closed photobioreactor system with "Christmas tree" design (brand name: GICON-PBR) consisting of a silicone double-wall tubing-system, developed in collaboration between the companies GICON and Wacker Chemical corporation, are discussed. Special attention is paid to the issue of temperature control for closed cultivation systems. The performance of the chilling system stabilizing the temperature of algae cultivation, which applies a thermal energy storage filled with Phase Change Material (PCM). Two kinds of the systems are considered: free cooling and with compressor units. The lumped-model equations were developed to analyze heat-transfer dynamics inside the installation and some results are presented here. The model equations describe energy balances for the chiller, PCM thermal storage and heat receiver. Influence of the heat transfer, fluid-flow-rate control, heat capacity of the system components as well as heat losses to ambient were taken into account. The results of PCM storage application are compared with reference water-filled buffer-tank. The study shows a great potential of PCM storage unit to stabilize the temperature of the algae cultivation system.

Keywords: microalgae production, photobioreactor, silicone double-wall tubing, control system, phase-changing materials.

1. Introduction

In accordance with the development of technical concepts of cultivation systems, the already existing interest in microalgae biomass is rising further and the demand for higher quality biomass and its high-value products, respectively, are bringing challenges to the development of photobioreactor concepts. In doing so, a stable biomass production with defined product quality is crucial to meet general market demands. In recent years, the worldwide production of microalgae biomass for all purposes is estimated to be in the range of a five-digit ton scale of dry weight (Spolaore et al., 2006; Darzins, Pienkos, & Edye, 2010; Rosello, Sastre, & Posten, 2010; Milledge, 2011, 2012; Enzing et al., 2014; Torzillo, & Zittelli, 2015; Laurens, 2017). In 2015, a revenue of more than 900 million euro reached by more than 100 companies in Europe has been reported (Verdelho, & Viera, 2015).

Looking at the market volume and price of possible microalgae-derived products, one can consider a product pyramid, in which volume and price are acting in counter-direction (Figure 1). This basic economic correlation explains the ground rule of higher market volume meaning lower product price. In that manner, looking at bulk-chemicals and even a possible use in bioenergy, low-cost products at a high volume scale are required. Thinking of applications as pharmaceuticals and in cosmetics, high product prices can be achieved at low market volumes. The requirements to the product quality rise with increasing value of the product.

On short term and middle term basis, profitable market sectors can be found in the fields of food and food supplements as well as animal feed supplements and aquaculture, respectively. Within these application sectors, by far, mainly produced microalgae are *Chlorella* and *Arthrospira* (*Spirulina*) with production volumes of 10,000 and 15,000 metric tons of dry weight, respectively (Slocombe, & Benemann, 2016). Carotenoids derived from microalgae are highly interesting compounds, as the synthetic production is not feasible in each case. In doing so, beta-carotene from *Dunaliella salina* and astaxanthin from *Haematococcus pluvialis* are other market applications, which are already commercially available and still induce rising interest. Per ton of astaxanthin, the product price ranges between 2,500 and 7,000 US Dollar (Li et al., 2011; Milledge, 2012; Cameron Coates, Trentacoste, & Gerwick, 2013; Panis, & Carreon, 2016). The product price of beta-carotene can be up to 1,500 US Dollar (Guedes, Amaro, & Malcata, 2011; Borowitzka, 2013). Even though, these products are already commercially available, there is still an increasing demand of these products at high quality scale, because of rising interests in market products derived from natural sources.

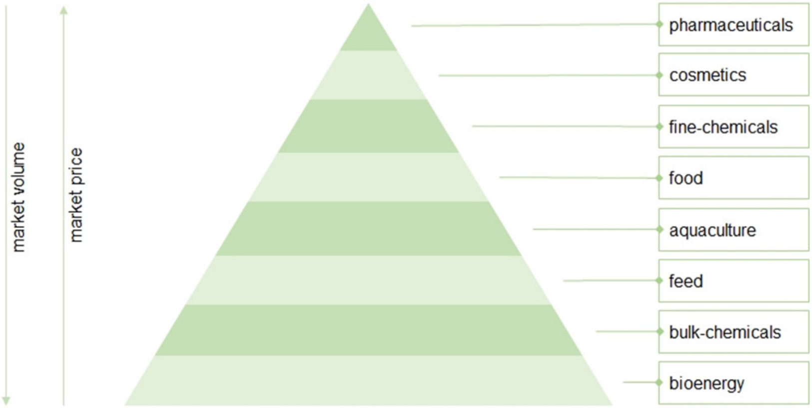

Fig. 1. Product pyramid of microalgae biomass in relation to market volume and price (Ahmed et al., 2014; Voort, Vulsteke, & Visser, 2015)

