CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF MECHANICAL ENGINEERING
DEPARTMENT OF PROCESS ENGINEERING

DESIGN OF PILOT-PLANT EFFECTIVE PHOTOBIOREACTORS

MASTER THESIS

VOJTĚCH BĚLOHLAV

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Title: **Design of pilot-plant effective photobioreactors**

Zásady pro vypracování:

V diplomové práci se zaměřte na možnosti využití emisního oxidu uhličitého k výrobě biopaliv 3. generace. V rámci práce zpracujte následující dílčí cíle:

1. Sumarizujte základní informace o technologiích, jejich procesních parametrech a výtěžnostech mikrořas. Zpracujte literární, průmyslovou a patentovou rešerši zaměřenou na konstrukci fotobioreaktorů pro instalaci v interiéru. Proveďte kritické zhodnocení jednotlivých konfigurací fotobioreaktorů z několika hledisek (konstrukce, výtěžnost řas, lokální klimatické podmínky aj.), definujte slabá místa konstrukcí a diskutujte možnosti optimalizace stávajících konfigurací z hlediska zvýšení výtěžnosti mikrořas.
2. Na základě kritické analýzy navrhněte tři technologická řešení intenzifikované produkce mikrořas v laboratorním měřítku a konstrukční řešení fotobioreaktorů včetně instalace podpůrných technologických okruhů.
3. Proveďte potřebné návrhové, procesní a pevnostní výpočty, a vypracujte konstrukční dokumentaci ke všem jednotkám ve formě kótované sestavy pro fotobioreaktory a ve formě aparátových listů pro ostatní klíčová zařízení.

Rozsah grafických prací:	dle potřeby
Rozsah průvodní zprávy:	dle doporučení vedoucího práce
Seznam odborné literatury:	dle doporučení vedoucího práce a vlastní rešerše
Vedoucí diplomové práce:	prof. Ing. Tomáš Jirout, Ph.D.
Konzultant diplomové práce:	Ing. Lukáš Krátký, Ph.D.
Datum zadání diplomové práce:	25. dubna 2016
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V Praze dne 19. dubna 2016

I declare that I have developed and written the enclosed master thesis completely by myself under the supervision, and have not used sources or means without declaration in the text. Any thoughts from others or literal quotations are clearly marked.

Prohlašuji, že jsem diplomovou práci vypracoval samostatně pod vedením vedoucího diplomové práce a uvedl jsem všechny použité podklady a literaturu.

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Vojtěch Bělohlav

Hereby I would like to thank to prof. Ing. Tomáš Jirout, Ph.D. and Ing. Lukáš Krátký, Ph.D. for their valuable advices and suggestions, which helped me to accomplish my master thesis.

Děkuji prof. Ing. Tomáši Jiroutovi, Ph.D. a Ing. Lukáši Krátkému, Ph.D. za cenné rady a připomínky, které mi pomohly k dokončení mé diplomové práce.

Anotační list

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Anotace česky: Diplomová práce je zaměřena na proces kultivace mikrořas a návrh modelových fotobioreaktorů. Hlavním cílem práce je návrh tří laboratorních zařízení pro produkci mikrořas včetně návrhu instalace podpůrných technologických okruhů. V rámci práce byla vypracována rešerše, která se zabývá technologií kultivace, procesními parametry a výtěžností řas. V návaznosti na kritické analýze fotobioreaktorů byla navržena tři technologická řešení za účelem intenzifikace produkce mikrořas v laboratorním měřítku. V práci je popsán návrh jednotlivých částí zařízení a výsledky návrhu jsou zobrazeny v 3D modelu. Celková konstrukce jednotlivých zařízení je zobrazena ve výkresu sestavení.

Anotace anglicky: The aim of this master thesis is the process of algae cultivation and design of the scale-up cultivation systems. The main objective of this work is to provide a design of the three different scale-up laboratory photobioreactors including technological support equipments. Within the research work, an overview of existing methods of algae cultivation, operational parameters and yield of algae has been elaborated. Furthermore, within the design section, a design of three photobioreactors for intensification of algae production has been elaborated. Therefore, with help of the modeling software, 3D models and design drawings of individual conceptions has been provided.

Klíčová slova: algae, microalgae, photobioreactor, cultivation, biomass, biofuels, řasy, mikrořasy, fotobioreaktor, biomasa, biopaliva

Využití: Laboratorní zařízení k produkci mikrořas.

Contents

1. Introduction

In the recent years, many countries in the world have made large effort to reduce energy generated by the combustion of fossil fuels in the recent years. Almost $80\ \%$ of global energy consumption was derived from fossil fuels in 2014. This consumption value means about $98\ \%$ of CO_2 emission caused by fossil fuel combustion. Another drawback is that these fuels are non-renewable and will deplete over time. For this purpose, new strategies are required to attain energy security as well as to mitigate CO_2 emission. Taking into account the above mentioned factors, using biofuels as potential source to meet future energy demand seems to be the most appropriate option. Production of liquid biofuels grows rapidly in the recent few years. The first generation biofuels have already reached commercial level. The main advantage of the second generation is that they do not directly compete with arable land and have therefore a lower environmental impact. On the other hand, they have a lower conversion rates in comparison with the first generation biofuels. Algae biomass is classified as a third generation feedstock and has a potential for biofuel, food, feed and chemical production. However, challenges to commercialize the production at a large scale need to be solved.

The aim of the first part of this diploma work is to provide an overview of existing design alternatives for algae cultivation. Algae can be cultivated from various aqueous systems. Currently, autotrophic production is the only method which is economically and technically feasible for scale-up production of algae biomass. Until now a number of different laboratory cultivation systems and systems used in industry have been developed. However, it is not easy to exactly assess which equipment or system is operationally appropriate. The type of algal species and the location of the equipment itself can greatly affect the productivity of algae. The comparison of various photobioreactor alternatives has been elaborated and their benefits and drawbacks have been specified.

The aim of this diploma work is to provide a design of three different scale-up laboratory cultivation systems. This work has been developed within the frames of a joint project of Czech Technical University in Prague, University of Chemistry and Technology in Prague and Unipetrol Centre of Research and Education. In the design section, a proposal of basic parameters of systems according to the selected operating requirements will be elaborated.

On order to compare various equipments, it is necessary to provide identical operational conditions for all photobioreactors. With the help of the modeling software, 3D models and design drawings of individual conceptions and a laboratory with attached equipments will be provided.

2. Theoretical part

Many countries in the world have made large effort to reduce energy generated by combustion of fossil fuels in the recent years. Almost $80\ \%$ of global energy consumption was derived from fossil fuels in year 2014 (Fig. 1). This consumption value means about $98\ \%$ of CO_2 emission caused by fossil fuel combustion. Another drawback is that these fuels are non-renewable and they will deplete over time. For this purpose, new strategies are required for energy security as well as to mitigate CO_2 emission [1].

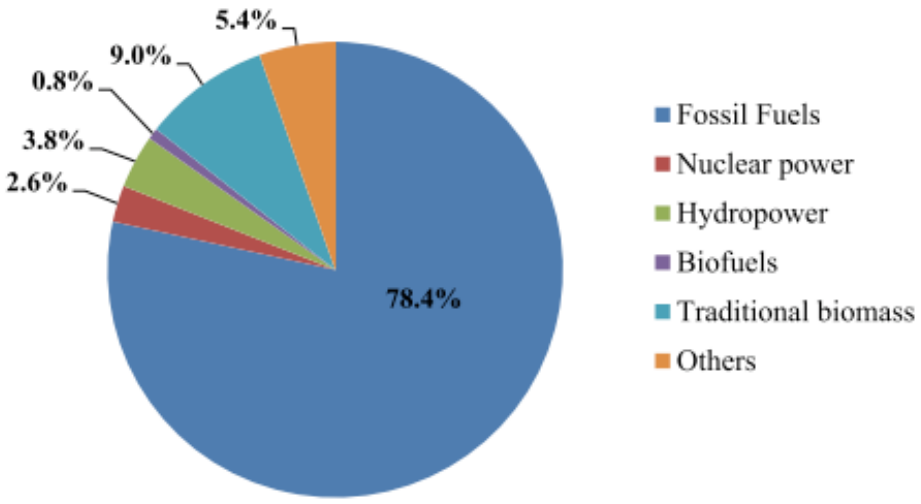

Fig. 1 Global energy consumption in 2014 [1]

Taking into account the above mentioned factors, using biofuels as potential source to meet future energy demand seems to be the most appropriate option. There is rapid global growth in liquid biofuels in the recent few years. The first generation biofuels mainly consisted of feedstocks, such as starch, oil crops and animal fats, have already reached commercial level. The second generation feedstocks derived from biomass sources are mostly agricultural and wood processing residues or non-edible components from food crops. The main advantage is that they do not directly compete with arable land and have therefore a lower environmental impact. On the other hand, they have a lower conversion rates in comparison with the first generation biofuels. Algae biomass is classified as a third generation feedstock and has a potential for biofuel, food, feed and chemical production. The main benefit of algae is their growth yields and low land requirement. Algae are possible to grow with large diversity of biomass content on salt water or waste water as well [2].

2.1. Algae

Algae are part of a large and diverse group of simple aquatic organisms that are mostly microscopic [3]. The characteristic of algae is that they are able to convert sunlight, CO_2 and water with nutrient to biomass through photosynthesis in the same way as other plants. By capturing CO_2 from the atmosphere, plants have the ability to produce oxygen and approximately 77 gigatons of fixed CO_2 leading to a production of 100 gigatons of biomass annually. However, algae have higher photosynthetic efficiency than other crops, which leads to a conversion of approximately 183 gigatons of CO_2 to 100 gigatons of algae biomass. They can grow at a faster rate than other land based crops and can live in diverse environment with basic nutrient requirements [1].

Algae represent a large variety of species, which live in a wide range of environmental conditions. Nowadays, it is estimated that more than $50\ 000$ species exist worldwide. On the other hand, limited number of around $30\ 000$ have been analyzed yet. The population of algae is generally defined according to their pigmentation, life cycle and basic cellular structure. Generally, therefore, algae can be divided into three groups according to the type of their life cycle [4].

Autotrophic

Only inorganic compounds such as CO_2, salts and light energy source are required for proper growth. Currently, it is the only production that is technically and economically feasible for large-scale production of algae biomass.

Heterotrophic

Only external source of organic compounds, nutrients and energy source are required because heterotrophic algae are non-photosynthetic. These systems provide a high degree of growth control but lower harvesting costs due to the higher cell densities that are achieved.

Mixotrophic

They are capable of using either process for growth. It means that light energy is not an absolutely limiting factor for growth because organic carbon substrates can support the growth as well.

The most important groups of algae according to the type of their pigmentation are:

- Red algae – Rhodophyceae
- Green algae – Chlorophyceae
- Brown algae – Phaeophyceae

The product range of algae biomass is very versatile and Figure 2 shows an overview of algae biomass potential applications.

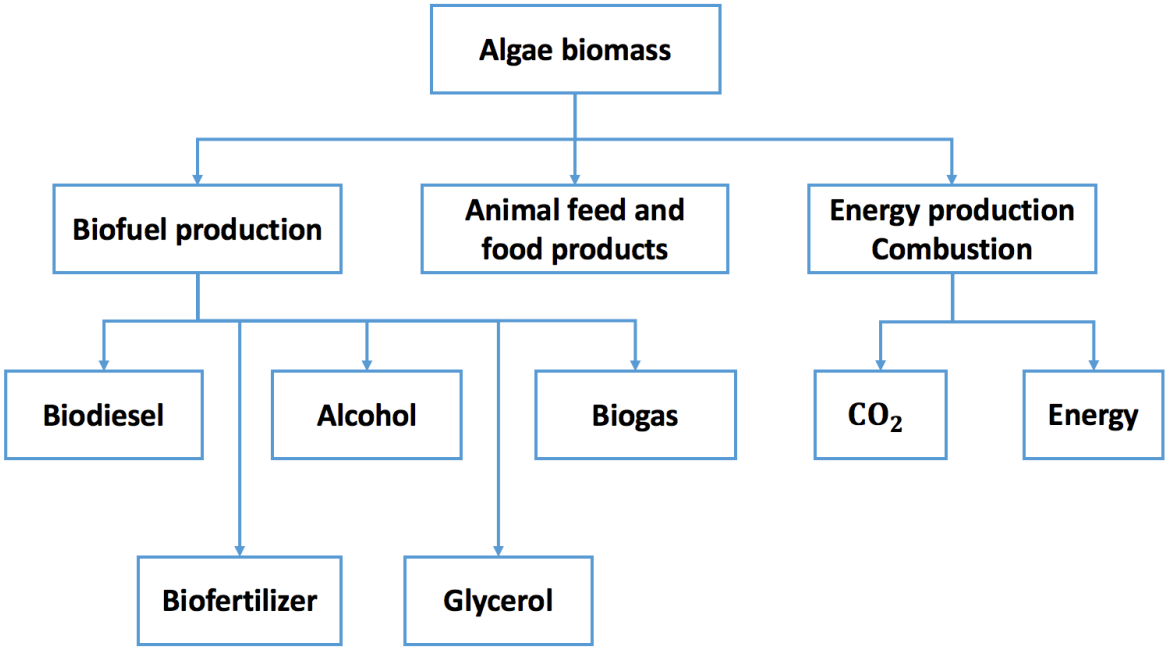

Fig. 2 Algae components and their potential applications [1]

The use of algae biomass for human consumption is restricted to very few species due to the strict food safety regulations. Those specific algae species have beneficial aspects including improved immune response, improved fertility and better weight control. Algae are also the natural food source for fish and shrimps. Some conversion technologies allow us to use algae in agricultural applications as a biofertilizer [4].

Algae biomass cellular structure consists mainly of lipids, proteins, carbohydrates and pigments. The lipid content is highly dependent on the algae species and lipids are extracted to produce for instance biodiesel, whereas carbohydrates are extracted to produce ethanol. The composition of lipids, proteins and carbohydrates of different algae species are shown in Table 1 [1].

Algae	Lipids [wt. %]	Proteins [wt. %]	Carbohydrates [wt. %]	Biomass productivity $[g_{biomass}\ L^{-1}\ day^{-1}]$
Anabaena cylindrica	4-7	43-56	25-30	-
Chlorella ellipsoidea	84	5	16	-
Chlorella pyrenoidosa	2	57	26	2.90-3.64
Chlorella vulgaris	14-22	51-58	12-17	0.02-0.20
Euglena gracilis	14-20	39-61	14-18	7.70
Prymnesium parvum	22-38	30-45	25-33	-
Scenedesmus obliquus	12-14	50-56	10-17	0.004-0.74
Spirulina maxima	6-7	60-71	13-16	0.21-0.25
Spirulina platensis	4-9	46-63	8-14	0.06-4.3
Tetraselmis maculata	3	52	15	0.12-0.32

Table 1 Compositions of algae in dry matter basis [1] [5]

It is possible to increase lipid concentration by optimizing the control of nitrogen level, light intensity, temperature, CO_2 concentration and harvesting procedure. In indication of the potential costs of liquid biofuel production it is more useful to consider lipid productivity, which takes into account overall biomass productivity, than lipid concentration in algae biomass [4].

2.2. Biofuel production

The first generation biofuels are still limited since they directly compete with agricultural land, which is normally used for food crops. For this purpose, they have generated a lot of controversy due to their influence on global food markets and on food security. The second generation biofuels are not directly competing with agricultural land because they are derived from agricultural, forest harvesting and wood processing residues. It is necessary to define conditions of biofuel resource to satisfy technical and economical demands. Firstly, it should be competitive or cost less than fossil fuels. It should fulfill demands of low or no additional land use in comparison with the first generation biofuels and it should enable air quality improvement with minimal water use. Taking into account all conditions needed to satisfy demands, algae seem to be the most appropriate option and they could meet these conditions.

Algae can be one of the main components for several different types of biofuels, for instance: biodiesel, methane, hydrogen, ethanol (Fig. 2). There are many advantages of using algae for the biodiesel production because they are easy to cultivate and can complete an entire growth cycle every few days [4].

Plant source	Seed oil content $\left[\frac{kg_{oil}}{kg_{biomass}}\right]$	Oil yield $\left[\frac{L_{oil}}{ha \cdot year}\right]$	Land use $\left[\frac{m^2}{kg_{biodiesel} \cdot year}\right]$	Biodiesel productivity $\left[\frac{kg_{biodiesel}}{ha \cdot year}\right]$
Corn	44	172	66	152
Soybean	18	636	18	562
Sunflower	40	1 070	11	946
Palm oil	36	5 366	2	4 747
Low oil content algae	30	58 700	0.2	51 927
Medium oil content algae	50	97 800	0.1	86 515
High oil content algae	70	136 900	0.1	121 104

Table 2 Comparison of algae with other biodiesel feedstocks [5]

Algae can grow almost anywhere, requiring sunlight and basic nutrients and, moreover, they require much less land area than other biofuel feedstocks. Despite the fact that the oil

contents in algae and seed plants are similar, there are significant differences in the overall biomass productivity and resulting oil yield according to the required land area (Table 2). Those attributes have the major influence on biodiesel productivity [5]. Moreover, algae biomass treatment differs from other biodiesel feedstocks due to they are microorganisms living essentially in liquid environments. All existing processes for algae biodiesel production include particular cultivation, harvesting, lipid extraction and conversion processes (Fig. 3).

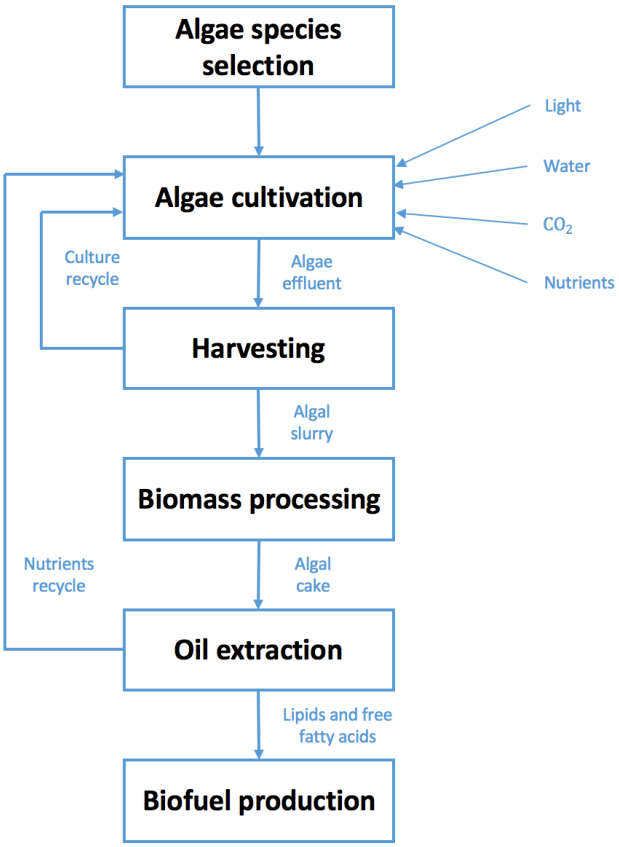

Fig. 3 Algae biodiesel production chain [5]

- Taking into account the factors mentioned in paragraph 2.1., autotrophic cultivation is the most common way of algae cultivation. Selection of the appropriate cultivation system for algae biofuels production is highly influenced by the type of algae species, applied technology and biological conversion process.
- Harvesting process is generally costly due to necessary water removal. It is important to choose appropriate harvesting method to minimize the operating cost because it accounts about 20-30 % of the total biofuel production costs on average. It is possible

to divide harvesting process into two steps. In the first step, biomass is separated from the bulk culture by flocculation, flotation or sedimentation. Thereafter biomass slurry is concentrated by techniques like centrifugation and filtration.

- For biodiesel production, it is necessary to extract lipids and fatty acids from algal biomass. Solvents, such as hexane or ethanol, are generally used for the lipid extraction. It is time-saving and efficient method that slightly reduces the degradation. However, ethanol can also extract undesirable components such as proteins or pigments.
- Generally, conversion processes of biomass into biofuels can be divided into three groups: chemical conversion, biochemical conversion and thermochemical conversion. A particular group contain further sub techniques and their final products. Conversion process of algae biomass is shown in Figure 4.

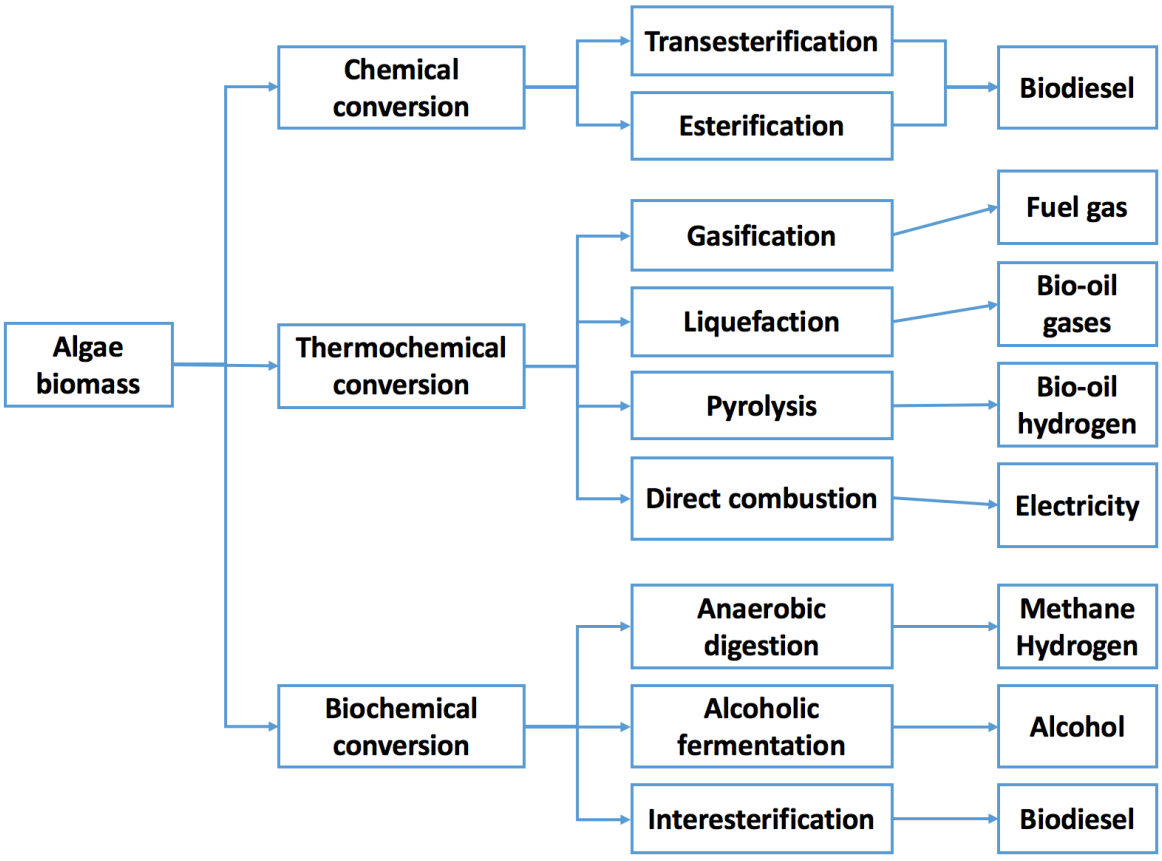

Fig. 4 Conversion process of algae biomass [1]

3. Background and motivation

Fossil fuels are the largest source of greenhouse gases. Mitigation strategies are therefore required to neutralize the excess of CO_2. The 2015 United Nations Climate Change Conference was held in Paris, where the participating 195 countries agreed to reduce emissions as part of the method for reducing greenhouse gas. The members agreed to reduce their CO_2 outputs and to do their best to decrease global warming.

For this purpose, new strategies are required for energy security as well as to mitigate emission. Therefore, renewable energy technologies expand and receive a lot of attention. Biofuels from algae biomass have the potential to replace fossil fuels; moreover, it is possible to use them to mitigate the CO_2 emission from the atmosphere. However, challenges to commercialize the production at large scale need to be solved. The demand for biofuels is not that high due to the low market price of fossil fuels, the high cost of the biofuels produced from algae and slow return of investment. Taking into account the previously mentioned influences, it is necessary to improve technologies before algae biofuel production can become economically viable. This should be accomplished together with political and economic support by governments, which will probably increase due to the outcomes of the United Nation agreement. Nowadays, there are many various kinds of systems for algae cultivation. Generally, cultivation systems can be further divided into open or closed systems depending on their design conditions.

The aim of this diploma work is to provide a design of the three different scale-up laboratory cultivation systems. This work has been developed within the frames of a joint project of Czech Technical University in Prague, University of Chemistry and Technology in Prague and Unipetrol Centre of Research and Education. Within the conceptual design and study of alternatives, an overview of existing methods of algae cultivation has been elaborated. The main objective of this section is to provide an overview of the techniques and equipment used for cultivating. Furthermore, within the design section, a design of basic parameters of systems according to the selected operating requirements has been elaborated. Therefore, with help of the modeling software, 3D models and design drawings of individual conceptions has been provided.

Finally, the aim of the project is to obtain economically and technically viable design of algae cultivation system, which could be applicable within the production system of Unipetrol refinery and petrochemical group. The most suitable design of the system should come from the experimental operation of each of the equipments according to the same operating conditions.

4. Photobioreactors

The main objective of the following section is to provide an overview of techniques and equipment used for algae cultivation. For the selection of the proper cultivation system, it is necessary to define operational parameters which most affect the function. It is required to consider environmental impact and adjust the entire system concept for the effective production of algae biomass as well. Finally, it is important to consider all characteristics of the various possibilities and evaluate their advantages and disadvantages.

4.1. Algae cultivation

Proper algae growth and biomass productivity depends on several properties and factors. Generally, algae need light and nutrients at a certain temperature to grow properly. However, too high intensity light or oxygen level can negatively affect growth. Type of dependence is strictly connected with the particular algae species. Some of them grow well at low temperatures and low light intensities, whereas others need higher irradiance. The selection of the most suitable species needs to take into account other factors, such as for instance equilibrium between operational parameters: level of oxygen and CO_2, pH, product concentration or water consumption. Algae biomass production is based on a simple scheme, which define all requirements of this biological process [7]:

$$CO_2 + H_2O + \text{nutrients} + \text{light energy} \rightarrow \text{biomass} + O_2 \quad (1)$$

4.1.1. Light

In all algae cultivation systems, the light source and light intensity are critical factors affecting the condition of the autotrophic algae growth. Generally, cultivation systems can be divided into two groups: outdoor and indoor. For outdoor cultivation system, sunlight is the major light source, whereas artificial light sources are used for indoor cultivation systems. On the other hand, it is also possible to use sunlight as a source for indoor systems by transmitting solar energy from outside to illuminate indoor systems with the help of optical fiber systems [6]. The main advantage of sunlight energy is that it is for free and abundant and therefore its

use avoids the necessity for investment or electricity costs. However, sunlight is primarily restricted to the surface that could lead to large surface area requirement. Moreover, sunlight intensity varies with day and night cycle, changing weather conditions and with seasonal changes. These aspects are strictly connected with algae growth rate and metabolism. Specifically, in the Czech Republic, it is necessary to consider these factors in the first place. The total duration of sunlight is $1400 - 1700$ hours per year, which represents approximately $16 - 20$ % sunlight during the whole year. Moreover, sunlight covers a wide spectral range but only light within the range of 400 and 700 nm is photosynthetically active radiation, which accounts for approximately 50 % of sunlight. The fluctuations in sunlight can be avoided by the application of artificial light sources. The main benefit is that artificial source is stable, controllable and it allows more choices in location. For this reason, the light utilization efficiency and algae biomass productivity are usually higher under artificial light sources, as compared with natural sunlight. On the other hand, the capital investment and operation costs are higher than for sunlight cultivation system which leads to higher final production costs [8]. The features and electricity consumption of using different artificial light sources are shown in Table 3.

Light source	Feature	Operation stability	Electricity consumption of the light source
Conventional artificial light sources	• **Higher biomass productivity** • **Higher stability** • **Large illumination area** • **Low constructing cost**	**High**	**High**
LED (Light-Emitting diode)	• **Lower energy consumption** • **Lower heat generation** • **Longer life-expectancy** • **Higher stability** • **Low constructing cost**	**High**	**Moderate**
Optical fiber excited by solar energy	• **Low electricity consumption** • **Good light path** • **Uniform light distribution** • **Lower space requirement** • **Low contamination risk** • **Lower cost**	**Low**	**Low**

Table 3 Artificial light sources features and electricity consumption [9]

The light energy received by autotrophic microorganisms depends on the irradiance $I\ [\mu E\ m^{-2}s^{-1}]$, which is expressed as photon flux density on the culture surface. The influence of irradiation on the *Chlorella* algae species areal productivity is shown in Table 4. Areal productivity $P_A\ [g\ m^{-2}\ day^{-1}]$ is a value that indicates the daily algal production per irradiated surface. Values of areal productivity from Table 4 are shown in Figure 5. Following to this, an increase of areal productivity with increasing irradiance is evident [24].

Cultivation system	Light configuration	Irradiance $[\mu E\ m^{-2}s^{-1}]$	Areal productivity $[g\ m^{-2}\ day^{-1}]$
Thin-layer	**Outdoor**	**400**	**22**
Thin-layer	**Outdoor**	**500**	**23**
Thin-layer	**Outdoor**	**540**	**19**
Thin-layer	**Outdoor**	**700**	**38**
Thin-layer with LED	**Indoor**	**141**	**18**
Thin-layer with LED	**Indoor**	**661**	**57**
Thin-layer with LED	**Indoor**	**2100**	**185**
Flat panel	**Indoor**	**17.5**	**1.3**
Flat panel	**Indoor**	**115**	**2.6**
Flat panel	**Indoor**	**980**	**47**
Tubular - conical helical	**Indoor**	**484**	**31**
Tubular - conical helical	**Outdoor**	**580**	**33**
Tubular - static mixer	**Indoor**	**150**	**7.6**
Tubular - static mixer	**Outdoor**	**333**	**14**
Tubular - static mixer	**Outdoor**	**400**	**10**
Tubular - static mixer	**Outdoor**	**420**	**37**
Tubular - static mixer	**Outdoor**	**420**	**46**
Column - rotating	**Indoor**	**1500**	**103**
Internally irradiated	**Indoor**	**205**	**14**
Internally irradiated, mechanically stirred	**Indoor**	**1750**	**136**

Table 4 Cultivation system performances [24]

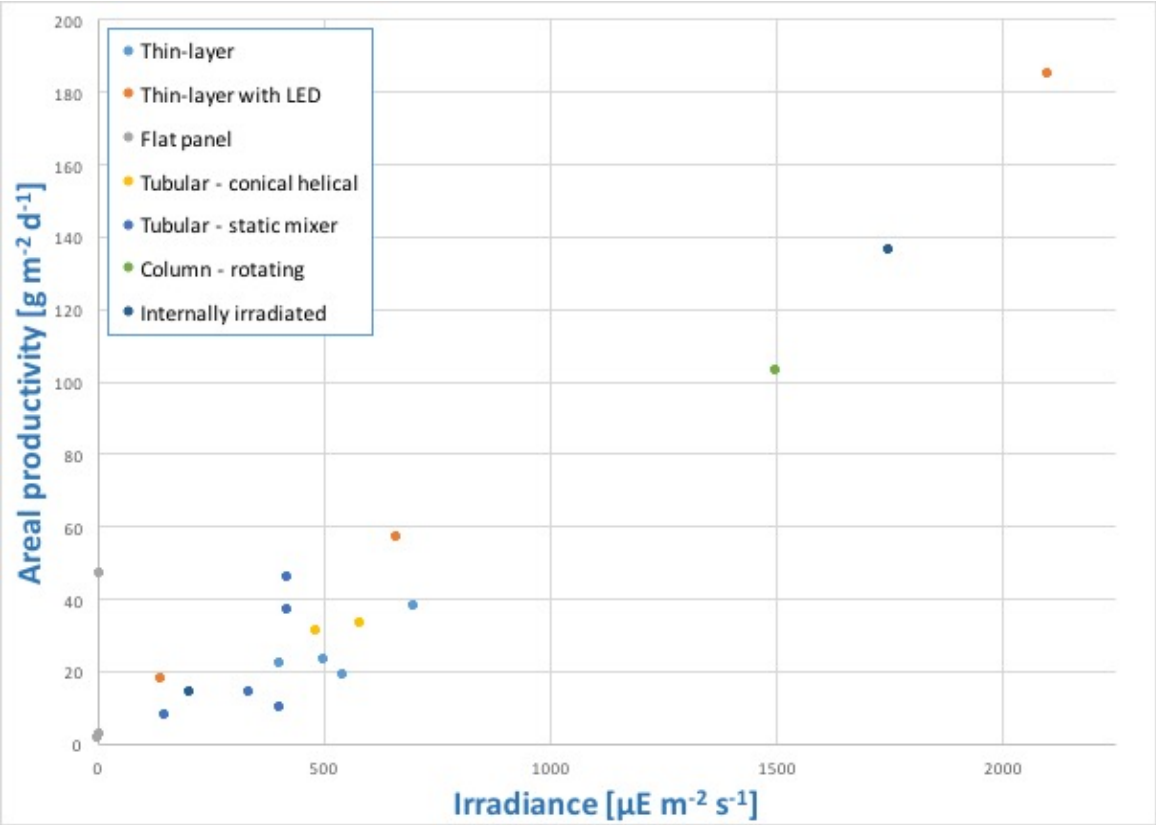

Fig. 5 Cultivation system performances

The choice of the light source should consider the balance between economic aspects and requirements for the end products. In conclusion, with respect to climate in the Czech Republic, use of artificial source of light seems to be better option. In electricity consumption and operation stability terms, LED light source appears as appropriate.

4.1.2. Temperature

Algae culture growth rate varies as much as the temperature changes. Although algae are possible to grow at a variety of temperatures, the optimal range is within 15 and 30 °C. However, some algae species tolerate a broad range of temperatures between 15 and 45 °C. For this reason, it is appropriate to use closed indoor system because of its easier temperature control [7].

4.1.3. Absorption of CO_2

Utilization of CO_2 by algae for their growth can be divided into two main stages: the absorption of CO_2 by the mass transfer and the fixation of CO_2 by photosynthesis. Besides light and water, also CO_2 is a necessary component for proper photosynthetic cultivation. The aim of the absorption is to reduce the mass transfer resistance. Transfer area can be increased by bubbling or absorption in packed bed. In bubbling, the gas stream is broken into small bubbles, which cause a wider area of contact between gas and water. The packed bed allows gas and water to get in contact in counter current manner. The fixation of CO_2 means uptake by algae for its their growth. Algal photosynthesis efficiency has been described in paragraph 2.1. Carbon fixation can increase with increasing CO_2 residence time in bioreactors. This residence time required by algae depends on temperature and number of available photons. For this reason, the time for CO_2 absorption from gas by water should be similar to the time required for fixation of CO_2 by algae [13]. To overcome the problems of CO_2 escape from working area, a proper storage mechanism is essential to maximize the utilization of CO_2 for algae growth. However, the mechanism must be suitable for O_2 removing from algae as well, because high level of O_2 around algae cells is undesirable. The source of CO_2 may be surrounding air at a CO_2 concentration of about 0.035 %. To intensify the growth, flue gas can be used, in which concentration of CO_2 ranges between 0.035 and 15 % [12].

As mentioned previously in paragraph 4.1.1., algal cells are able to utilize the photosynthetic active radiation with the wavelength range between 400 and 700 nm. In addition, it is well known that carbon is the most important element in algae cells and it can reach up to 50 % of the dry biomass. The influence of the light conditions and CO_2 concentration on CO_2 fixation rate in *Chlorella vulgaris* species has been studied in [30]. The study has demonstrated the influence of five different light spectrums and one as a blank test - control. The irradiation has been set at $200\ \mu mol\ m^{-2}s^{-1}$. Data measured (Fig. 6) in bubble column photobioreactor show that blue-spectrum light was the least efficient in CO_2 fixation at all aeration concentrations. However, increasing concentration of CO_2 in the gas mixture had significant impacts on CO_2 fixation in other luminescent spectrums.

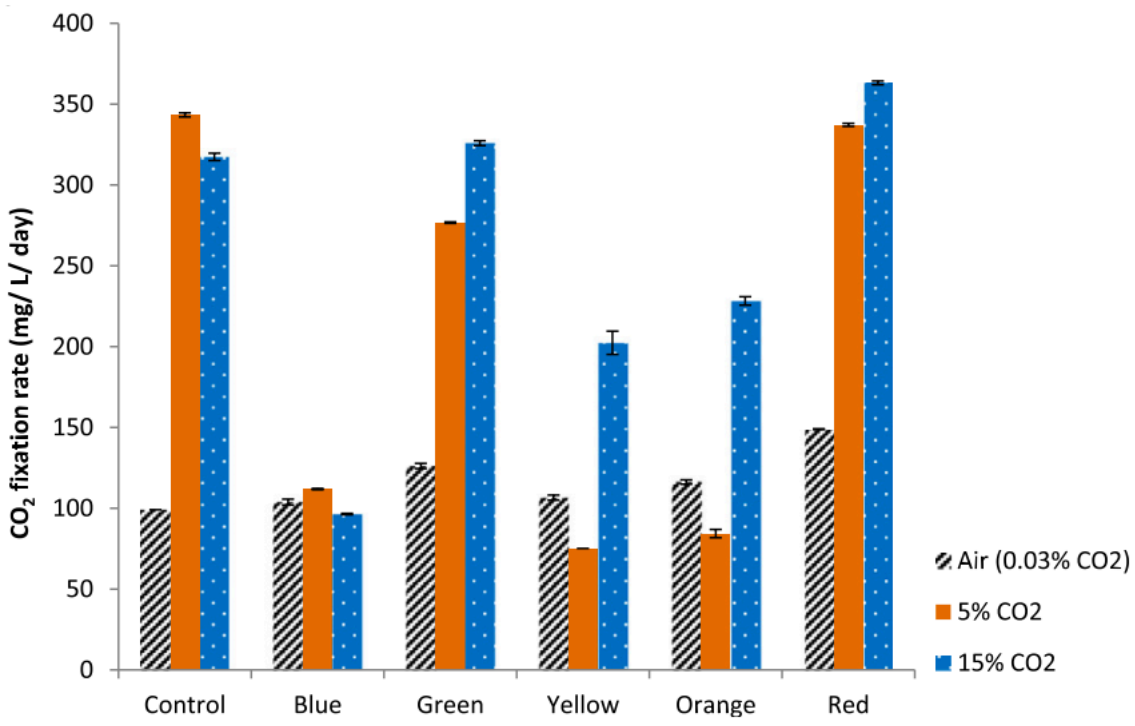

Fig. 6 Effect of various aeration conditions on CO_2 fixation rate in Chlorella in six different luminescent spectrums [30]

4.1.4. Nutrients

Algae require two major nutrients for proper growth: compounds of nitrogen and phosphorus. Both of them play a significant role in controlling growth rates and lipid production. Specifically, nitrogen is important for the metabolic processes. Other essential are for instance: carbon, oxygen, hydrogen, potassium, sulfur, calcium, sodium, magnesium and chlorine [10].

4.1.5. pH

Each of algae species has its narrow optimal range of pH. The optimal pH of most cultured algae species is in the range of 7-9. However, some species have their optimal pH value in acid or basic ranges. The pH of the medium is connected to the concentration of CO_2. Since pH is so fundamental, it is necessary to control it during the growth [11].

4.1.6. Agitation

Agitation is important for proper algae cultivation. It is necessary to prevent sedimentation of algae cells and ensure that all cells will have uniform average exposure time to light and nutrients. Stirring should also facilitate heat transfer and thus avoid formation of thermal gradient. Stirring technique can also be used to brake the gas stream into small bubbles, as mentioned in paragraph 4.1.3. On the other hand, stirring has to be optimized carefully because high intensity agitation may cause cell death from shear [11].

4.2. Environmental impact

Algae production could have significant influence on environmental impact due to the consumption of energy in the production process. Many of these impacts could affect system design and operation conditions. Nowadays, there is much progress in technologies to reduce the level of greenhouse gases in atmosphere. These technologies can be divided into three main groups: conservation, direct mitigation and indirect mitigation. Method used for reducing electric energy consumption is called conservation. Direct mitigation method is used to capture CO_2 directly from atmosphere and indirect mitigation is used to reduce CO_2 emission from production. CO_2 mitigation by algae biofuels production is considered to be in indirect mitigation method and its influence on environment has been described in paragraph 2.1. One of the suggested benefits of algae production is possible elimination of arable land occupation, thereby minimizing competition with food production (paragraph 2.).

Another advantage of algae production is that, besides biomass production, it can provide a pathway for the removal of nutrients, such as nitrogen and phosphorus, and also chemical and organic contaminants, heavy metals and pathogens from water. Studies have shown that algae can grow in fresh drinking water, saline or brackish water and even wastewater effluent. Moreover, wastewater rich in CO_2 content provides a support for proper algae growth. These features can reduce about of the energy used in cultivation of algae by about $50\ \%$ due to negative fertilizer impact on the cost of biofuels production. Therefore, combining algae biofuel production with wastewater treatment can offer a cost effective strategy since it can provide improvement in water quality as well as biomass production. On the other hand, there is also a drawback of algae cultivation in wastewater because algae harvesting may

become difficult and therefore more advanced technologies are needed to remove algae from the effluent, which means a higher cost. To reduce increasing cost, it is possible to use recirculating water in the system [14].

General scheme for algae oil production is show in Figure 7. The overall system consists of four main processing modules: algae growth, algae harvesting, algae oil separation and production. Hernández [15] presented optimal system design of biorefineries using CO_2 emissions from industrial plants and medium recirculation in algae processing.