Besides these applications, there are being produced only a few more microalgae at the moment, e.g. *Phaedactylum*, *Odontella* and *Tetraselmis*. Other microalgae, although there are known several hundred thousand of them, are not yet approved to be put on the market directly as whole biomass or derived products. It still takes several years and a cost-intensive process to get approved a certain microalgae or microalgae-derived product. Also, today's need for high quality standards is rising people's awareness. Nevertheless, additional microalgae strains will be available to be produced in the near future, lots of them are delicate to cultivate, which may be challenging for existing photobioreactor systems.

2. Algae cultivation systems

Today, most of the worldwide produced microalgae are being cultivated in open cultivation systems (Benemann, 2013). These systems are relatively cheap in terms of investment costs, but hard to maintain at stable growth conditions, which then result in defined product quality and need lots of areal space. Furthermore, as a consequence of being non-enclosed systems, the water demand is high, as a result of high evaporation and risks of contamination, and leads to challenges regarding process stability.

These downsides can be solved by the use of closed systems. Those photobioreactors are usually arranged in a vertical manner, so that the use of sunlight is more effective due to a higher light dilution and distribution in relation to the incoming sunlight per ground area. In fact, the above mentioned systems induce higher investment costs in contrast to open cultivation systems, but allow for higher productivities of microalgae biomass. The stable production of microalgae biomass, with consistent and defined product quality, requires several conditions to be fulfilled by a cultivation system. Next to economic feasibility, the ability of the system to maintain good and environmentally fitted conditions for the microalgae growth represents the main challenge. And so, ensuring a light supply in a consistent way for each algal cell, in terms of distribution and dilution of sunlight, as well as temperature control are important. Because of the closed system, the suspension temperature rises quickly in accordance with incoming radiation. So, excess heat must be often removed in order to keep microalgae under best growth conditions. Several concepts for microalgae cultivation were considered in the past in order to find optimal ranges of light intensity and suspension temperature as well as their control.

In principle, closed photobioreactors, and to be more precisely, their transparent wall materials, require a protection against changing and harsh environmental conditions, like hail, stormy weather or freezing temperatures during winter, so that the photobioreactors are often installed in greenhouses. Especially rigid and brittle materials like glass and hard-PVC (polyvinyl chloride) have to be covered (by a greenhouse) and installed in areas with no risks of harsh weather conditions, respectively. Table 1 presents basic design concepts of photobioreactors available on the market. The materials typically used for those reactors are shown in Table 2.

From a geometrical point of view, one can divide the basic concepts in planar/rectangular and tubular designs, being installed horizontally and vertically, respectively.

Table 1. Typical design concepts for photobioreactors

Basic design of light collector	Planar		Tubular				
Installation in relation to ground area	Horizontal	Vertical	Horizontal	Vertical			
Basic shape	Zick-Zack-structure	Flat panel	Serpentine-tubular	Serpentine-tubular	Cylindrical-helical-tubular	Conical-helical-tubular	Circular tank
Primary mixing	Pump	Air-lift	Pump	Pump			Air-lift
E.g.	Zick-Zack PBR(1)	Flat-Panel-Airlift(2)	Aquasearch Growth Module (AGM)(3)	Glass tubular-PBR(4)	Biocoil(5)	"Christmas tree" — PBR (GICON-PBR)(6)	"Hanging-Gardens"(7)

(1) (Jacobi et al., 2011), (2) (Graziella, Chini, Zittelli et al., 2013), (3) (Olaizola, 2000), (4) (Pulz, 2001), (5) (Robinson, Morrison, & Bamforth, 1988), (6) (Mueller-Rees et al., 2011), (7) (Koller, 2015)

Table 2. Commonly used materials for light collectors of photobioreactor systems (Kübler, & Müller, 2014; Geier et al., 2012; Weißbach, 2012)

Material class	Glass	Polymer				
		Thermoplast				Elastomer
E.g.	Borosilicate	Vinyl polymer e.g. PVC		Polyacrylate e.g. PMMA	Polyethylene (PE)	Silicone
		Hard-PVC	Soft-PVC			
Properties	hard/brittle	• without plasticizer • hart/brittle • up to 60°C	• with plasticizer • flexible/elastic	• hard/brittle • high strength • up to 70°C • "crystal clear"	• soft and flexible/elastic • up to 80/100°C	• soft and flexible/elastic • up to 200°C

The planar systems, so-called flat plate collectors, usually use an air-lift principle to mix the microalgae culture. Providing these systems with sufficient compressed air is rather cost intensive. The actual mixing per unit volume is then usually less energy consuming in relation to pumped-driven mixing set-ups, which are being used in tubular systems. Tubular systems are usually arranged in a serpentine and slope manner, respectively, or wound up helically around a cylindrical cone. The geographical orientation is not important for helical systems, but, it is indeed crucial for flat plate or serpentine tubular systems.