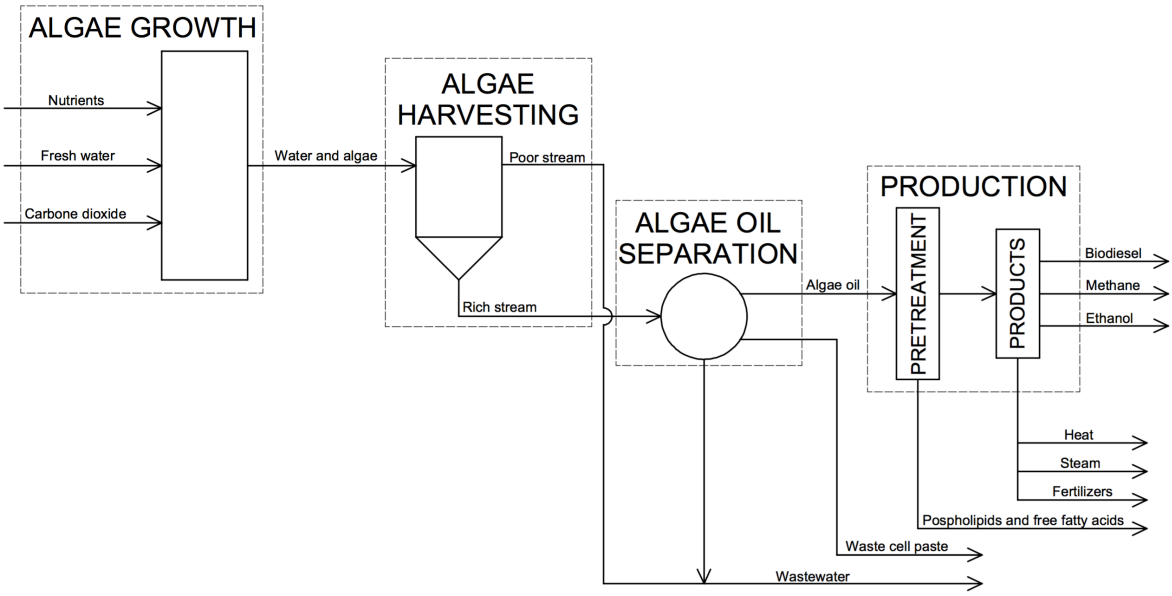

Fig. 7 General algae oil production scheme [15]

It is important to mention that algae harvesting module consumes much energy and therefore it represents $20 - 30\ \%$ of total biofuel production costs on average. In this module, it can be seen that there are two outlet streams: poor and rich. In other words, the rich stream has a high algae content and low water content, whereas the poor stream presents a low algae content and a high water content. The rich stream is used to obtain the algae oil and poor stream is discharged as a waste to the environment. However, there is an alternative option of handling the poor stream, namely in another part of the process. This option is shown in Figure 8. Similar concept is used in algae oil separation module, where water can be reused in the algae growth stage. In comparison with the first general scheme, flue gases are used as a main source of CO_2, which is absorbed in water [15].

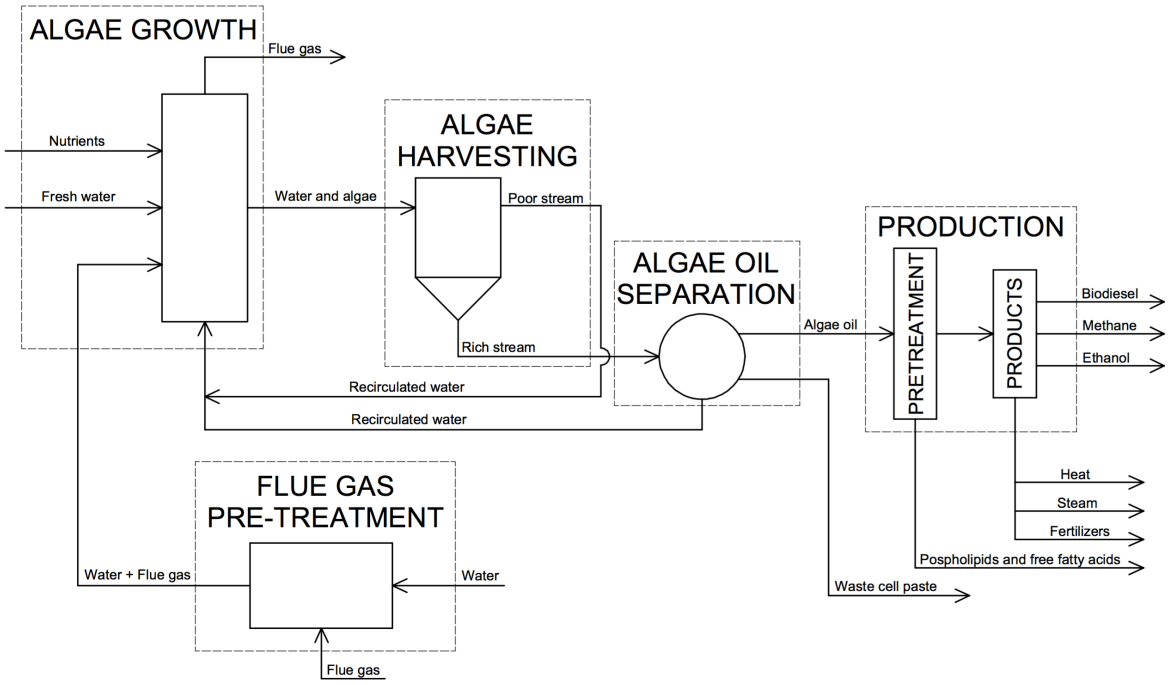

Fig. 8 Optimized algae oil production [15]

The results of the study show the importance of using flue gases as a source of CO_2 for algae growth. The positive economic effect related to biomass processing reduced the costs, associated mainly with the growth stage of the process, by almost $90\ \%$. Another savings are in investment and operating costs. Furthermore, all of this has been achieved in relation to mitigation of CO_2 emission [15].

4.3. Study of design alternatives

The aim of this paragraph is to provide an overview of existing design alternatives for algae cultivation. From the designs comparisons, it should be possible to obtain the most suitable cultivation systems. Algae can be cultivated from various aqueous systems. Currently, autotrophic production is the only method which is economically and technically feasible for scale-up production of algae biomass. Autotrophic cultivation systems can be divided into three main groups: open pond system, closed photobioreactor systems and hybrid photobioreactors [4].

4.3.1. Open pond systems

There is a number of open pond systems used for algae cultivation such as raceway, thin-layer cascade or shallow ponds. Nutrients are supplied to algae by channeling runoff water from land area, industrial disposal water or water treatment plant.

Raceway pond system

The most commonly used open cultivation system is the raceway pond (Fig. 9). The algae, water and nutrients are circulated around a racetrack using paddle wheels to keep algae suspended in water and allow utilization of CO_2 from atmosphere. Generally, the pond is shallow to provide an light penetration into algae in order to maximize photosynthesis effect. Raceway pond operates continuously: water and nutrition are supplied into the pond, whereas mature algae are removed. It has a potential to produce relatively large quantity of algae. However, the main drawback is that it is difficult to control surrounding environmental condition such as medium temperature, weather and possibility of contamination. These condition can significantly affect algae biomass production due to evaporation losses, temperature fluctuation in algae growth, CO_2 deficiencies, inefficient agitation and light limitation [1].

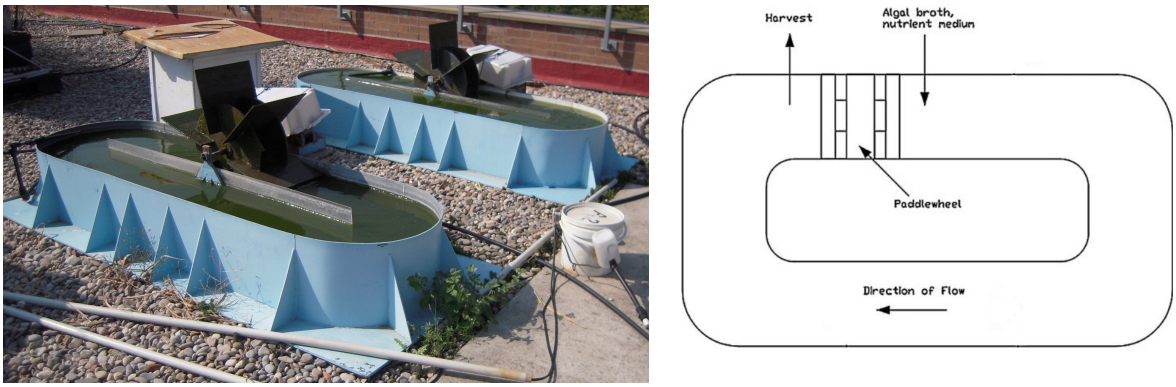

Fig. 9 Raceway pond system [18] [4]

Thin-layer cascade system

The thin-layer cascade cultivation system consists of a basin, retention tank connected by pump and pipelines to a horizontal sloping cascade plate (Fig. 10). Algal suspension flows in a thin layer from the basin (section A) over a slightly sloping cascade (B) that is exposed to sunlight. After exposure, the suspension is collected in a retention tank (C). Finally, suspension is pumped back to the basin from retention tank via tubes (D). The thickness of the layer in the plate can be regulated by a baffle located at the end of the cascade [16].

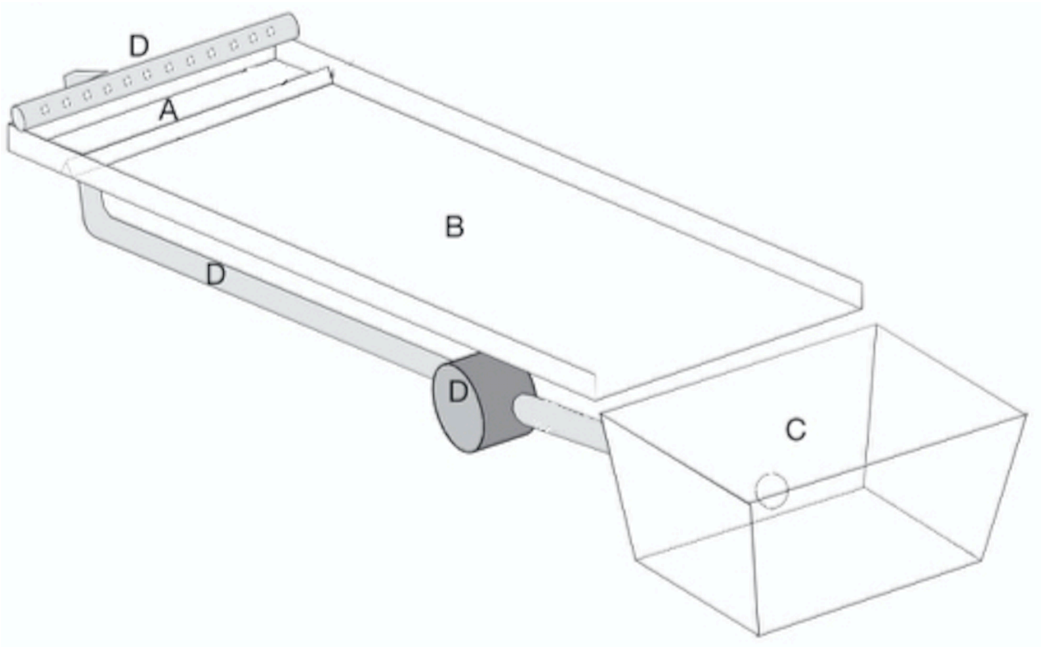

Fig. 10 Thin-layer cascade system scheme [16]

Existing design of thin-layer cascade cultivation system is shown in Figure 12 and scheme is shown in Figure 11. The layer thickness is regulated in such a way that remains below $10\ \mathrm{mm}$. This feature eliminates light limitation in comparison with raceway pond system leading to easier penetration into algae. For instance, biomass productivity in raceway ponds is 1 gram of dry matter per square meter per day. On the other hand, productivity in thin-layer cascade system can reach 40 grams of dry matter per square meter per day, due to the short light path [7].

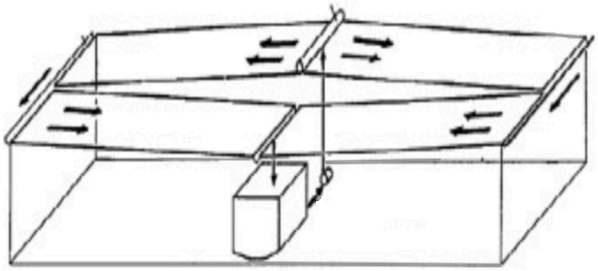

Fig. 11 Cascade system scheme [24]

Fig. 12 Cascade system, Centre Algatech [19]

Rotating annular biofilm photobioreactor

The rotating annular biofilm system consists of a cylinder provided with a growth surface. The cylinder is submerged in growth medium. The scheme of system is shown in Figure 13. It is possible to use pond with one column (Fig. 13a) or an enhanced raceway with a paddle wheel and rotating columns (Fig. 13b). These types of photobioreactors are used to grow biofilms for secondary wastewater treatment and are valued for their efficiency and good gas exchange [26].

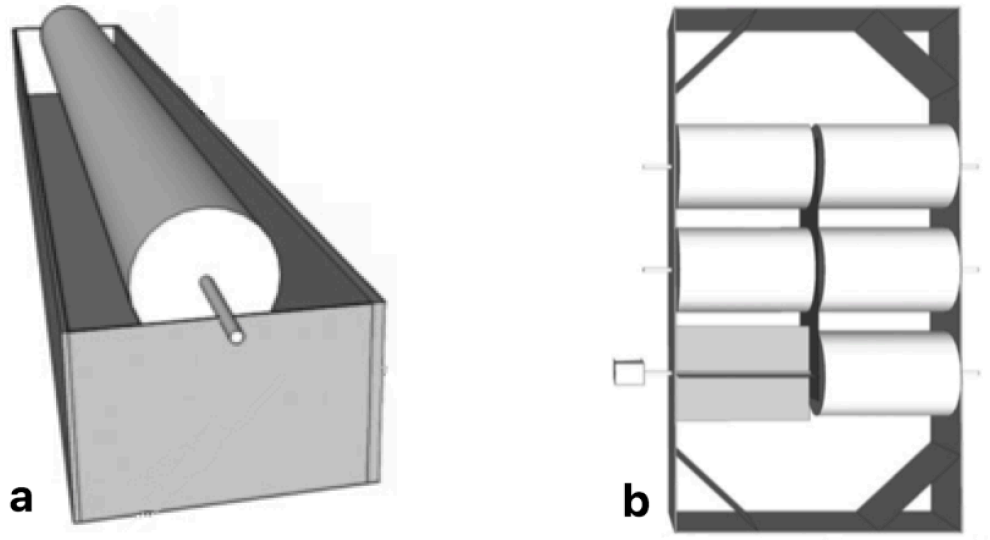

Fig. 13 Rotating annular biofilm photobioreactor [26]

4.3.2. Closed photobioreactor systems

To overcome the problems associated with open pond system, photobioreactor systems are used for algae cultivation. The main advantage is high productivity thanks to an effective control of the operating conditions, such as temperature, CO_2 concentration or pH. Moreover, it is possible to reduce the risk of a contamination and the photobioreactor design allows one to cultivate single algae species for longer period than does open raceway pond. Generally, closed systems are able to produce large quantity of algae biomass. Nevertheless, capital costs of closed system are much higher in comparison with open ones. There are many types of closed bioreactor systems such as tubular reactor, flat plate reactor or column reactor [1].

Tubular photobioreactor

The photobioreactor consists of an array of transparent tubes that capture sunlight (Fig. 14). Tubular reactors can be distinguished by their arrangement: horizontal, vertical, inclined or helix. Algae are recirculated either with a pump or an airlift system that can intensify absorption and desorption CO_2 and O_2 between the liquid medium and aeration gas. Aeration gas can also provide the agitation, which is very important to enhance the gas exchange. On the other hand, it is necessary to consider the possibility of fouling and higher capital costs.

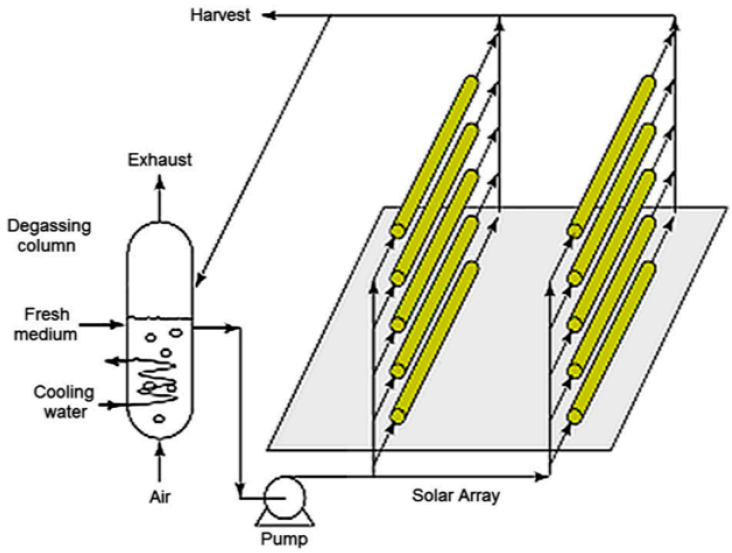

Fig. 14 Tubular photobioreactor scheme [11]

It is possible to divide the tubular reactor design into two main sections: the airlift system and the solar array. The airlift system allows O_2 and CO_2 to be released from the system and transferred into the system, respectively, as well as to provide a harvest of biomass. The solar receiver section consists of tubes, generally $0.1\ \mathrm{m}$ or less in diameter, allowing the light to penetrate efficiently thanks to a high surface/volume ration [4]. However, the length of the tubes is limited due to the dissolved O_2 accumulation. Results indicate that the areal biomass productivity in vertically stacked photobioreactor is by $25 - 70\ \%$ higher than in horizontal one. It is expected that productivities can reach $10 - 20$ grams of dry matter per square meter per day [2]. Existing tubular reactor is shown in Figure 15.

Fig. 15 Vertically stacked tubular photobioreactor [20]

Flat panel photobioreactor

The main advantage of the flat panel photobioreactor (Fig. 17) is a large surface area exposed to illumination. The photobioreactors are made of a transparent plate for maximum solar energy capture. High radiation absorbance is secured by thin layer of dense culture flow across the flat plate. The productivity is significantly influenced by shading and diffuse light penetration between the single panels. The flat plate section is generally $10\ \mathrm{mm}$ thick on average and stirring the culture is ensured by an air flux at the bottom of the plate. The fresh medium is fed by a pump and a suspension of water and algae cultures is withdrawn from the plate and collected in a tank. When a recycle is used (Fig. 16), part of this algal suspension is pumped back to the reactor [17].

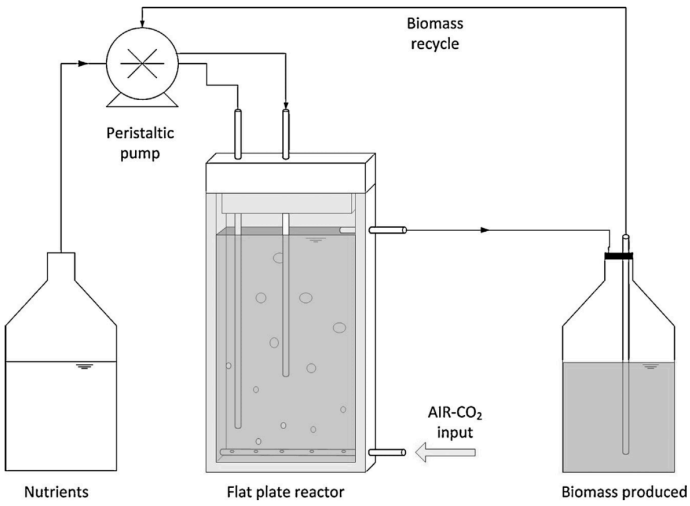

Fig. 16 Scheme of flat panel photobioreactor with recycle [17]

Fig. 17 Flat panel photobioreactor [22]

Column photobioreactor

The main benefit of column photobioreactors (Fig. 18) is the most efficient agitation, high volumetric mass transfer rates and controllable growth conditions. Moreover, columns require less energy for cooling because of the low surface to volume ratio and the photobioreactor ensures a circulation of the algae culture without moving parts or mechanical pumping, which leads to a low shear stress. A vertical orientation of the construction decreases requirements for land area [12]. The columns are aerated from the bottom and illumination is provided through transparent walls. The illumination area is smaller in comparison with the tubular photobioreactor and, therefore, internal illumination can be used in the design. Generally, column photobioreactor function is similar to tubular photobioreactor, but the construction is more sophisticated and thus costly [4].

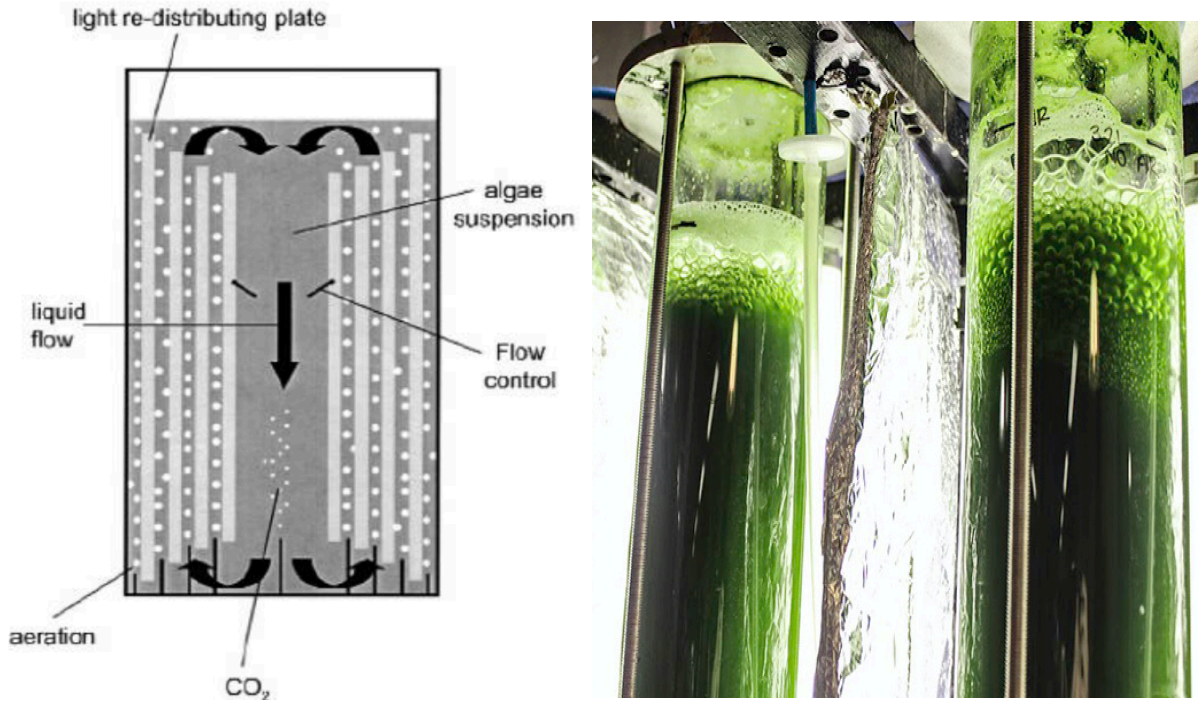

Fig. 18 Column photobioreactor [12] [21]

Internally irradiated stirred tank photobioreactor

The aim of this construction is to scale-up the photobioreactor by keeping the light supply coefficient constant. Moreover, the photobioreactor should provide good stirring properties, as well as low hydrodynamic stress. It is possible to use both artificial and solar light source

for illumination. Internally irradiated stirred tank photobioreactor scheme is shown in Figure 19. The fluorescent lamps are placed in the glass tubes and the distance between tubes and wall of the photobioreactor is designed according to impeller properties [25].

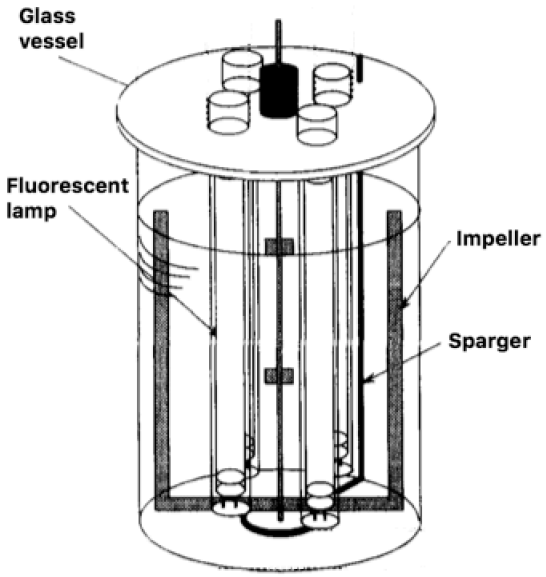

Fig. 19 Internally irradiated stirred tank photobioreactor[25]

Couette Taylor photobioreactor

The Couette Taylor photobioreactor consists of two concentric cylinders. The inner cylinder rotates on the main axis and the working medium swirls in the annular region between those two cylinders. At a low cylinder rotation speed, Couette flow (laminar circular flow) is developed in the working area. However, in case that the rotation speed increases above a critical value, the medium with algae overcomes viscous forces and the flow transforms into Taylor vortices (pairs of oppositely rotating toroidal vortices). At least one cylinder is designed from a transparent material to make the illumination possible. Model of Taylor vortex algal photobioreactor is shown in Figure 20 [28].

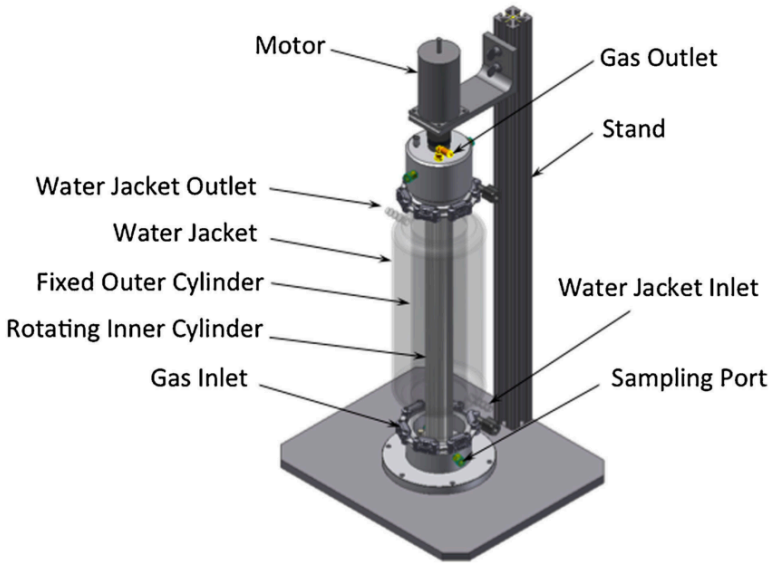

Fig. 20 Taylor vortex algal photobioreactor [28]

A scheme of the photobioreactor with internal light source is shown in Figure 21. Couette Taylor photobioreactor with internal light source consist of the housing (1) with a thermostatic jacket (6), attached to a rack (7). The cooled flask (2) with cooling water (10) is used to control temperature of the light source (9). Sensors (4 and 5) serve to monitor the cultivation process. The algal suspension (8) is operated by a rotating cylinder (3) [27].

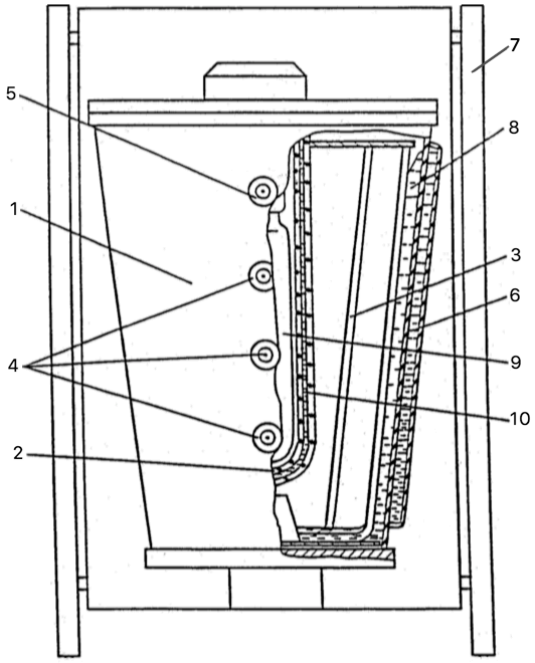

Fig. 21 Photobioreactor with internal light source scheme [27]

Photobioreactor with internal optical-fiber illumination

The lighting design of a photobioreactor with the internal optical-fiber illumination (Fig. 22) is similar to the internally stirred tank photobioreactor. The main aim in the construction of the photobioreactor is to provide a high illuminated surface-area to volume ratio. The photobioreactor consists of a vessel with internal illuminating surface for enhancing the light efficiency and cylinders with fiber optics. This method provides an efficient light radiation system, but its complicated design leads to fouling problems [29].

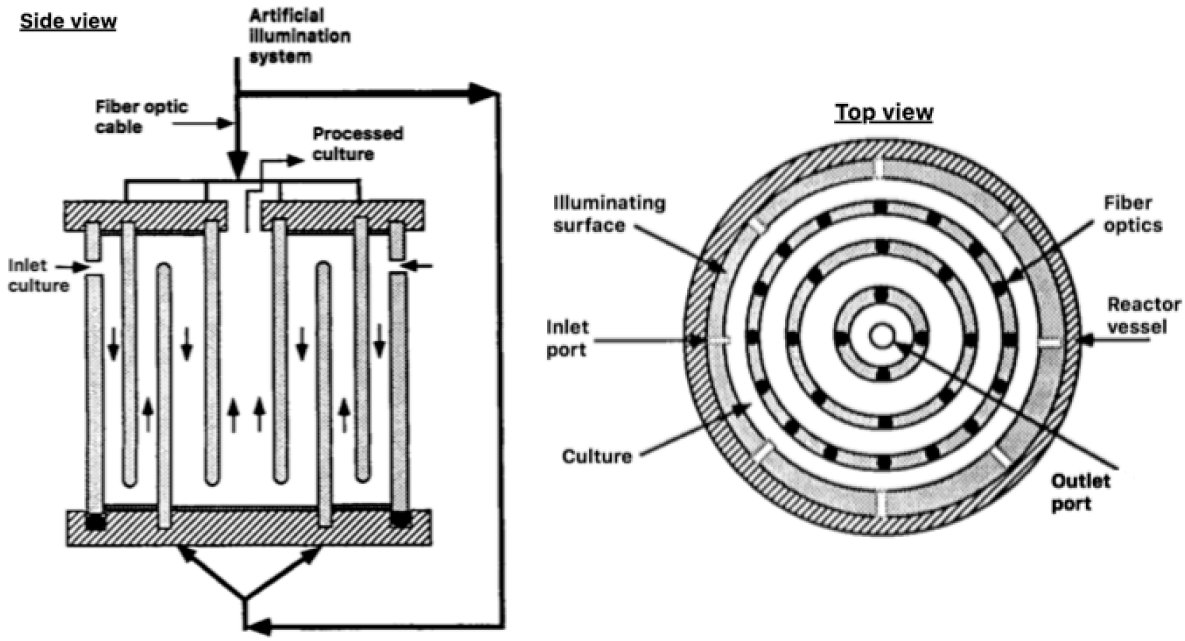

Fig. 22 Photobioreactor with internal optical-fiber illumination [29]

4.3.3. Hybrid photobioreactor systems

The hybrid photobioreactor systems represent a combination of closed photobioreactors and open pond systems used for different growth stages. In the first stage, algae are cultivated in closed systems in order to minimize contamination risk from environments and maximize cell growth. In the second stage, algae are exposed to nutrient rich open pond system. The aim of this method is to increase algae productivity with higher lipid content. However, such an increased production cannot compensate for the capital and operating costs of this method [1].

4.3.4. Comparison of design alternatives

The aim of the following section is to provide a comparison overview of open pond systems and closed photobioreactor systems for algae cultivation. It is important to consider all characteristics and operational parameters which most affect the system function as well as the implementation. The summary comparison is shown in Table 5.

	Closed photobioreactor systems	Open pond systems
Contamination control	Easy	Difficult
Sterility	Achievable	None
Process control	Easy	Difficult
Mixing	Uniform	Very poor
Area/volume ratio	$20 - 200\ \mathrm{m}^{-1}$	$5 - 10\ \mathrm{m}^{-1}$
Algal cell density	High	Low
Investment	High	Low
Operation costs	High	Low
Light utilization efficiency	High	Poor
Temperature control	Uniform	Difficult
Productivity	Higher	Lower
Evaporation of growth medium	Low	High
Gas transfer control	High	Low
O_2 inhibition	Problematic	Uniform

Table 5 Comparison of open pond and closed photobioreactor systems [5]

The main benefits and drawbacks of design alternatives are shown in Table 6.

	Advantages	Disadvantages
Raceway pond	• Low capital cost • Low operation cost • Easy to clean • Low energy inputs • Scale-up possibilities	• Low biomass productivity • Large area of land is needed • Limited to a few algae species • Poor CO_2 utilization efficiency • Poor light utilization efficiency • Contamination risk • Low temperature control • Evaporation of growth medium • Harvesting costs
Thin-layer cascade	• Easy penetration into algae • Short light path • High biomass productivity	• Contamination risk • Low temperature control • Large area of land is needed
Rotating annular biofilm photobioreactor	• Low capital cost • Easy to clean • Scale-up possibilities • High gas exchange	• Large area of land is needed • Contamination risk • Evaporation of growth medium
Tubular photobioreactor	• Suitable for outdoor cultures • Large illumination surface area • Easy to implement and operate • High biomass concentration • Shorter harvest time • High area/volume ratio • High agitation efficiency	• High capital cost • Dissolved O_2 and CO_2 • Fouling
Flat panel photobioreactor	• Relatively cheap • High biomass productivities • Easy to clean and sterilize • Low O_2 accumulation • Large illumination surface area • Low contamination risk	• Difficulties in temperature control • CO_2 diffusion rate control • Difficult to scale-up • Hydrodynamic stress may occur

Table 6 Advantages and disadvantages of design alternatives

	Advantages	Disadvantages
Column photobioreactor	• Compact • High mass transfer • Low energy consumption • Good agitation with low shear stress • Easy to sterilize • High area/volume ratio	• Relatively expensive • High maintenance cost • Small illumination area • Higher shear stress on algae • Relatively difficult to scale-up
Internally stirred tank photobioreactor	• Good agitation • Scale-up possibilities • High mass transfer	• High maintenance cost • Higher shear stress on algae
Couette Taylor photobioreactor	• Good agitation with low shear stress • Scale-up possibilities	• Relatively expensive • High maintenance cost • Sterilization problems • High energy consumption
Photobioreactor with internal optic-fiber illumination	• Large illumination surface area • Compact	• Relatively expensive • Sterilization problems • Relatively difficult to scale-up • Fouling • Agitation problems • Temperature control

Table 6 Continued

4.4. Results of concept design selection

The first part of the algae cultivation process, described in paragraph 4, is focused on the operational parameters and factors that affect the algae cultivation. The light is a fundamental parameter which significantly affects the production of algae biomass: increasing progress in areal productivity with increasing irradiance has been demonstrated. The main benefit of photobioreactors is the ability to mitigate CO_2 from the atmosphere, which is significantly influenced by the light conditions as well. The influence of aeration and lighting conditions on fixation rate of CO_2 has been described in paragraph 4.1.3. The economic conditions and features associated with the location of cultivation system should also be taken into account during the light source designing. The designed photobioreactors should be able to operate in indoor, as well as outdoor conditions. However, for the laboratory equipment design, the light source will be provided by artificial lighting. In terms of electric energy consumption and operation stability, LED light source appears as appropriate. In terms of CO_2 fixation in *Chlorella* species, the use of red-spectrum light seems to be the best option. Stirring is an important feature for proper algae cultivation. Accordingly, stirring should provide a sufficient agitation to prevent algae cells sedimentation. On the other hand, stirring has to be optimized carefully because high levels of agitation would result in cell death from shear. Taking into account these characteristics, stirring through aeration seems to be the most appropriate solution to the problem.

Until now a number of various laboratory, as well as industrial cultivation have been developed. However, it is not possible to exactly assess which equipment or system is operationally appropriate. Also the type of algal species and the location of the equipment itself can greatly affect the productivity of algae. The comparison of various photobioreactor alternatives has been elaborated and their benefits and drawbacks have been specified.

The aim of this diploma work is to provide a design of the three different scale-up laboratory cultivation systems. Taking into account all the specifics and properties for laboratory equipment designing, three design alternatives have been selected:

- Raceway pond system
- Flat panel photobioreactor
- Tubular photobioreactor

In the following part of master thesis, a design of basic parameters of systems according to the selected operating requirements should be elaborated. In addition to that, with help of the modeling software, 3D models and design drawings of individual conceptions should be provided.

5. Design part

Before the design of photobioreactors, it is necessary to define the basic conditions for their proper function and the possibility of construction realization. Great number of various photobioreactor designs working at various operating conditions has been published in many publications worldwide. Therefore, comparison of different design variants is very complex and it is also difficult to define which operating conditions of the equipment affect the function the most. However, parameters which have the highest influence on the algal production in general are described in paragraph 4.1. Apparently, parameters exerting the highest influence vary mainly depending on the type of algae species used for cultivation, on the photobioreactor design or on ambient conditions.

The main objective of this work is to obtain three design variants of pilot-plant photobioreactors that could be compared. It is possible to define numerous comparing criteria; however, one of the fundamental parameters of performance is algae production. On the other hand, an assessment of a possibility to scale-up to full operating facilities, as well as the impact of the surrounding environment, is important. Therefore, a ratio of the irradiated area of photobioreactor to the built-up area around the photobioreactor seems to be a suitable parameter for comparison.

In order to compare various equipments, it is necessary to provide identical operational conditions for all photobioreactors. This is not so complicated in case of providing the same light and temperature conditions. However, ensuring a constant effect of CO_2 seems to be more problematic; in other words, ensuring the same absorption of CO_2 into the processed medium can be different in each of the photobioreactor designs. From this point of view, using external retention vessel seems to be the most appropriate, providing the CO_2 absorption into processed medium outside the photobioreactor part of the equipment. It would thus ensure that the absorption performance is the same, and this construction variant seems to be more appropriate from the viewpoint of temperature control and further modification of the processed medium as well. It is also appropriate to ensure that the photobioreactor part of the equipment will process the same amount of medium and that the irradiated area will be same too. Therefore, the ratio of the irradiated area to the volume of the equipment should be identical. Moreover, it is appropriate to propose a design

variation so as to ensure the same retention time of the processed medium in the photobioreactor section and it is also necessary that all equipment could be installed in a university laboratory.

The selection of basic design and operational conditions are defined:

- The external retention vessel will provide process conditions for absorption of CO_2 and temperature control. The volume of retention vessel is chosen $100\,\mathrm{l}$. The construction of retention vessel enables the dosage of fresh medium, nutrients and pH control of the processed medium.
- The algae cultivation system requires the possibility of irradiation time control. Therefore, it is necessary to ensure circulation of processed media in photobioreactor section.
- The volume of photobioreactor section is chosen to process $100\,\mathrm{l}$ of algae/water mixture.
- In order to compare each photobioreactor performance, it is necessary to design same irradiation area in photobioreactor section and ensure the same residence time as well.

The following paragraphs are focused on the design of photobioreactors components and retention vessel. All equipments should be processed in the 3D model and design drawings.

5.1. Retention vessel

The retention vessel is proposed so that it could process $100\ \mathrm{L}$ of the medium, i.e., the mixture of water and algae. If $20\ \mathrm{L}$ is considered as a reserve, the vessel should be designed for $120\ \mathrm{L}$ capacity and polyethylene is used as a construction material. A description of the retention vessel nozzles is shown in the scheme in Figure 23. The nozzle N1 is used for processed medium input from photobioreactor section into retention vessel, whereas nozzle N2 is used for a reversed transport. It is also possible to use the nozzle N9 for the output of the processed medium from retention vessel but this particular nozzle is used for sampling the water/algae mixture, as well as for cleaning the vessel. The nozzle N3 is used for the input of fresh water and nutrients to ensure a proper algae growth. Due to differing growth needs of various algal species, it is necessary to control temperature of the processed medium. Therefore, the nozzles N4 and N5 are attached to the retention vessel to enable the heat exchanger connection, and thus to avoid undesirable temperature changes. Installation of the heat exchanger would be needed only in case of use of intense local light source for the irradiation of the processed medium. The local source could significantly influence the temperature and consequently the growth of algae.

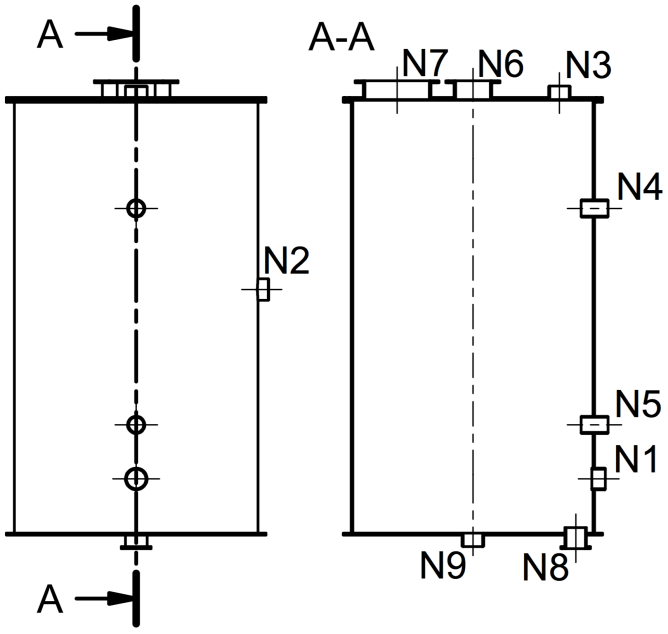

Fig. 23 Retention vessel scheme, N1 – mixture inlet, N2 – mixture outlet, N3 – fresh medium inlet, N4 – heat exchanger inlet, N5 – heat exchanger outlet, N6 – stirrer attachment, N7 – gas outlet, N8 – gas inlet, N9 – processed medium outlet

Generally, the retention vessel is used mainly to provide proper absorption condition for nutrients and the processed medium; however, it is also used for algae relaxation which means that algae also need a non-irradiated section to calm and further develop their growth. According to the type of algal species, the needs of the exposure to irradiance and of the relaxing in the calm section vary, and so does the ratio of light and dark periods. This ratio affects not only the rate of growth, but also has an impact on the development of algae and their structure (Tab. 7). Due to this fact, it is necessary to design the retention vessel and the photobioreactors so that to allow to modify the retention time in the irradiated area of the photobioreactors and the retention time in the vessel and to allow further exploration of the influence of light and dark ratio.