The materials, which are being used for light collectors of photobioreactor systems, are glass — usually borosilicate-based (Tredici, 2004; Pulz, Broneske, & Waldeck, 2013), or transparent plastics such as, vinyl polymers (PVC), polyacrylates (polymethyl methacrylate, PMMA) or silicones, like silicone rubber, and also polyethylene (Posten, & Wilhelm, 2016; Carvalho et al., 2014; Matthes et al., 2015; Raes et al., 2014; Watanabe, de la Noue, & Hall, 1995). The selected materials have to have certain chemical resistance in terms of pH value, salinity and susceptibility to hydrolysis. Also, durability with respect to mechanical and optical properties under thermal and radiation-intensive stress is crucial (Tredici, 2004, Carvalho et al., 2014). For the construction of serpentine-shaped modules rigid materials, such as glass or hard PVC (PVC-U) or PMMA, are being used. In doing so, rectilinear tubular basic forms and bent elements are being assembled with the help of special coupling parts to a complete module. The downside of using such rigid forms is, that the maximum length of individual tubes is about 6 m with respect to the packing size for transport and logistics. By using couplings to connect the units into a total construction of a serpentine shape, a high number of couplings is necessary, resulting in additional investment costs and contamination risks. When using silicone or soft-PVC materials there is the possibility of producing actual clutchless and flexible tubes for light collectors through the use of appropriate manufacturing techniques (e.g., extrusion). Silicones, in general, stand out due to their high resistance to aging (Geier et al., 2012).

Light collectors of flat shapes usually consist of rigid PVC or PMMA based plastics. Glass tubes arranged in a serpentine manner for the use in photobioreactors have been first described in 1987 by the IGV GmbH in Germany (Pulz, Broneske, & Waldeck, 2013). The use of flexible plastic based tubular systems can be found on the one hand in the so-called Biocoil (usually consisting of PVC or PE) or also in the Christmas tree photobioreactor (brand name: GICON-PBR), where silicone is used to form a double-wall tubing-system, developed in collaboration between the companies GICON and Wacker Chemical corporation (Mueller-Rees et al., 2011; Silva, & Reis, 2015). Silicone is the only material among the mentioned and compatible ones, which is flexible, transparent, UV-stable, tolerant to high salt concentrations and high temperatures (enough for steam sterilization) and is approved for food grade. By using flexible plastics, it is possible to arrange the tubes in a curved shape. In doing so, a truncated cone shaped light collector has been developed by the company GICON (see Figure 2), which mimics a natural tree in such a manner, that, in accordance with the position of the sun, a proper light entry during the entire day can be ensured. The system uses a double-wall tubing-system consisting of a transparent, food grade approved, silicone (Figure 3), which is wound up helically around a frame.

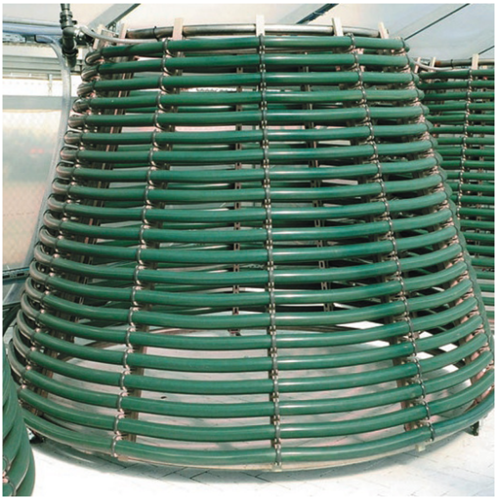

Fig. 2. Truncated cone shaped light collector (“Christmas tree” GICON-PBR) (Posten et al., 2018)

Fig. 3. Cross section of double wall tubing system of GICON-PBR (photo: S. Matthes)

The cross section of the double-wall tubing-system shows the two chambers, which, next to the microalgae suspensions, can be used for temperature control media. In combination with the flexibility of the material itself, this feature allows for installing the light collector outdoors without the need of a greenhouse, which is necessary when using rigid materials like glass, hard-PVC or PMMA, unless harsh weather conditions can be excluded.

3. Temperature control methods

Next to providing the microalgae culture with all required nutrients, an important issue is a removal of excess heat from the photobioreactor system. The temperature control of the microalgae suspension in closed PBR systems is a major challenge and, in fact, a downside and critical issue of most of the available systems, because of the lack of an implementation of an effectively working temperature control. In most cases, the use of evaporative cooling is the only option of closed systems, mainly because of single tube used to construct reactors. Using evaporative cooling requires sprinkling the surface of the light collecting tubes. In doing so, the water must be free of salts and other particles, which may cause scaling issues (see Figure 4). So, in most cases, the water needs to be desalted, which is a major cost factor. Other options are the implementation of heat exchangers in mixing tanks (Sierra et al., 2008; Chisti, 2007), but in this case, biofouling at the cooling pipes may occur.

The double wall tubing system of the above-mentioned silicone tube (Figure 3) uses a closed cycle (smaller tube) for cooling water as an integrated system, so that a gentle and consistent removal of the excess heat ensures a defined temperature control. In doing so, the water consumption because of evaporation and scaling issues of the light entry surfaces can be avoided.

Fig. 4. Scaling of light entry surface of glass tubular PBR (photo: S. Matthes)

Silicone materials may have lower transmission in the photo-synthetically active range of the solar spectrum, especially, in comparison to glass and PMMA. However, as mentioned above, it is common to install photobioreactors consisting of these materials, within a greenhouse. Hence, the incoming solar radiation first transmits through the roof of the greenhouse before entering the light collector system. It is obvious, that their transmission cannot be neglected and has to be taken into account. The materials used for the roofs of greenhouses are rigid glass or plastics or also films with defined thickness, which have transmission factors of 0.8 to 0.9 (Pearson, Wheldon, & Hadley, 1995; Kittas, & Baille, 1998; Critten, & Bailey, 2002). Also, as a result of shading because of the framework structure, there is a reduction of the illuminated area. For instance, by using single pane safety glass including argon a transmission of 84 per cent can be reached (Saint-Gobain Glass Deutschland GmbH, 2015). Older greenhouses may have transmission factors of only 0.48 to 0.6 (Ting, & Giacomelli, 1987). Finally, the overall transmission may be reduced tremendously in comparison to the installation of light collectors outdoors, like, for instance, silicone-based tubular systems.

3.1. Temperature control system based on phase-changing materials

The optimal temperatures for cultivation of microalgae is different during day and night, around 27 and 16 degree, respectively. The temperatures above 35 degree kept for several hours may have deadly consequences for these microalgae. As it was mentioned above, the temperature stabilization may pose some technical and economical problems. The implementation of a heat storage filled with phase-changing material — see Figure 5, into thermodynamic loop of the GICON-PBR system (Figure 2) can help to solve some of the challenges. The performance and characteristics of such chilling system stabilizing the temperature of algae cultivation, are studied here.

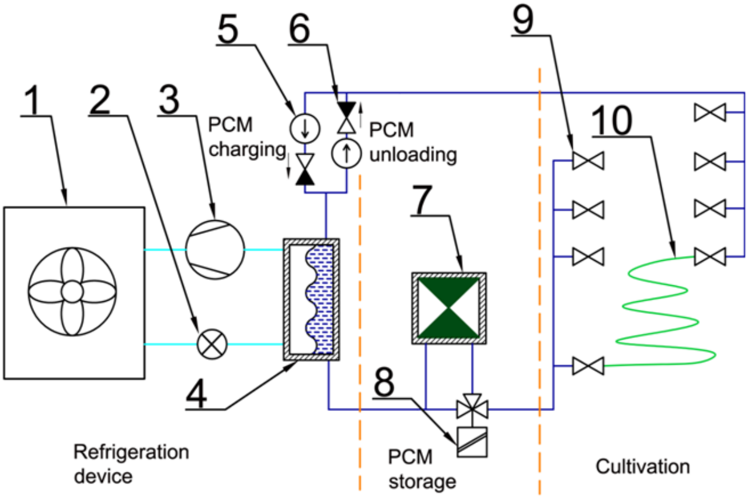

Fig. 5. Refrigeration installation (1 — condenser, 2 — expansion valve, 3 — compressor, 4 — evaporator, 5 — pump, 6 — check valve, 7 — PCM cold storage, 8 — three-way valve with electronic control, 9 — valve, 10 — algae cultivation unit)

3.2. Model description

The here presented calculations are based on the model of PBR with the chilling system working under realistic weather conditions (air temperature and isolation) found for Koethen municipality in 2015 — see Figure 6, where long term investigations of "Christmas tree" PBR were performed. Various PCM materials produced by Rubitherm Technologies GmbH (RT18HC, RT21, RT21HC, RT22HC) where considered in order to find an optimal one.