Species	Purpose	Light / Dark ratio
Chlorella vulgaris	**Biomass and lipid production**	**12 / 12**
Chlorella vulgaris	**Saturated fatty acids accumulation**	**16 / 8**
Chlorella vulgaris	**Monounsaturated fatty acids accumulation**	**8 / 16**
Chlorella	**Biogas effluent nutrition reduction**	**14 / 10**

Table 7 Light and dark ratio influence on algal growth [31]

Effect of varying aeration conditions on CO_2 fixation rate in algae was described in paragraph 4.1.3. In order to further examine the effects of aeration conditions in combination with other operational parameters on algal growth, it is necessary to ensure the possibility to vary the CO_2/air ratio in the aeration gas. To comply with this requirement, the aeration gas is prepared in a mixing chamber connected to an air compressor station and CO_2 pressurized vessel. The aeration gas is injected into the retention vessel through the flange N8 shown in the scheme on Figure 23. Absorption in the retention vessel can be intensified by large interface areas between the gas and the culture medium, the interface being constituted by membranes, through which gas diffuses into the culture. Mesh of membrane pipes is attached at the bottom of the retention vessel to provide an aeration of gas into the processed medium (Fig. 25).

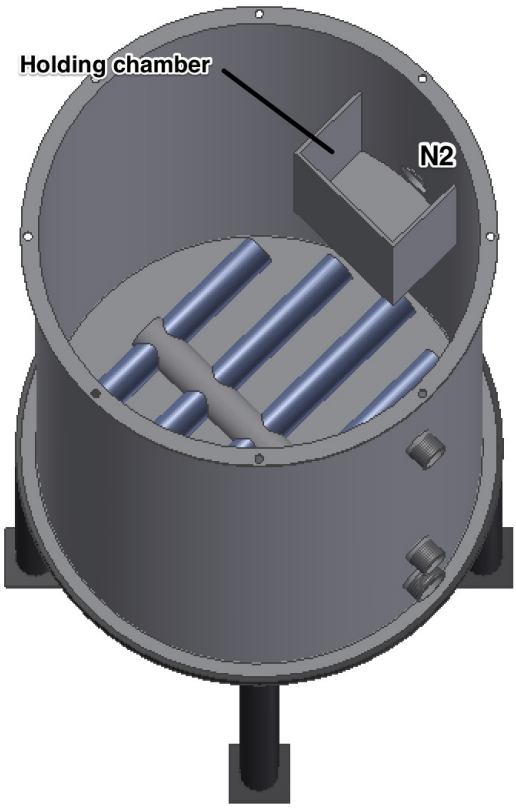

Fig. 24 Holding chamber

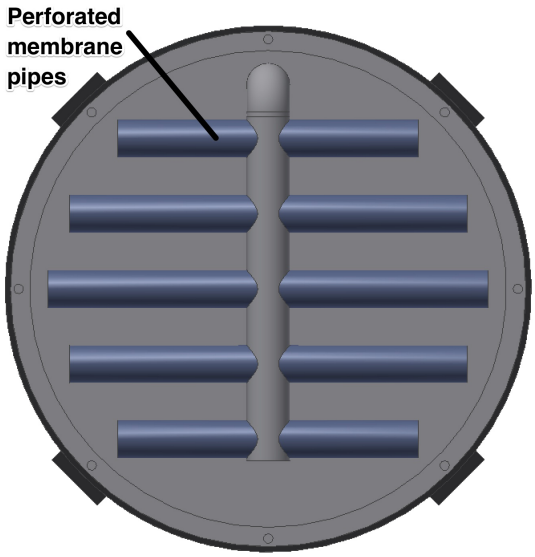

Fig. 25 Aeration system

During the aeration, an agitation of the processed medium occurs in the retention vessel and this can prevent the algae sedimentation on the bottom of the vessel. Agitation is an important factor because the medium must be homogenized in the vessel during the supply of nutrients. Agitation can be further intensified by using a mechanical stirrer, which can be attached onto the flange N6 (Fig. 23). The stirrer can increase the interface areas between the gas and the culture medium also by stirring the aerated gas. However, it is also important to ensure that the shear forces provided by the stirrer cannot damage the algal structure and thus affect the proper growth. To prevent problems with the flow of processed medium and algal growth, it is necessary to guarantee that the undissolved gas does not come from the retention vessel into the photobioreactor section. To implement this, the holding chamber (Fig. 24) is attached to the nozzle N2. Undissolved gas and oxygen produced during the algal growth are discharged by the flange N7 (Fig. 23). The overall construction of the retention vessel is shown in Figure 26.

Fig. 26 Retention vessel 3D model, N1 – mixture inlet, N2 – mixture outlet, N3 – fresh medium inlet, N4 – heat exchanger inlet, N5 – heat exchanger outlet, N6 – stirrer attachment, N7 – gas outlet, N8 – gas inlet, N9 – processed medium outlet

5.2. Flat panel photobioreactor

Nowadays, there exist a large number of different design options of flat panel photobioreactors. The variants usually differ in the rake angle of the panel and also in the length of the distance between the plates. It is the weakness of the flat panel photobioreactors that they require adequate agitation of the processed medium in the irradiated area and sufficient irradiance. The agitation of the processed medium is a very important operating parameter due to panel distances, which are larger here to ensure irradiance of the entire medium volume. On the other hand, the main benefit of this type of photobioreactors consists in a high ratio of the irradiated photobioreactor area to the area of the laboratory, which is occupied by this equipment. Therefore, with the help of appropriate design parameters, it is possible to achieve a large irradiated area at a low demand for space.

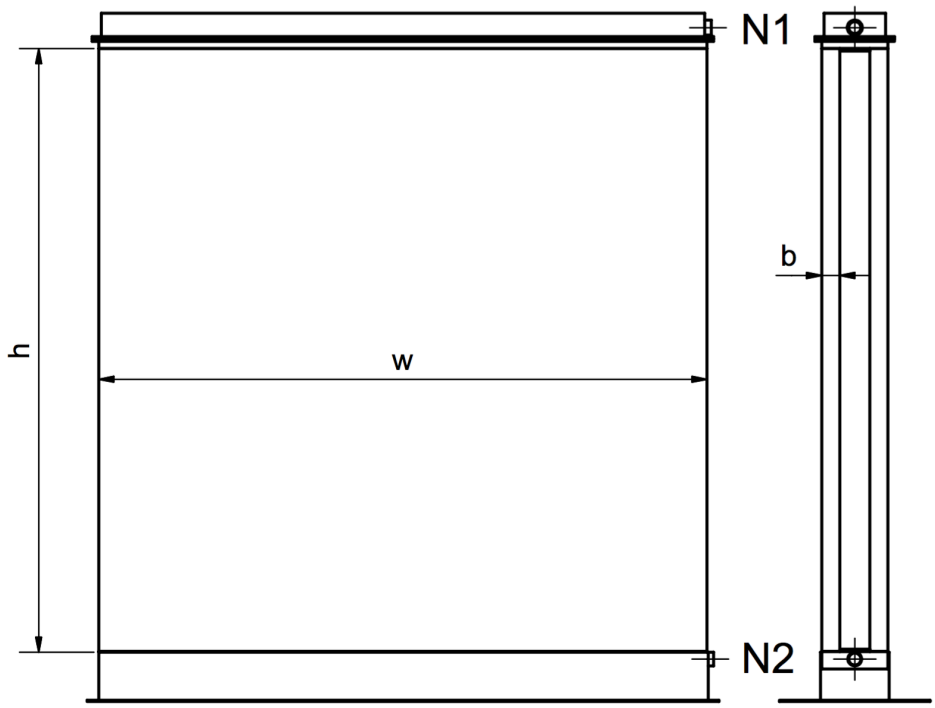

Fig. 27 Flat panel photobioreactor scheme, N1 – algal and water mixture inlet, N2 – algal and water mixture outlet, w – panel width, h – panel height, b – distance between panels

The processing function of the flat panel photobioreactor indicates that one of the most important operating conditions in the designing is the necessity to ensure a sufficient agitation of the processed medium during its flow between the panels. According to the capabilities of agitation, it is possible to change the size of the distance between the panels and, accordingly, also the amount of the processed medium in the photobioreactor section.

It is also necessary to design the system so that it can work both in outdoor and indoor conditions. For this reason, the construction should be adapted in order to yield a sufficient area irradiated by central light source but, at the same time, to provide design conditions for the use of a local artificial light source and to explore its influence on algae production.

The amount of the processed medium intended for the flat-panel pilot-plant photobioreactor, which should be assembled in the university laboratory, is the same as that in the retention vessel. Therefore, the photobioreactor section is designed for $100\ \mathrm{L}$ of the processed medium and the construction is formed from polyethylene terephthalate panels. The flat panel photobioreactor scheme is shown in Figure 27. The processed medium is supplied from the retention vessel into the flat panel photobioreactor through the nozzle N1. The processed algae/water mixture is treated during the flow between the panels and then it is discharged back into the retention vessel through the nozzle N2.

For the construction of the flat panel pilot-plant photobioreactor, two panels have been used, separated by gap. This gap can be used for processing setting with a local light source. Using this setting, it would be possible to increase the irradiance performance and then investigate the effect of the local light source on the algae production. As a basic setting, a photobioreactor with a central light source is considered. Height and width of the panel were chosen as input design parameters, so the photobioreactor will be able to work in university laboratory conditions: the height is $\mathrm{h} = 2\ \mathrm{m}$, the width is $\mathrm{w} = 2\ \mathrm{m}$ and the gap between the panels is $\mathrm{b} = 45\ \mathrm{mm}$. However, the construction of the photobioreactor provides the opportunity to insert internal panels, which can regulate the volume of processed medium in the photobioreactor section. More specifically, volume can be regulated by shifting the internal panels in rails (Fig. 28). With the help of the rails, the volume of processed medium in the flat panel photobioreactor $\mathrm{V_{FPP}}$ can be controlled in the range shown in Table 8. Consequently, the irradiated area of the flat panel photobioreactor can be defined by

$$\mathrm{A_{FPP}} = \mathrm{h} \cdot \mathrm{w} \cdot \mathrm{n_P} = 2 \cdot 2 \cdot 2 = 8.0\ \mathrm{m^2} \qquad (2)$$

where $\mathrm{n_P}$ $[\mathrm{dimensionless\ quantity}]$ is the number of panels.

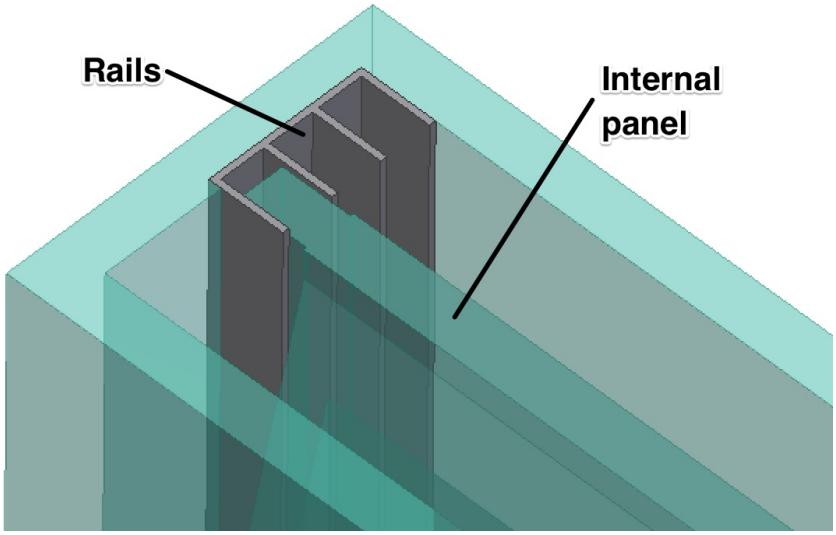

Fig. 28 Rails for regulation of processed medium volume

Taking into account the factors previously mentioned in the introduction to this paragraph, stirring the processed medium is an important operating parameter to ensure its proper irradiance. The need for agitation increases with increasing processed medium volume in the photobioreactor section. During the flow over a flat panel, the flow of processed media can be in laminar regime due to the low flow rates. The agitation process can be ensured by removable internal panels: it is possible to change the profile of the panels and provide a stirring of the processed medium during the flow. One of the options is to use a series of static mixers, which could be fixed on the internal panel. From a design point of view, an easier option could be to use fixed barriers, which could provide changes of the velocity and the direction of the flow of the processed medium layers. The flow conditions in flat panel photobioreactor are described in paragraph 5.5. For the construction of a pilot-plant flat panel photobioreactor, an internal panel design with inclined barriers was chosen. However, since the panels can be easily removed, it is possible to change the profile of the barriers and examine the influence on the agitation during the flow and the subsequent effect on the algae production. The design of the internal panel is shown in Figure 29.

b [mm]	V_{FPP} [L]
20	100
28	160
36	220

Table 8 Flat panel photobioreactor volume parameters

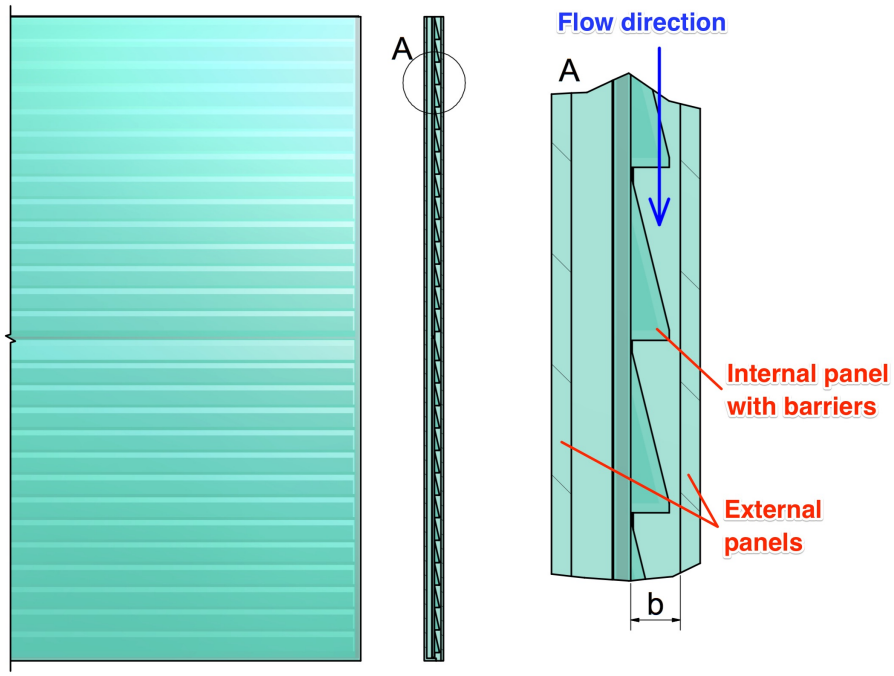

Fig. 29 Internal panel design, b – distance between panels

The construction of the flat panel pilot-plant photobioreactor consists of four smaller internal panels with barriers in order to make the manipulation and replacement easier. The total area of the part of the laboratory occupied by the flat panel photobioreactor is $A_{FPP\_lab} = 0.45\ m^2$. Consequently, the ratio of the irradiated photobioreactor area to the area of the laboratory can be defined by

$$\frac{A_{FPP}}{A_{FPP\_lab}} = \frac{8.0\ m^2}{0.45\ m^2} = 17.8 \qquad (3)$$

The overall construction of the flat panel pilot-plant photobioreactor is shown in Figure 30 and all parts of photobioreactor are shown in Figure 31.

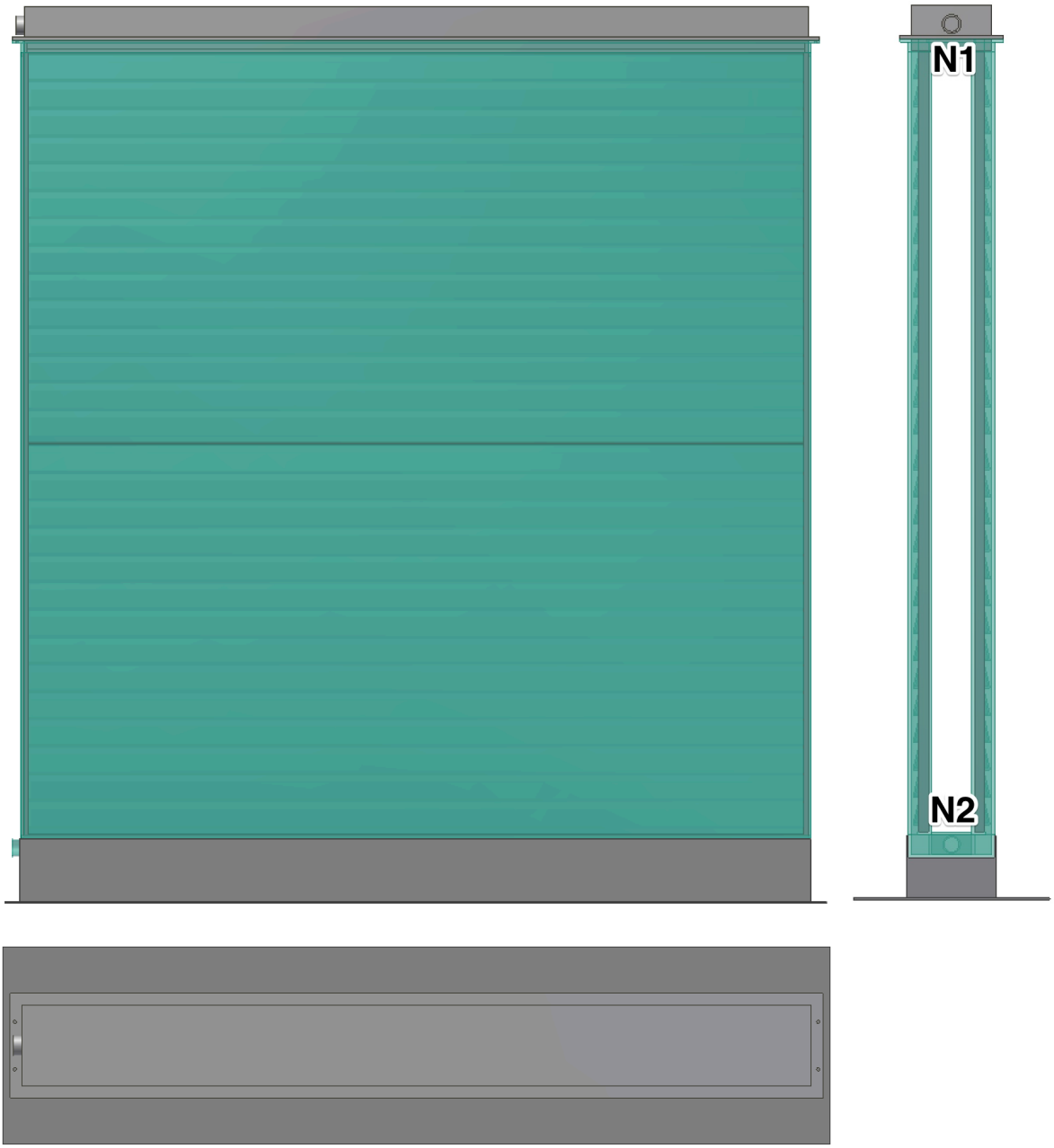

Fig. 30 Flat panel photobioreactor, N1 - algal and water mixture inlet, N2 - algal and water mixture outlet

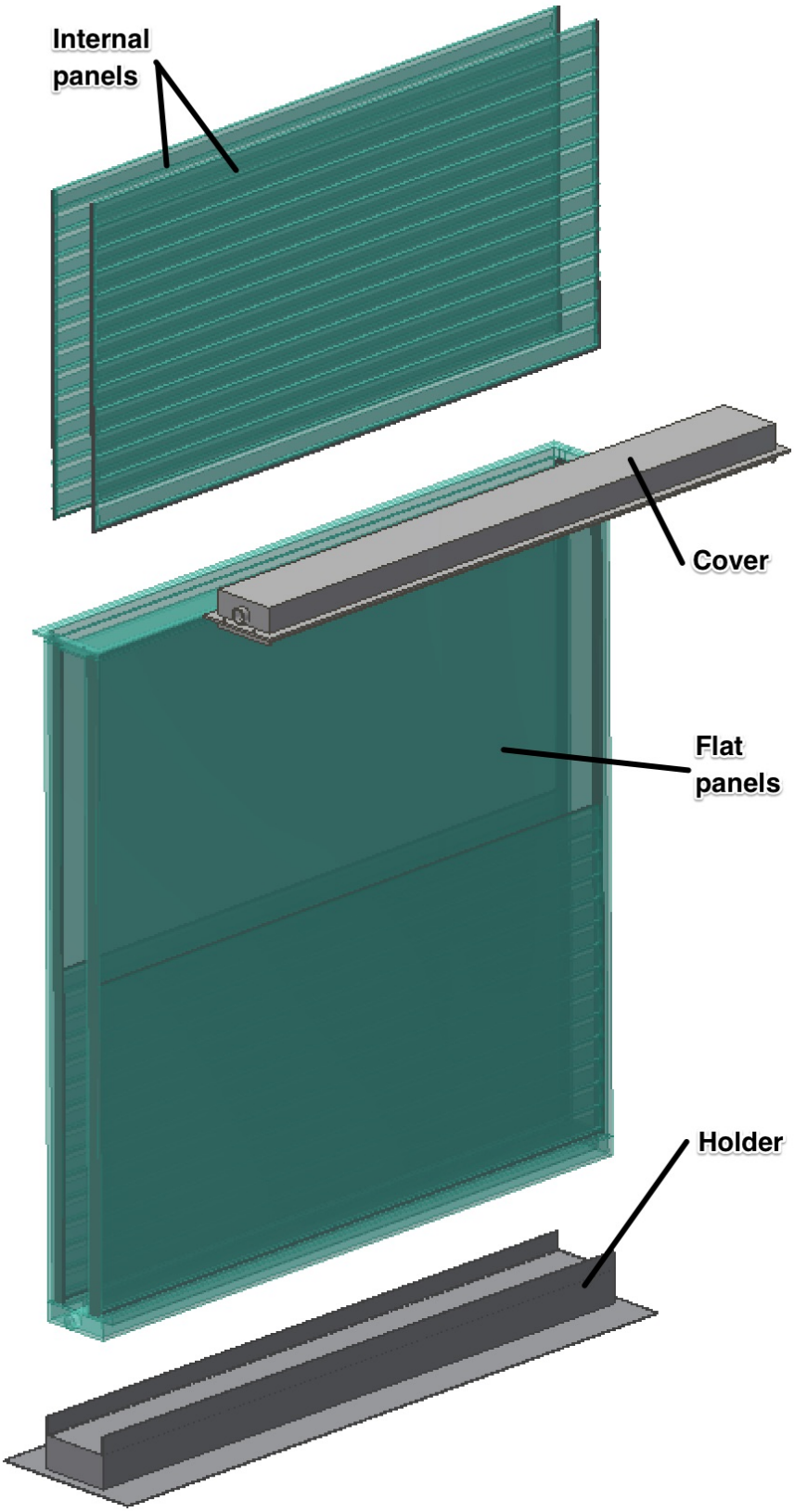

Fig. 31 Flat panel photobioreactor

5.3. Tubular photobioreactor

The tubular photobioreactor is one of the most widely used closed systems for algae cultivation and its function is relatively simple. It operates on the principle that the processed medium flows through the irradiated transparent tube. A large number of various tubular reactor designs are mentioned in the literature. The main benefit of its construction is the possibility of adaptation to the areal dimensions of the lab in which the photobioreactor is installed.