The lumped-model equations were developed to analyze heat-transfer dynamics inside the installation (Karwacki et al., 2017). The model equations describe energy balances for the chiller, PCM thermal storage and heat receiver. Influence of the heat transfer, fluid-flow-rate control, heat capacity of the system components as well as heat losses to ambient were taken into account.

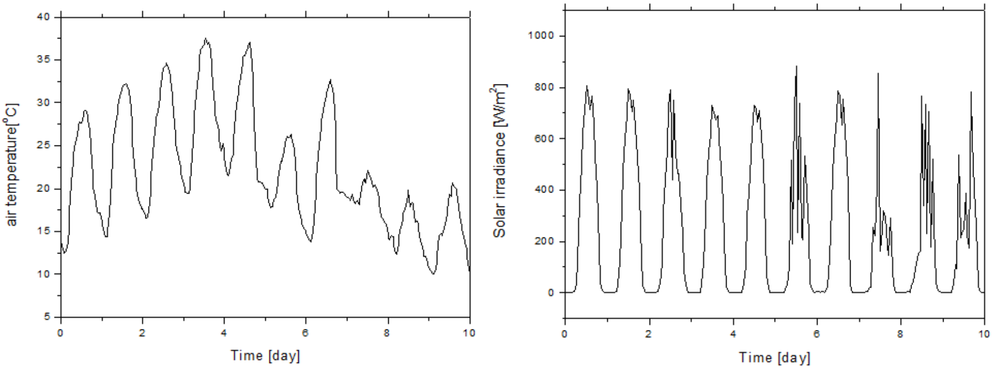

Fig. 6. Air temperatures and solar irradiance recorded at Koethen during first 10 days of July 2015 (from GICON)

Thermal load of PBR reactor results from solar insulation $\dot{Q}_{sol}$, heat exchange between the algae suspension and ambient air $\dot{Q}_{kon}$ and radiative heat flux exchanged between reactor and ambient air $\dot{Q}_{RAD}$.

The thermal load from solar insulation is related to cross-section of reactor, perpendicular to solar rays A_C, which changes during a day and must be calculated at first. The thermal power absorbed by algae is given as:

$$\dot{Q}_{sol} = \alpha \, A_C \, I \tag{1}$$

where: α — absorptance of algae suspension (it is assumed 0.8 here) and
I — solar irradiance.

The heat exchange between algae suspension and ambient air is given by equation

$$\dot{Q}_{kon} = k_0 A_0 \left(T_A - T_S\right) \tag{2}$$

where: k_0 — heat transfer coefficient, A_0 — heat exchange surface, T_A — algae suspension temperature, T_S — ambient temperature. The heat transfer coefficient includes heat transfer of the tube and coefficient of heat transfer from ambient air side (Pudlik, 2012).

The thermal load from radiative heat flux exchanged between reactor and ambient air:

$$\dot{Q}_{RAD} = \varepsilon \cdot A_e \cdot \sigma \cdot \left(T_A^4 - T_S^4\right)$$

where: ε — emissivity coefficient of the algae suspension (it is assumed 0.8 here; Bramson, 1968), Ae — surface of the emitting body and $\sigma = 5.6703 \cdot 10^{-8}$ (W/m^{2}K^4) — the Stefan-Boltzmann Constant.

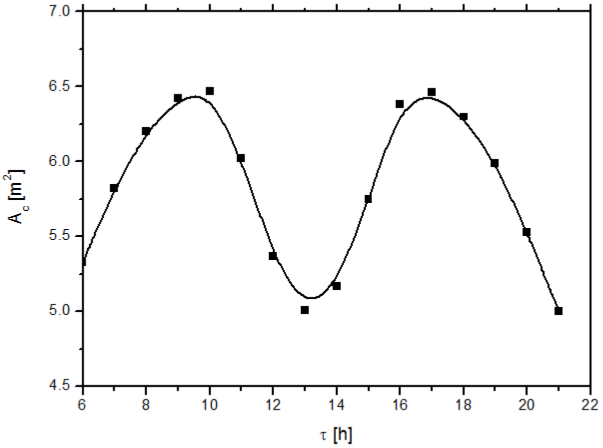

Fig. 7. Estimated value of cross-section of reactor, perpendicular to solar rays — A_C, in Koethen 15.07 for local time τ

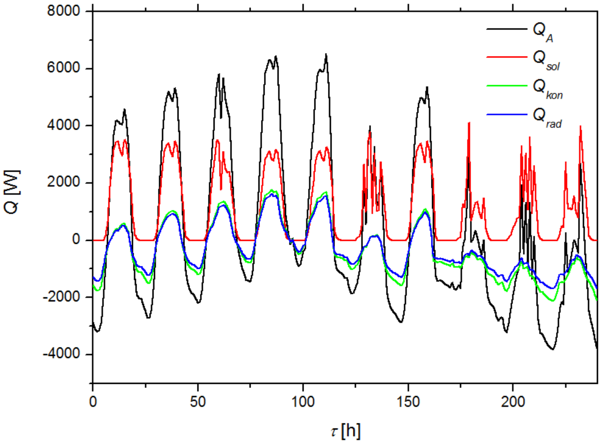

Fig. 8. Thermal load of GICON-PBR reactor during 10 days of July 2015 — $\dot{Q}_A$, and contributions from solar insulation, $\dot{Q}_{sol}$, heat exchange between the algae suspension and ambient air, $\dot{Q}_{kon}$, and radiative heat flux exchanged between reactor and ambient air, $\dot{Q}_{RAD}$; suspension temperature 25°C

In order to estimate the thermal load and contribution from various processes it was assumed that suspension temperature is constant and equal 25°C. The cross-section of reactor, perpendicular to solar rays A_C; was calculated taking into account the change of solar altitude during the day, year and for location (Koethen was assumed here). The results of calculations are presented in Figure 7.

Later, thermal load of PBR reactor $\dot{Q}_A$, as well as contributions from solar insulation $\dot{Q}_{sol}$, heat exchange between the algae suspension and ambient air $\dot{Q}_{kon}$, and radiative heat flux exchanged between reactor and ambient air $\dot{Q}_{RAD}$, was determined — see Figure 8. It is easily seen that the contribution from solar insulation is largest, around 3000 W (exceeds even more than 2 times other similar contributions). When ambient temperature declines the $\dot{Q}_{kon}$ and $\dot{Q}_{RAD}$ can assume even negative values.

It was assumed that shell and tube thermal energy storage will be applied of geometry shown in Figure 9. Heat exchange will find place at tube surfaces separated by 0.01 m. The tubes containing water are placed in container filled with chosen PCM material.

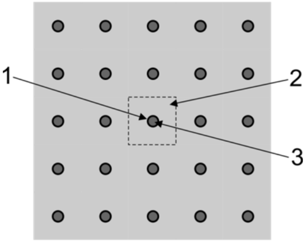

Fig. 9. Cross-section of heat storage (and exchanger): 1 — tube made from polypropylene, 2 — PCM material, 3 — water as heat transfer fluid

3.3. Results and discussion

Series of calculations have been performed for the 6 cases presented in Table 1. Figure 10 presents averages suspension temperature for the cases 1 and 2; heat storage filled with water volume of about 5,5 (10 tubes) and 550 dm^3 (1000 tubes), respectively. The blue lines represent maximum day and night temperatures, i.e. 28 and 16°C, respectively. It was found that there are 6 days when the temperature exceeds the 28°C.

Table 1. Parameters of considered cases

No.	Material	Tube number	*M* [kg]
1	water	10	5.47
2	water	1000	546.6
3	RT18HC	1000	421.3
4	RT21	1000	421.3
5	RT21HC	1000	421.3
6	RT22HC	1000	382.9