For the construction of the pilot plant photobioreactor in the university laboratories, it seems preferable to use a vertical tubular photobioreactor design. The main advantage of this construction is that it has a high ratio of the irradiated photobioreactor area to the area of the laboratory, which is occupied by this equipment.

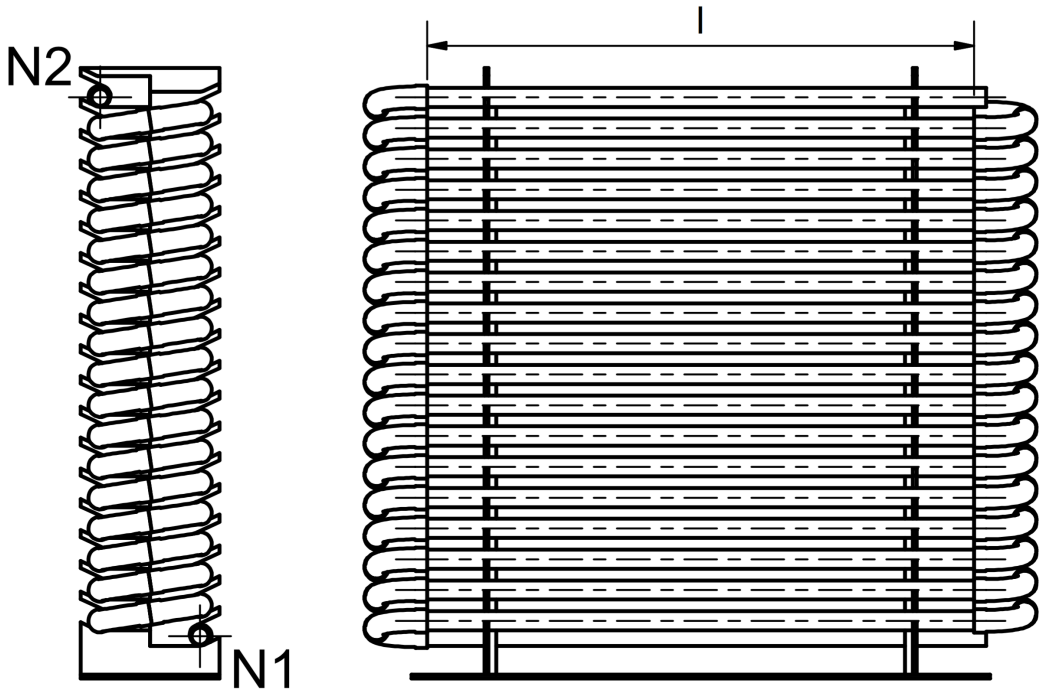

Fig. 32 Tubular photobioreactor scheme, N1 – algal and water mixture inlet, N2 – algal and water mixture outlet, l – irradiated length of tube

The pilot-plant tubular photobioreactor installed in the university laboratory is designed to process $100\,\mathrm{L}$ of a medium in its section – the same amount as in the flat panel photobioreactor. Taking into account the previously mentioned requirements, in order to compare various photobioreactors, it is necessary to provide the same operational

conditions. To comply with this requirement, it is necessary to work with the same amount of the processed medium for both cases, as well as to keep irradiated areas equal. Consequently, in case of connection with the retention vessel, $200\ \mathrm{L}$ of algae/water mixture will be processed. The tubular photobioreactor consists of 36 polymethylmethacrylate tubes, placed in two vertical rows. These tubes are joined together by 70 knees. A tubular photobioreactor scheme is shown in Figure 32.

The distance between the vertical rows of tubes is selected so that it eliminates the mutual shading from the light source, be it a central room artificial lighting or the sunlight. However, the photobioreactor design is adapted for an artificial local irradiation as well. The artificial lighting can be attached on both sides of the photobioreactor and also into the inner space between the vertical rows. The processed medium from the retention vessel is supplied into the tubular photobioreactor through the nozzle N1, whereas the output from the photobioreactor and the return back to the vessel is secured by N2.

The region where algae receive enough light for photosynthesis is quite shallow, specifically in $20 - 50\ \mathrm{mm}$ range [32]. Due to this fact, tubes with $50\ \mathrm{mm}$ outer diameter and $3\ \mathrm{mm}$ wall thickness are used for the tubular photobioreactor. For the preselected amount of the processed medium in the photobioreactor section and the number of tubes, the tube length of $1\,480\ \mathrm{mm}$ is required. Consequently, it is possible to determine the irradiated photobioreactor area. However, the part of the tube, used as a connection to the knees, requires to be included in the calculation as well. Therefore, the total length of the irradiated tube is $1\,418\ \mathrm{mm}$. The irradiated area of the tubular photobioreactor can be defined by

$$A_{TP} = n_T \cdot \pi \cdot d_{ex} \cdot l_T = 36 \cdot \pi \cdot 0.05 \cdot 1.418 = 8.01\ \mathrm{m}^2 \tag{4}$$

where n_T [dimensionless quantity] is the number of tubes, d_{ex} [m] is the external diameter of tube and l_T [m] is the irradiated length of tube. The total area of the part of the laboratory, occupied by the tubular panel photobioreactor, is $A_{TP\_lab} = 0.63\ \mathrm{m}^2$. Consequently, the ratio of the irradiated photobioreactor area to the area of the occupied part of the laboratory can be defined by

$$\frac{A_{TP}}{A_{TP\_lab}} = \frac{8.01\ \mathrm{m}^2}{0.63\ \mathrm{m}^2} = 12.7 \tag{5}$$

Requirements to ensure agitation during the flow are the same as in the case of the flat panel photobioreactor because it is necessary to irradiate the total volume of the processed medium inside the transparent tubes. An insufficient agitation could also lead to a sedimentation of the produced algae inside the photobioreactor section. Changes in flow regimes are suitable to ensure the agitation during the flow of the fluid inside the pipe with a circular cross section. Fluid can flow in laminar or turbulent regime. To assess the character of the flow, the Reynolds number is used. In the laminar flow, the agitation does not occur and the flow rate profile of the fluid is parabolic. When a certain value of the Reynolds number corresponding to the turbulent flow range is reached, the flow path very quickly dissipates throughout the tube cross section. It is often stated that the beginning of the turbulent region is at a Reynolds number $\mathrm{Re} = 2\,300$. Therefore, the flow regime can be defined by a value of the Reynolds number

$$\mathrm{Re} = \frac{\mathrm{D} \cdot \mathrm{v}}{\nu} = \frac{\mathrm{D} \cdot \mathrm{v} \cdot \rho}{\mu} \tag{6}$$

where $\mathrm{D}\,[\mathrm{m}]$, $\mathrm{v}\,[\mathrm{m\,s^{-1}}]$, $\nu\,[\mathrm{m^2\,s^{-1}}]$, $\mu\,[\mathrm{Pa\,s}]$, and $\rho\,[\mathrm{kg\,m^{-3}}]$ are the characteristic dimension, the velocity, the kinematic viscosity, the dynamic viscosity, and the density, respectively. From the definition of the Reynolds number is apparent that the flow regime and agitation conditions can be affected by a flow velocity modification in the tubular photobioreactor. However, the flow velocity affects the residence time of the processed medium in the photobioreactor section: the residence time of the medium in the irradiated area decreases with increasing flow velocity. According to these conditions, it is important to take into account several factors and to try to find an optimal flow rate, which would improve the algae production. It is also possible to use static mixers attached inside the pipes, which ensure sufficient agitation of the medium and thus extend the residence time. Therefore, it is important to ensure the easy dismounting of the pipes and knees to allow insertion of the static mixers. The overall construction of the tubular pilot-plant photobioreactor is shown in Figure 33 and all parts of the photobioreactor are shown in Figure 34.

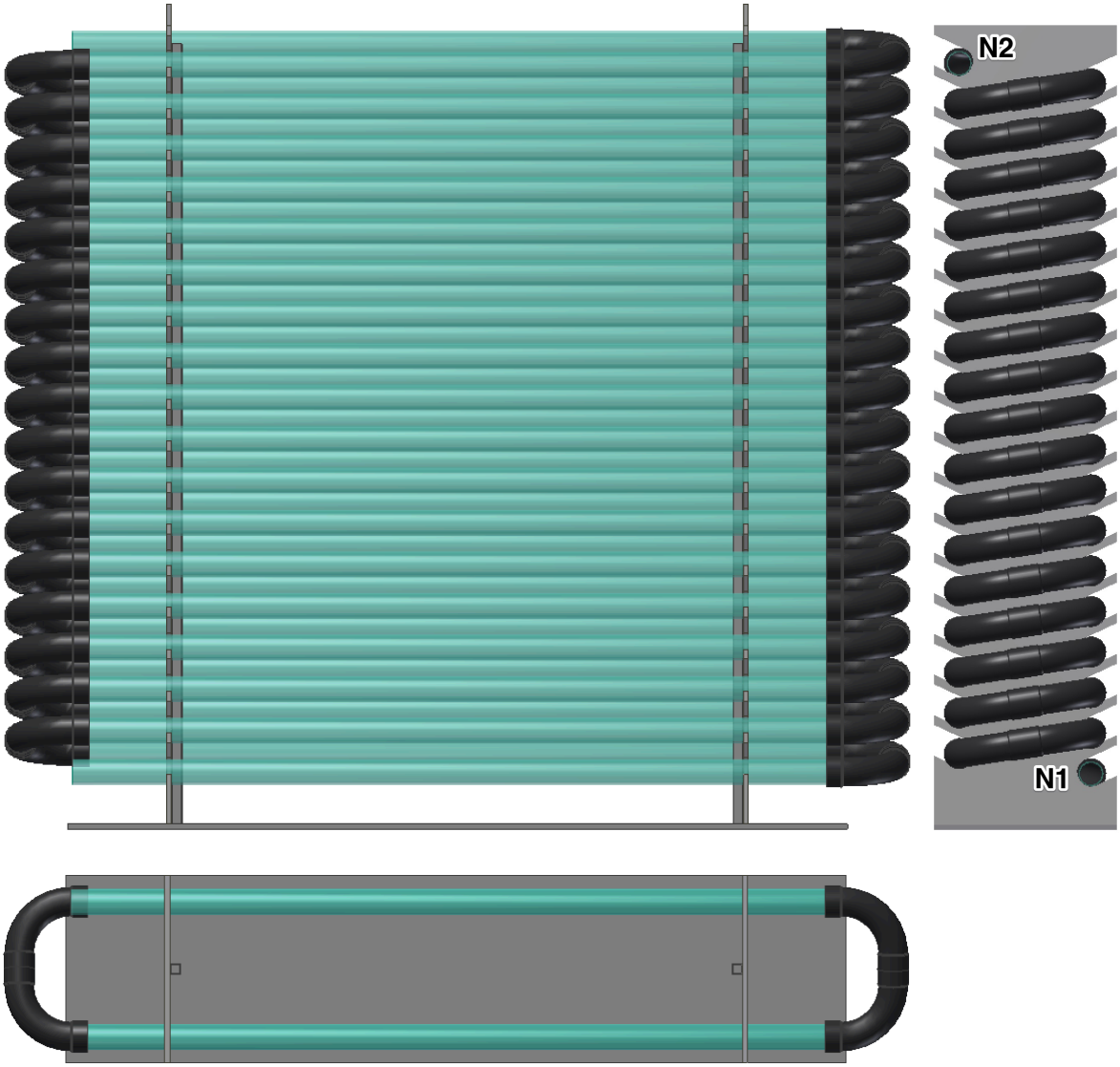

Fig. 33 Tubular photobioreactor, N1 – algal and water mixture inlet, N2 – algal and water mixture outlet

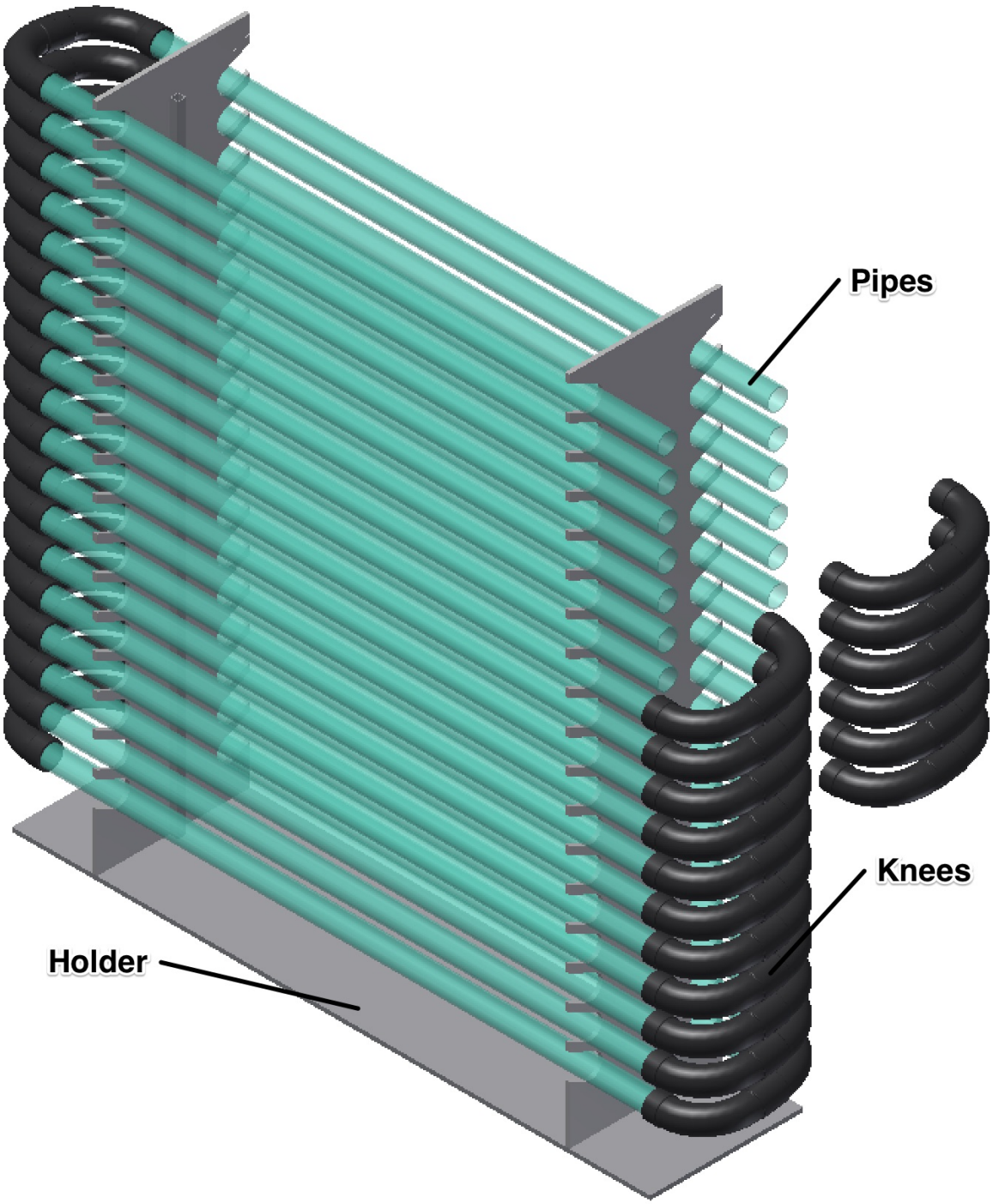

Fig. 34 Tubular photobioreactor

5.4. Track photobioreactor

The raceway photobioreactor is one the most frequently used open cultivation systems for algae production. As was mentioned in paragraph 4.3., the main benefits of this photobioreactor are low capital and operational costs. On the other hand, the main drawback is a high requirement for surface area, so that these photobioreactors are primarily used in outdoor conditions. The need to stir the processed medium is even more significant in comparison with two previously mentioned versions (paragraph 5.2. and 5.3.). Agitation process is usually provided by a rotating cylinder with variously shaped blades. Rotating blades enable the medium to flow as well. Generally, the level of algae/water mixture is high in the raceway photobioreactor section and, therefore, the irradiation of light source through the processed medium is complicated. The agitation process is also important in order to eliminate algae sedimentation.

The cascade photobioreactor has a similar construction and function as the raceway one. Moreover, it is possible to irradiate the entire volume of the medium inside the photobioreactor section so that there is no need to provide agitation here. The medium flow is driven by gravity. However, the main disadvantage is a short residence time in the irradiated area. To extend the residence time, it is necessary to design very large irradiated area.

A combination of the raceway and cascade photobioreactors seems to be the most appropriate option. Thus, the aim of the track photobioreactor design part is to enable the processed medium level, as well as the residence time to be controlled. Sufficient agitation conditions represent another important requirement; the possibility to incline the track platforms would also be a benefit. For the simple raceway operational mode, the track platforms can be in a horizontal position and the medium circulation can be ensured by a pump. Alternatively, in the cascade operational mode, the photobioreactor platforms can be mutually inclined and this inclination would affect the medium flow. The scheme of both variants is shown in Figure 35.

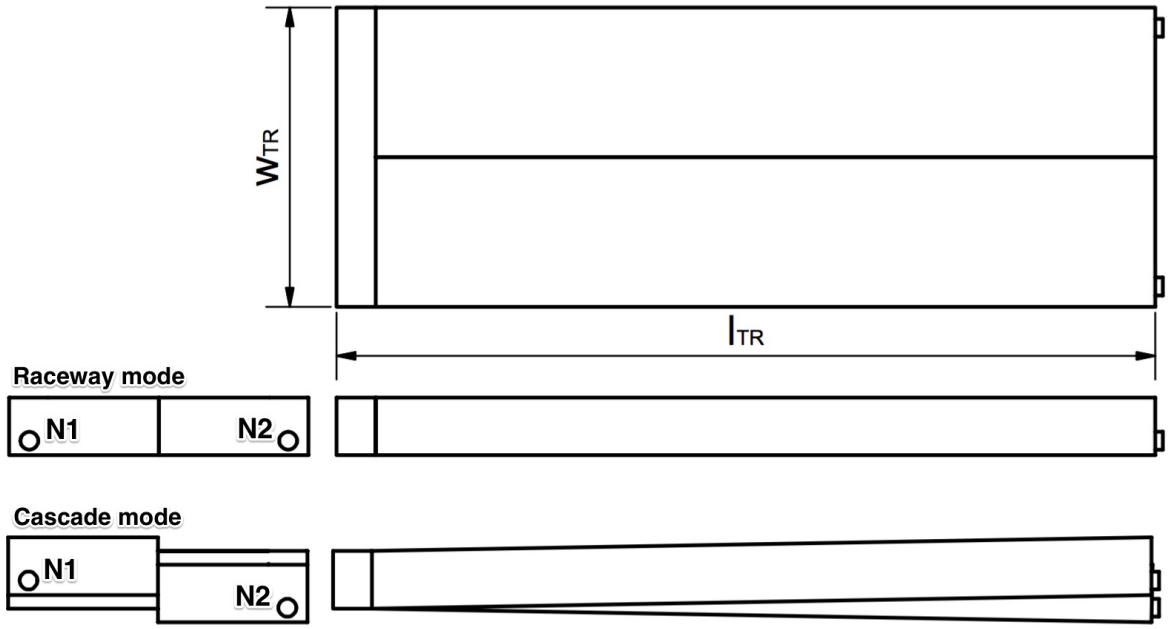

Fig. 35 Track photobioreactor scheme, N1 – algal and water mixture inlet, N2 – algal and water mixture outlet, l_{TR} – track photobioreactor length, w_{TR} - track photobioreactor width

The raceway/cascade photobioreactor cannot in principle achieve the same irradiated areas as the tubular and flat panel photobioreactors. The volume of the processed medium can be regulated in the photobioreactor section and the maximum volume is designed to $V_{TRP} = 220\ L$. The irradiated area of the track photobioreactor can be defined by

$$A_{TRP} = w_{TR} \cdot l_{TR} = 0.784 \cdot 2.2 = 1.72\ m^2 \quad (7)$$

The total area of the part of the laboratory, occupied by the track photobioreactor, is $A_{TRP\_lab} = 1.76\ m^2$. According to this, the irradiated area is almost identical to the occupied area of the laboratory

$$\frac{A_{TRP}}{A_{TRP\_lab}} = \frac{1.72\ m^2}{1.76\ m^2} = 0.97 \quad (8)$$

Track platforms can be tilted by adjustable screws (Fig. 37). To increase the residence time, the barrier and various obstacles can be attached onto the track platforms. For instance, it is possible to use barriers which are shown in Figure 36. It is possible to use variously shaped barriers, which can also help to stir the processed medium during the flow. Part of the processed medium can flow between the barriers and other part can flow over the top barrier

edge in case of higher medium level in photobioreactor section. Static mixers can be attached to track platform as well and further intensify the agitation process.