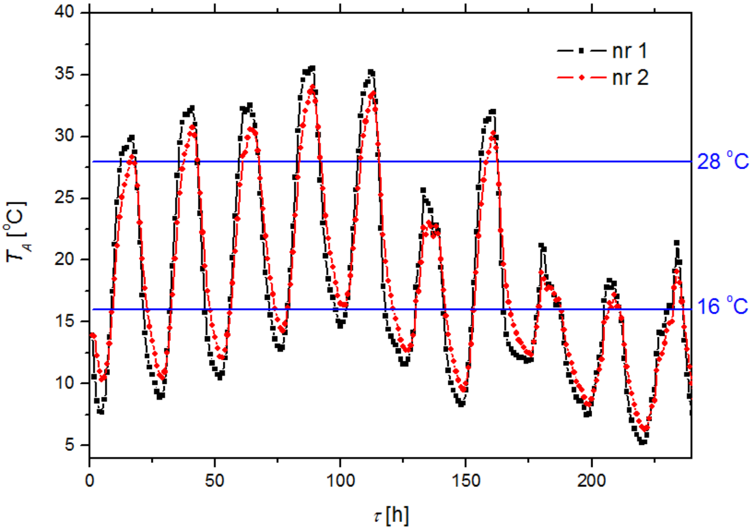

Fig. 10. Averaged algae-suspension temperature T_A during 10 days of July 2015 for the cases 1 and 2

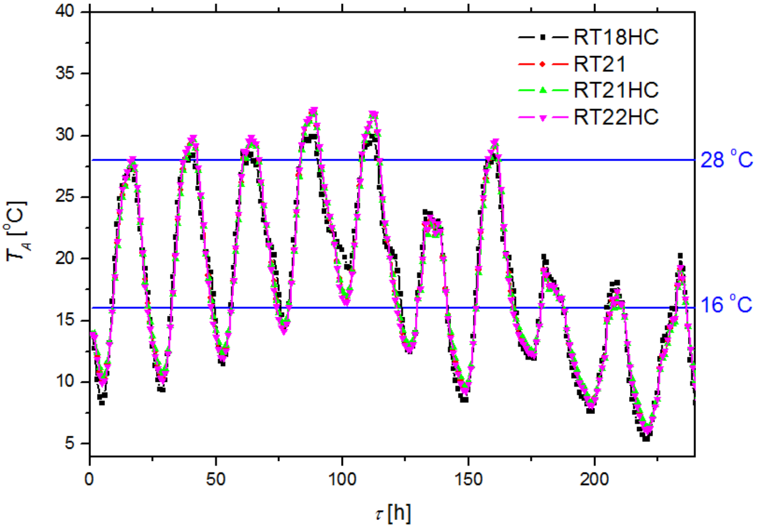

Fig. 11. Averaged algae-suspension temperature T_A during 10 days of July 2015 for the cases 3 till 6

Figure 11 presents averaged suspension temperature for the cases 3 till 6. It can be seen by comparing Figure 10 and 11 that PCM materials allow to reduce maximum values of suspension temperature, however, there are still days when temperature 28°C is exceeded. From detailed information in Figure 12 (for the day 4 and 5 when maximum temperatures are reached) it is obvious that the best results in temperature control in our system are achieved for RT18HC material, which accumulated cooling capacity at most. In the case of this material temperature 30°C have never been exceeded.

It is also seen from Figure 12 and 13 that during the night the suspension temperature may fall below optimal 16 C. However, this can be easily solved by turn-off cooling or by decreasing the cooling liquid flux.

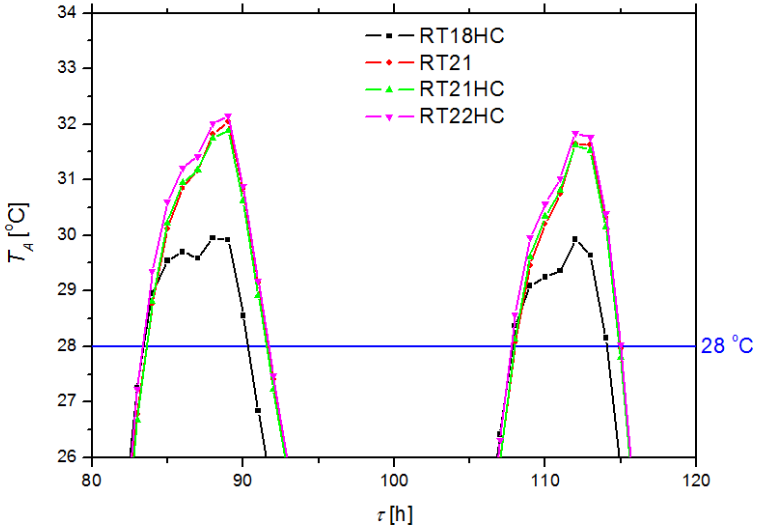

Fig. 12. Averaged algae-suspension temperature T_A during 2 days of July 2015 for the cases 3 till 6

4. Conclusions

The incoming sunlight intensity is the only process parameter, which is not easily controllable, as it is affected by clouds and other weather conditions, but strongly influences the culture temperature. The temperature control within optimal range is important to maintain ideal growth conditions for microalgae. Here, it was found that additional buffer cooling capacity by applying PCM storage can enable temperature stabilization of algae suspension. It was found that application of storage filled with RT18HC PCM material enable e.g. to limit the maximal temperature to 30°C, for GICON-PBR reactor placed in Koethen. The presented model will be verified by planned experiment in IMP PAN Gdańsk.

An efficient temperature control system allowed a year-round phototrophic cultivation at outdoor conditions using the "Christmas tree" photobioreactor (cultivation tests were performed at microalgae platform at Anhalt University of Applied Sciences, Koethen/Germany). The same microalgae culture was maintained, without having to re-inoculate fresh one from the laboratory (Matthes et al. 2015a, 2015b). In accordance with the incoming solar radiation over the whole year, the biomass productivity behaves in a defined way (see Figure 13). This demonstrates the possibility of a determined and plannable production.

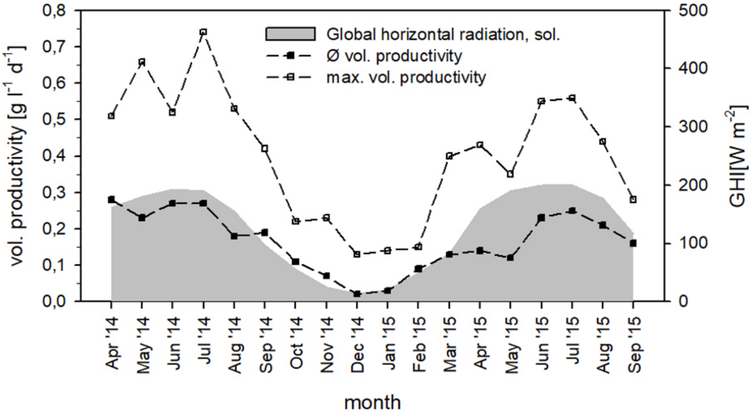

Fig. 13. Volumetric biomass productivity and incoming solar radiation of year-round production of microalgae cultivation

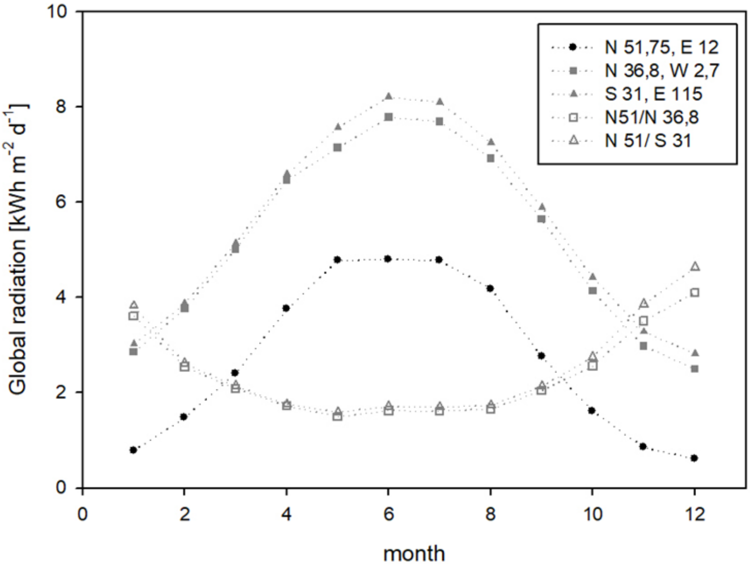

Fig. 14. Profiles of year-round radiation, based on monthly data obtained and adopted from NASA SSE Release 6.0; July 1983 till June 2005 (Retrieved from: https://eosweb.larc.nasa.gov/sse/)

Low values of biomass productivities in the winter months are a result of very low incoming solar radiation, typical for the location at Anhalt University of Applied Sciences in Koethen (Germany) at a northern latitude of almost 52°. Comparing the yearly radiation profile to other locations worldwide, preferably closer and within the tropics, respectively, it can be concluded, that the entire radiation profile reaches higher values (Figure 14). With regard to the results in Figure 13, not only a higher biomass production from spring to fall, but even higher growth rates in winter months should be possible in those locations, making a year-round production even more feasible.

A plannable production with stable and defined product qualities is an important condition for increasing amounts of microalgae biomass and microalgae-derived high value products. A sustainable and resource-conserving way of microalgae production, especially when looking at fresh water consumption, ensures a viable way of biomass production in the future.

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