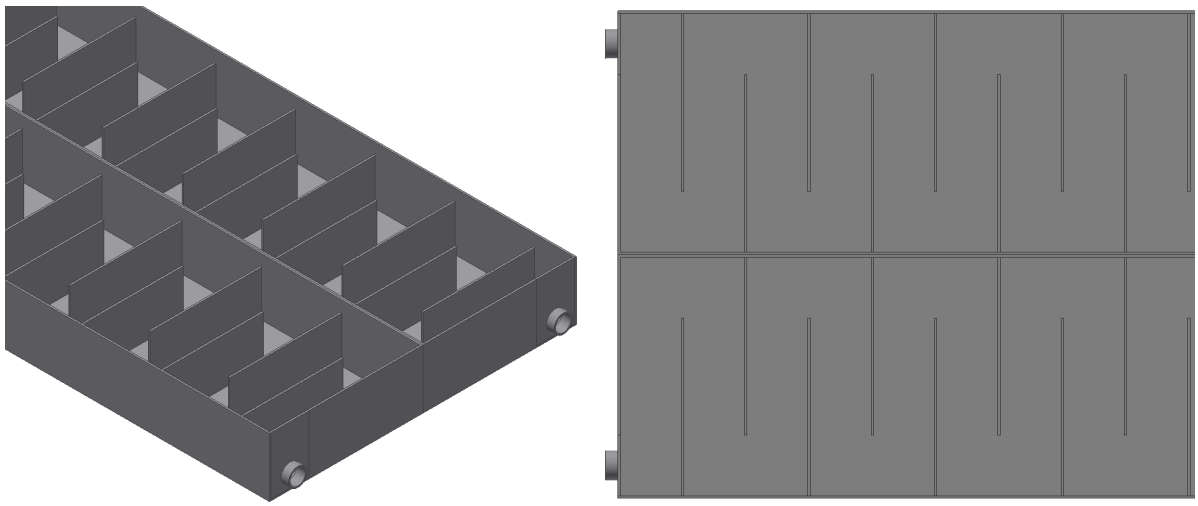

Fig. 36 Track photobioreactor barriers

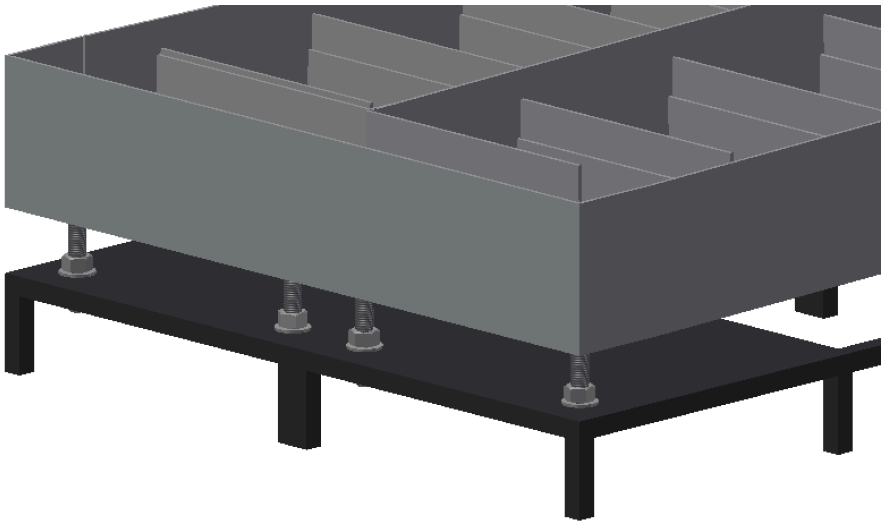

Fig. 37 Track platform inclination by adjustable screws

Track photobioreactor allows many operational modes and settings possibilities that can be used. The influence of different operating settings relating to the shape and type of barriers to the flow characteristics of the medium and the subsequent production of algae could be the target of further exploration. Polyethylene terephthalate panels are selected as a construction material. The overall track pilot-plant photobioreactor design is shown in Figure 38 and 39.

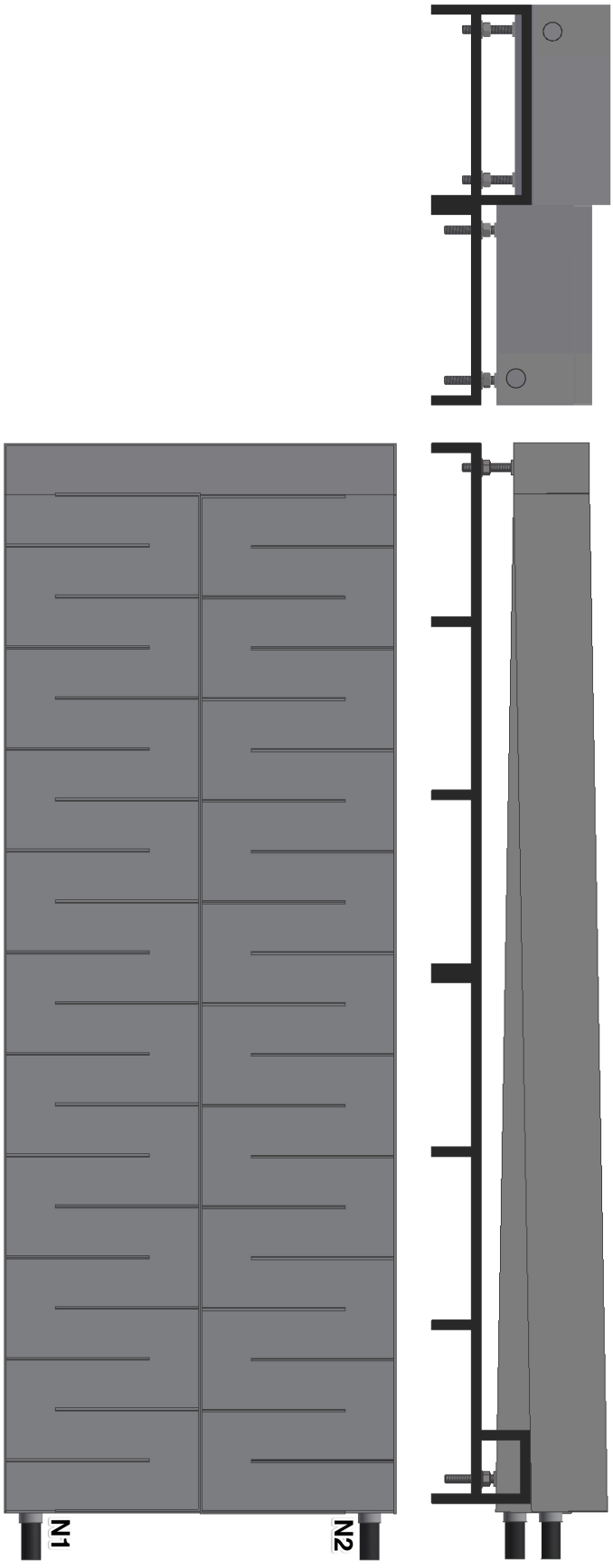

Fig. 38 Track photobioreactor, N1 – algal and water mixture inlet, N2 – algal and water mixture outlet

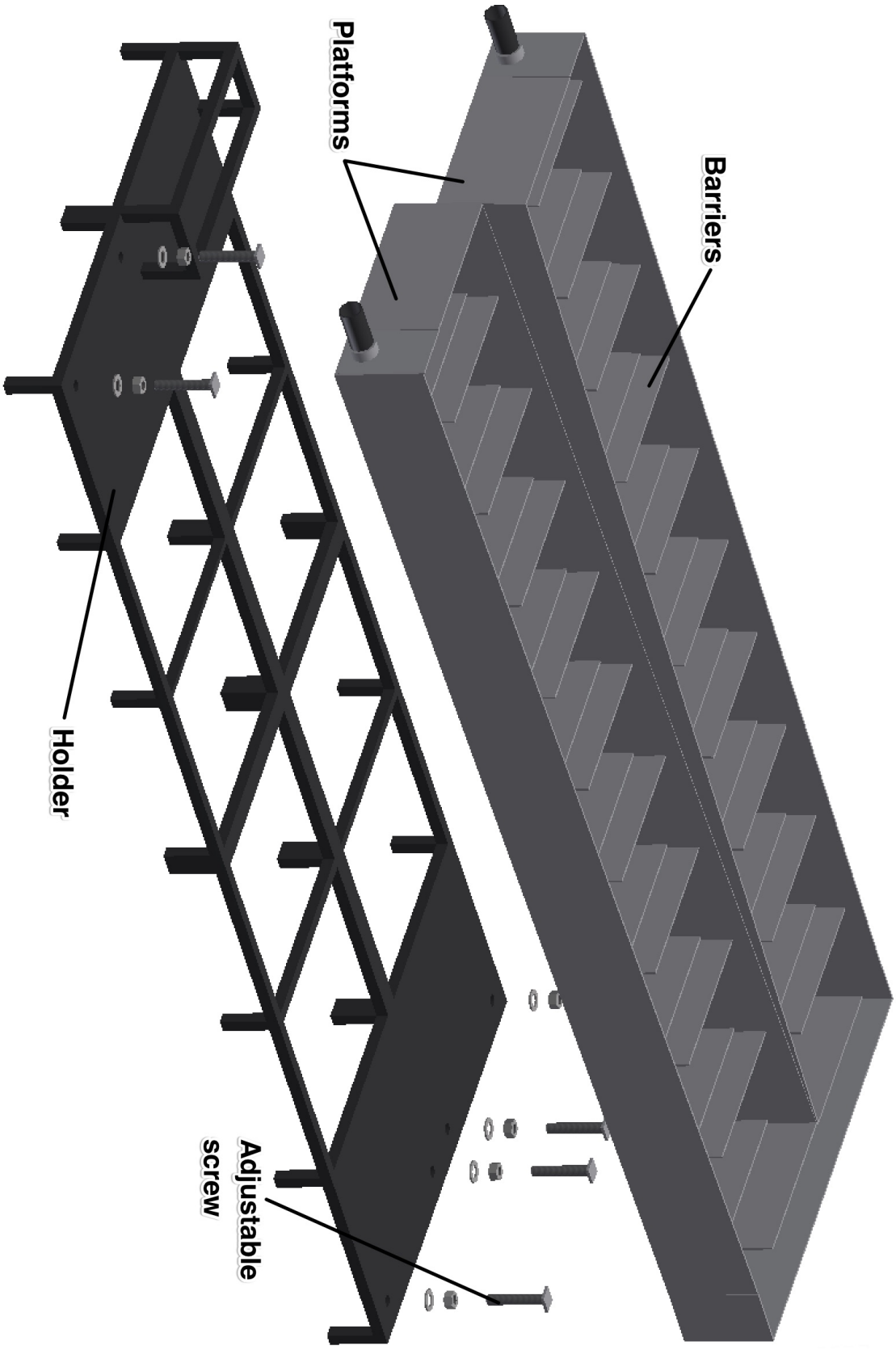

Fig. 39 Track photobioreactor

5.5. CTU laboratory

The aim of this paragraph is to describe a design of university laboratory for three pilot-plant photobioreactors. In order to elaborate comparison of the photobioreactor performances, it is necessary to ensure the same operational and environmental condition to all equipments. The lab is located in Czech Technical University in Prague laboratories, specifically in Department of Process Engineering. The scheme of the laboratory is shown in Figure 40.

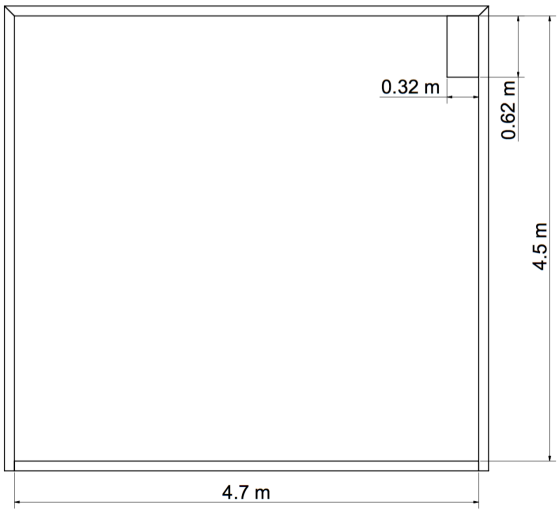

Fig. 40 CTU laboratory scheme

By the operational and environmental conditions is meant same irradiation intensity and environmental temperature. It is also important to ensure that function of each photobioreactor does not have an influence on the other photobioreactors function. According to this requirement, it would be appropriate to install each equipment in separate room. In each room is a need to provide sufficient space for manipulation with photobioreactors and all supporting equipments. In order to irradiate entire volume of the processed medium with central light source, it is needful to provide sufficient space around the irradiated area of photobioreactor section. Therefore, mutual shading from surrounding walls or supporting equipments should be eliminated. Creating a separate area for photobioreactor technical support seems to be the most appropriate option. The retention vessel is aerated with help of CO_2 pressurized vessel and oil-free air compressor (Appendix 6) according to the possibility to change the properties of aerated gas. For setting the desired concentration of CO_2 in air, gas mixer is used. All equipment used for aeration are placed centrally in area for technical support. It means that aerated gas will be distributed individually into photobioreactor rooms. The tools and equipment used for the controlling

and maintenance of photobioreactors should be placed in areas of technical support as well. The scheme of laboratory layout with dimensional disposition are shown in Figure 41.

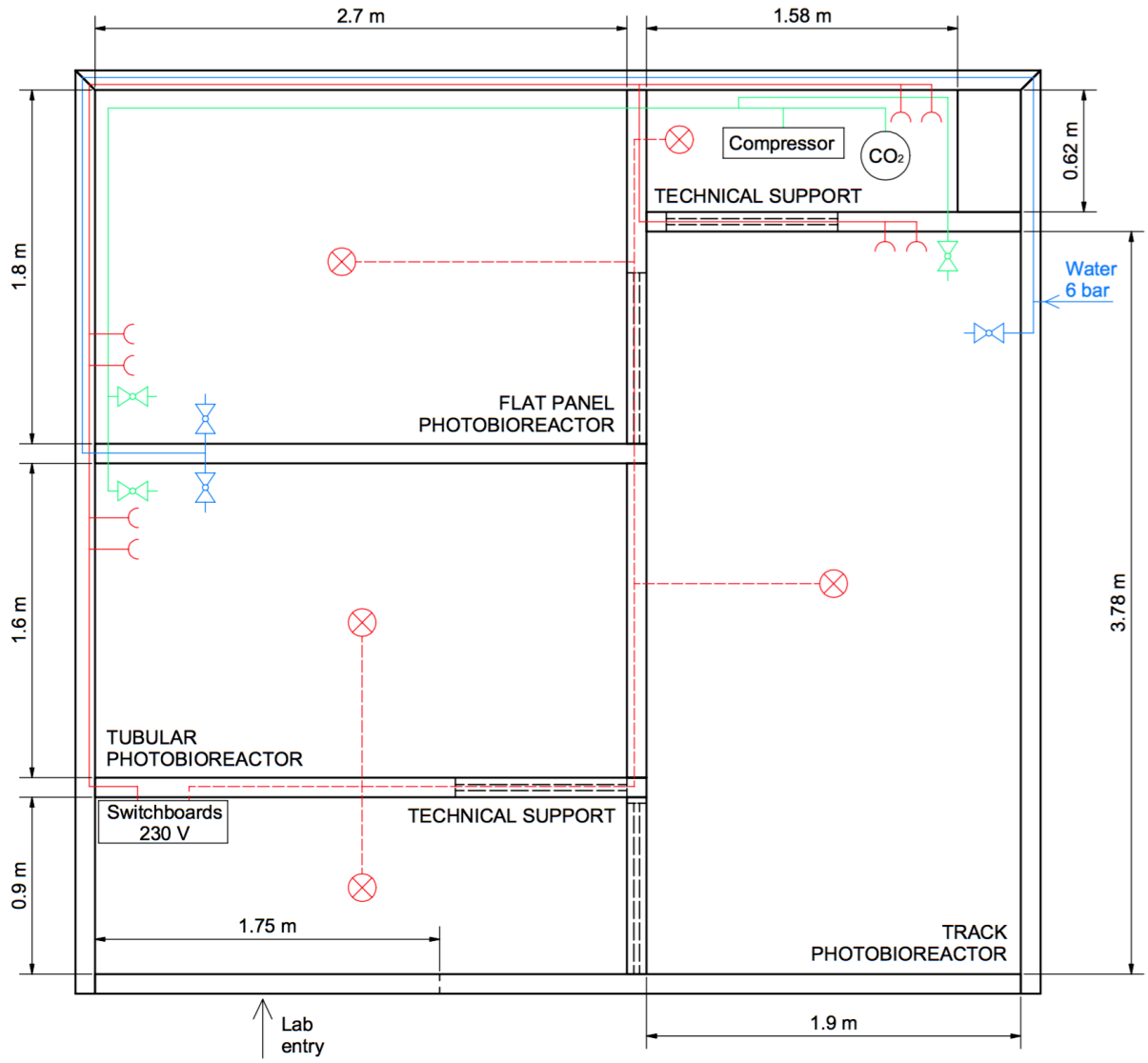

Fig. 41 CTU laboratory layout

Before designing of laboratory layout, it is necessary to specify all supporting equipments that are used for connecting of retention vessel and photobioreactor section. Circulation of the processed medium between the vessel and photobioreactor is ensured by a pump. To evaluate the performance of the algae production is needed to measure the most important parameters affecting the algae growth. Therefore, measuring equipments are placed in photobioreactors system as well. The factors that most affect the algae growth are described in paragraph 4.1. During the algae cultivation, concentration of CO_2, temperature changes after passing through the irradiated area and pH of processed medium are measured. To assess the effect of operating parameters on the growth of algae, it is also necessary to

regulate the flow rate, which have an influence on the residence time in the irradiated area. According to flow rate, it would be advisable to measure the head drop in photobioreactor section. For each variant of photobioreactor system, piping and instrumentation diagrams has been elaborated. Diagrams are shown in Figures 42, 43 and 44.

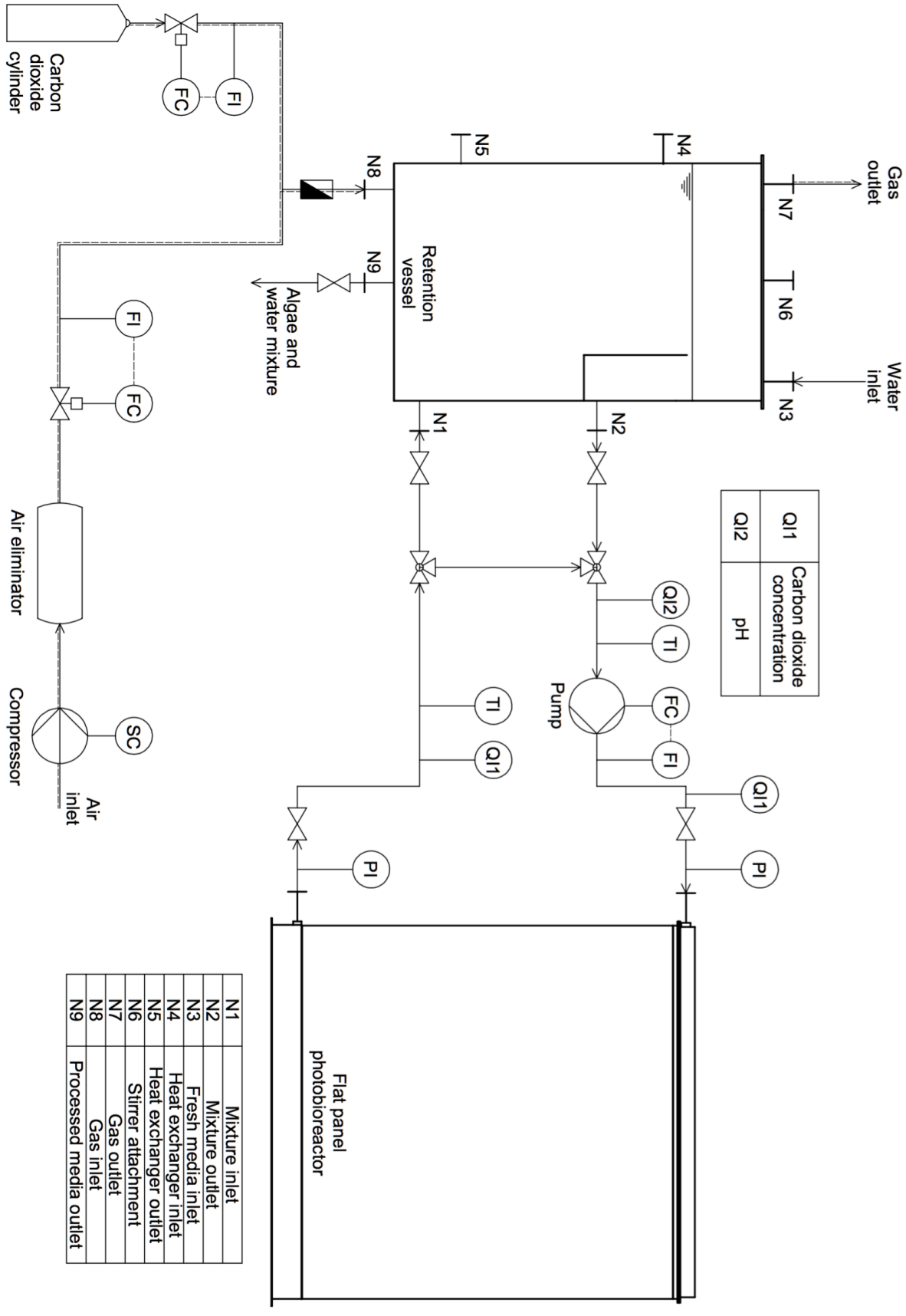

Fig. 42 Flat panel photobioreactor piping and instrumentation diagram

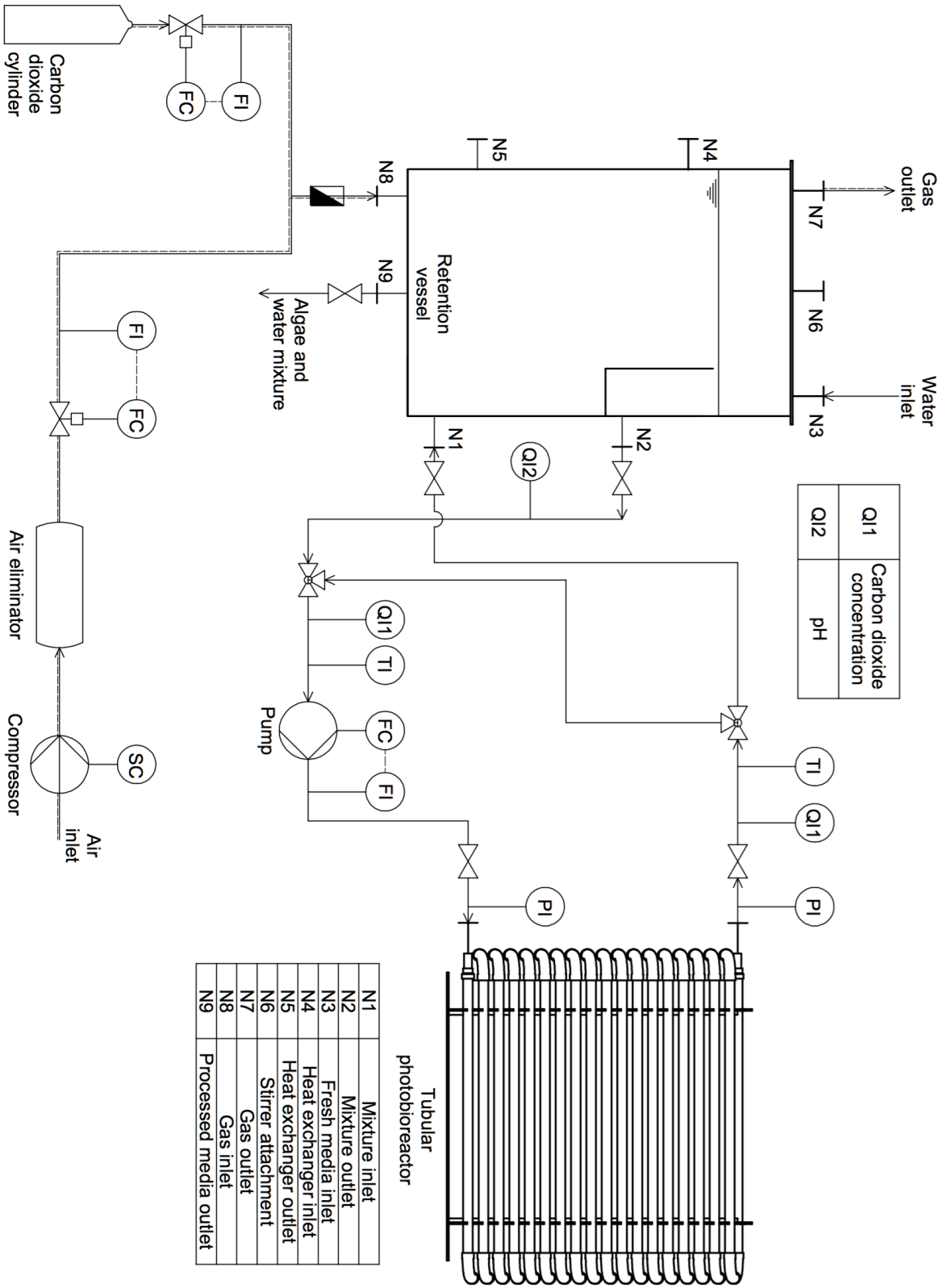

Fig. 43 Tubular photobioreactor piping and instrumentation diagram

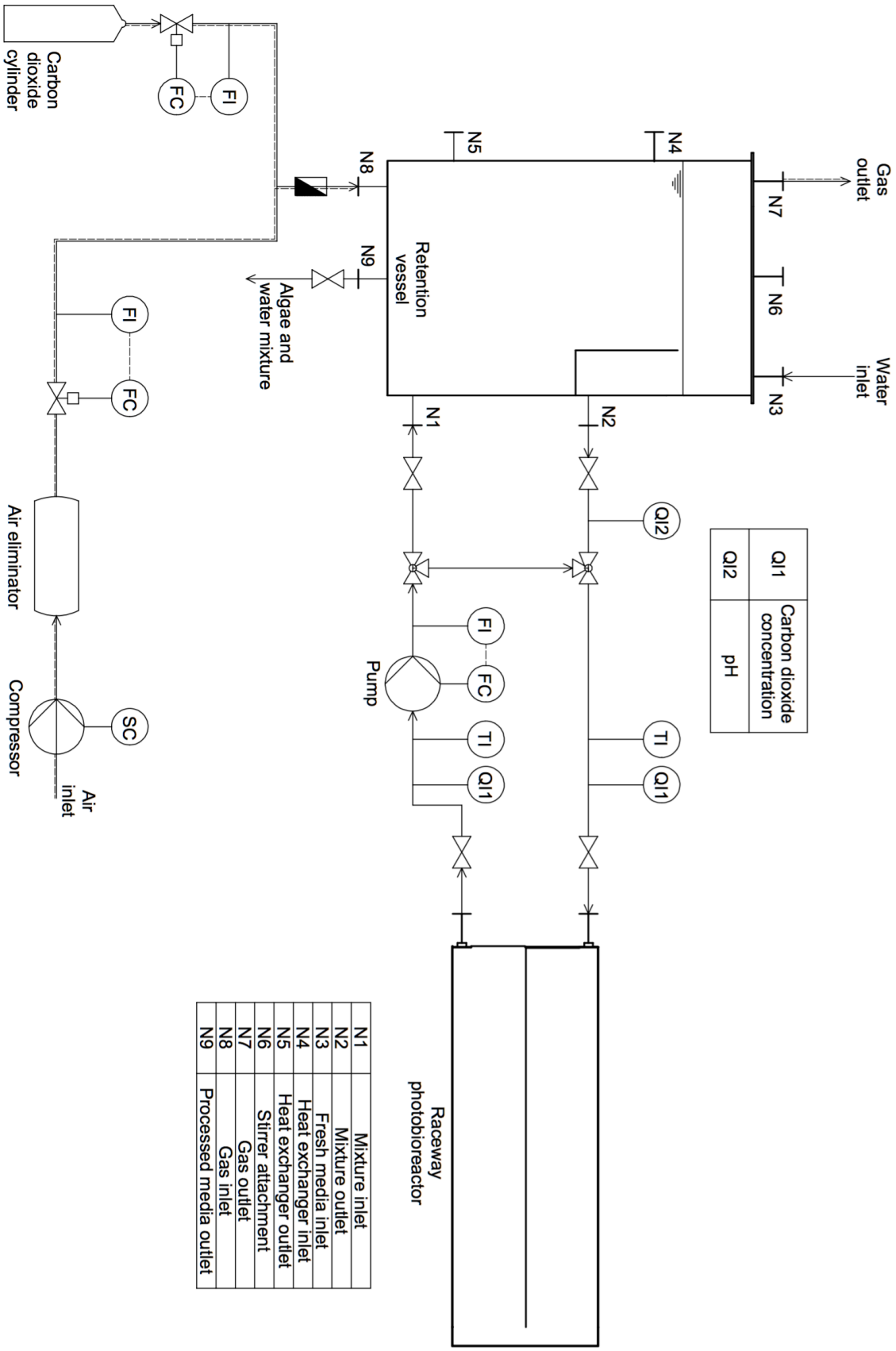

Fig. 44 Track photobioreactor piping and instrumentation diagram

At the inlet and outlet of photobioreactors sections are placed pairs of measuring sensors to monitor changes in temperature, CO_2 concentration and head drop. The pH is monitored on the inlet of photobioreactor section and flow rate is measured on the outlet of the pump. In order to regulate the ratio between the residence time of processed medium in retention vessel and photobioreactor section, the connection piping is placed between the photobioreactor section outlet and pump inlet as is shown in piping and instrumentation diagrams. Therefore, part of the processed medium can be irradiated for required time in photobioreactor section, whereas part of the medium can be aerated in the retention vessel at the same time. It is necessary to choose proper pump that ensure the circulation of the processed medium but also eliminate possibility of algae structure damage due to the high shear stress. According to previously mentioned factors, use of a peristaltic pump seems to be the most appropriate option. Peristaltic pumps transport material by mechanically squeezing the space enclosed by the flexible tube. Main advantage is that the pumped medium is completely enclosed with no possibility of leakage except in the case of a tube failure. Another advantage is the continuous pumping of the material. Flow rate supplied into the system can be controlled by a frequency converter.

The water is selected as the basic medium for the calculation of pump parameters. The final calculation will be adjusted by correcting parameter for a pumping of water and algae mixture. Dynamic viscosity of water at $25\ °C$ is $\mu_w = 0.0011\ \mathrm{Pa\ s}$. The density of water at the same temperature is $\rho_w = 997\ \mathrm{kg\ m^{-3}}$. Required delivery flow rate of the pump is determined from the required flow regime and residence time of the processed medium in photobioreactor. The velocity influence on agitation of medium in tubular photobioreactor has been described in paragraph 4.5. Due to the sufficient development of turbulence, Reynolds number was selected in the higher range than the critical value. Therefore, mean flow velocity in tubular photobioreactor is chosen to $v_{TP} = 0.2\ \mathrm{m\ s^{-1}}$. The Reynolds number can be derived from the equation (6)

$$\mathrm{Re}_{TP} = \frac{d_{in} \cdot v_{TP} \cdot \rho_w}{\mu_w} = \frac{0.044 \cdot 0.2 \cdot 997}{0.0011} = 7\,976 \qquad (9)$$

where $d_{in}\ [\mathrm{m}]$ is the tube internal diameter. The Reynolds number indicates that flow is in a turbulent region and stirring of processed medium is ensured. Consequently, residence time of the processed medium in photobioreactor section can be derived

$$t_{TP} = \frac{V_{TP}}{\dot{V}_{TP}} = \frac{\frac{\pi \cdot {d_{in}}^2}{4} \cdot n_T \cdot l_T}{v_{TP} \cdot \frac{\pi \cdot {d_{in}}^2}{4}} = \frac{n_T \cdot l_T}{v_{TP}} = \frac{36 \cdot 1.418}{0.2} = 255.2\ \mathrm{s} \tag{10}$$

where $V_{TP}\ [m^3]$ is the volume of processed medium in irradiated area, $\dot{V}_{TP}\ [m^3 s^{-1}]$ is the volumetric flow of processed medium in tubular photobioreactor. In order to compare the performances of photobioreactors, it is necessary to ensure the same residence time in all photobioreactors. However, in the case of track photobioreactor, the need of flow rate is higher due to the larger processed medium volume in photobioreactor section, which is more than double. Required delivery flow rate to track photobioreactor can be derived from the equality of the residence time

$$\dot{V}_{TRP} = \frac{V_{TRP}}{t_{TP}} = \frac{V_{TRP}}{t_{TP}} = \frac{220}{255.2} = 0.86\ \mathrm{L\ s^{-1}} = 3\ 096\ \mathrm{L\ h^{-1}} \tag{11}$$

For the selected operational parameters, it is necessary to determine if the agitation in flat panel photobioreactor is ensured. Flow regime can be derived from the Reynolds number for the flow between two parallel panels

$$Re_{FPP} = \frac{v_{FPP} \cdot D_{FPP} \cdot \rho_w}{\mu_w} = \frac{v_{FPP} \cdot n_P \cdot 4 \cdot b \cdot \rho_w}{\mu_w} \tag{12}$$

where $D_{FPP}\ [m]$ is the characteristic dimension of flat panel photobioreactor and $v_{FPP}\ [m\ s^{-1}]$ is the mean flow velocity in flat panel photobioreactor. Required flow velocity can be derived from the equality of the residence time

$$v_{FPP} = \frac{\dot{V}_{FPP}}{S_{FPP}} = \frac{\frac{V_{FPP}}{t_{TP}}}{2 \cdot b \cdot w} = \frac{\frac{0.164}{255.2}}{2 \cdot 0.02 \cdot 2.005} = 8.01 \cdot 10^{-3}\ \mathrm{m\ s^{-1}} \tag{13}$$

where $S_{FPP}\ [m^2]$ is the cross-section of flow in flat panel photobioreactor. The Reynolds number can be derived from the equation (12) and (13)

$$Re_{FPP} = \frac{8.01 \cdot 10^{-3} \cdot 2 \cdot 4 \cdot 0.02 \cdot 997}{0.0011} = 1\ 161 \tag{14}$$

According to flow between two parallel panels, the range of $\mathrm{Re} = 1\,000$ to $1\,500$ corresponds to transition regime of flow. The Reynolds number indicates that flow is in a transition regime and stirring of processed medium is not ensured. Therefore, for selected operational conditions, it is necessary to use internal panels with fixed barriers in design of flat panel photobioreactor.

The minimum power that peristaltic pump produces must be in equilibrium with the minimum power needed to compensate the losses of the system. The most significant losses will arise during the flow of processed medium in the tubular photobioreactor. Therefore, the pump power is designed with the help of the head loss calculation in tubular photobioreactor. The correlation, which relates to the head loss in hydraulically rough pipes for turbulent regime, contains a dimensionless friction factor λ, known as the Darcy friction factor. The friction factor can be calculated with help of the Reynolds number and the relative roughness of pipe $\mathrm{k_{rel}}$

$$\lambda = \left\{2 \cdot \log\left[0.27 \cdot \mathrm{k_{rel}} + \left(\frac{7}{\mathrm{Re_{TP}}}\right)^{0.9}\right]\right\}^{-2} \tag{15}$$

The relative roughness of pipe can be derived from the absolute pipe roughness $\mathrm{k_{abs}}$, which is for polymethylmethacrylate tubes $\mathrm{k_{abs}} = 0.002\ \mathrm{mm}$

$$\mathrm{k_{rel}} = \frac{\mathrm{k_{abs}}}{\mathrm{d_{in}}} = \frac{0.002 \cdot 10^{-3}}{0.044} = 0.000045 \tag{16}$$

Consequently, the friction factor can be derived from equations (9), (15) and (16)

$$\lambda = \left\{2 \cdot \log\left[0.27 \cdot 0.000045 + \left(\frac{7}{7\,976}\right)^{0.9}\right]\right\}^{-2} = 0.033 \tag{17}$$

Using this friction factor, head loss can be derived from the equation

$$\Delta \mathrm{p_1} = \lambda \cdot \frac{\mathrm{l_{TP}}}{\mathrm{d_{in}}} \cdot \frac{\mathrm{v_{TP}^2}}{2} \cdot \rho_\mathrm{w} = 0.033 \cdot \frac{66.58}{0.044} \cdot \frac{0.2^2}{2} \cdot 997 = 995.7\ \mathrm{Pa} \tag{18}$$

where $\mathrm{l_{TP}}\ [\mathrm{m}]$ is the length of tubular photobioreactor section. Minor head losses can be calculated with help of minor loss coefficient of the knee ξ_K. The coefficient of bending loss caused by changing the flow direction in knees can be derived

$$\xi_b = \frac{\pi}{2} \cdot \lambda \cdot \frac{r_K}{d_{in}} = \frac{\pi}{2} \cdot 0.033 \cdot \frac{0.1}{0.044} = 0.12 \tag{19}$$

where r_K [m] is the knee radius. The friction loss coefficient is defined by

$$\xi_f = 0.21 \cdot \left(\frac{r_K}{d_{in}}\right)^{-\frac{1}{2}} = 0.21 \cdot \left(\frac{0.1}{0.044}\right)^{-\frac{1}{2}} = 0.14 \tag{20}$$

The banding minor losses coefficient can be derived from equations (19) and (20)

$$\xi_K = \xi_b + \xi_f = 0.12 + 0.14 = 0.26 \tag{21}$$

The minor head loss can be derived

$$\Delta p_2 = \xi_K \cdot n_K \cdot \frac{v_{TP}^2}{2} \cdot \rho_w = 0.26 \cdot 70 \cdot \frac{0.2^2}{2} \cdot 997 = 362.9 \text{ Pa} \tag{22}$$

The total loss can be derived from the equations (14) and (18)

$$\Delta p_f = \Delta p_1 + \Delta p_2 = 995.7 + 362.9 = 1\,358.6 \text{ Pa} \tag{23}$$

The pressure at the input in the retention vessel, p_{RV} is supposed to assume a value equal to to hydrostatic pressure at the bottom of retention vessel

$$p_{RV} = L_{RV} \cdot \rho_w \cdot g = 0.65 \cdot 997 \cdot 9.81 = 6\,357.4 \text{ Pa} \tag{24}$$

where the L_{RV} [m] is the level of processed medium in retention vessel and g [m s^{-2}] is the gravitational acceleration.

The pressure which must be delivered by the pump p_p can be derived from equations (23) and Bernoulli equation

$$\frac{p_p}{\rho_w \cdot g} + \frac{v_{TP}^2}{2 \cdot g} = \frac{p_{RV}}{\rho_w \cdot g} + \frac{v_{TP}^2}{2 \cdot g} + z_2 + \frac{\Delta p_f}{\rho_w \cdot g} \tag{25}$$

$$p_p = z_2 \cdot g \cdot \rho_w + p_{RV} + \Delta p_f \tag{26}$$

$$p_p = 1.4 \cdot 9.81 \cdot 997 + 6\,357.4 + 1\,358.6 = 21.41 \text{ kPa}$$

where z_2 $[m]$ is the height of photobioreactor outlet. The scheme of the Bernoulli calculation is shown in Figure 45.

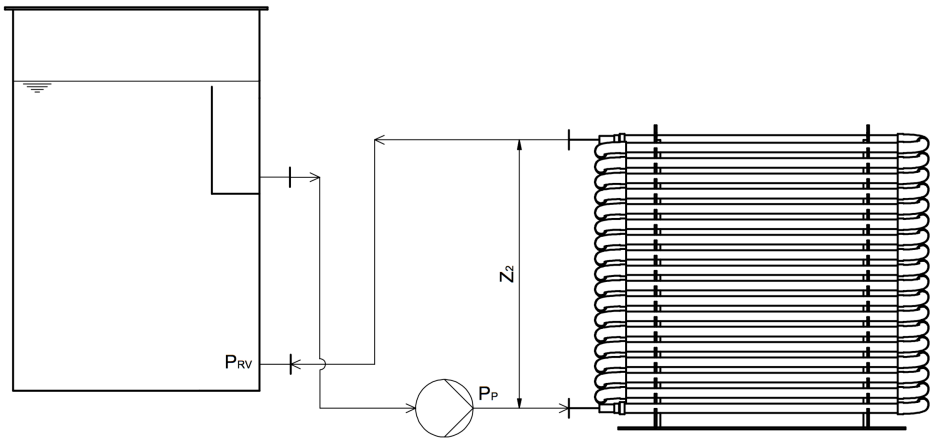

Fig. 45 Bernoulli calculation scheme

Taking into account that water and algae mixture has a higher density and viscosity than pure water, it is necessary to consider higher pressure demands on the system. Therefore, the pressure supplied by the pump to the system, p_p, is considered to assume a value of 50 kPa. To ensure a proper pumping in the system, Hydro-Tech P_classic 35 pump has been chosen. The specification of the pump is described in Data Sheet (Appendix 5). For all photobioreactors and retention vessel, dimensional drawing has been created. Drawings are attached in Appendix. For each component of the photobioreactor systems, a 3D model was created. Figures 46 - 48 show the final construction of photobioreactor systems.

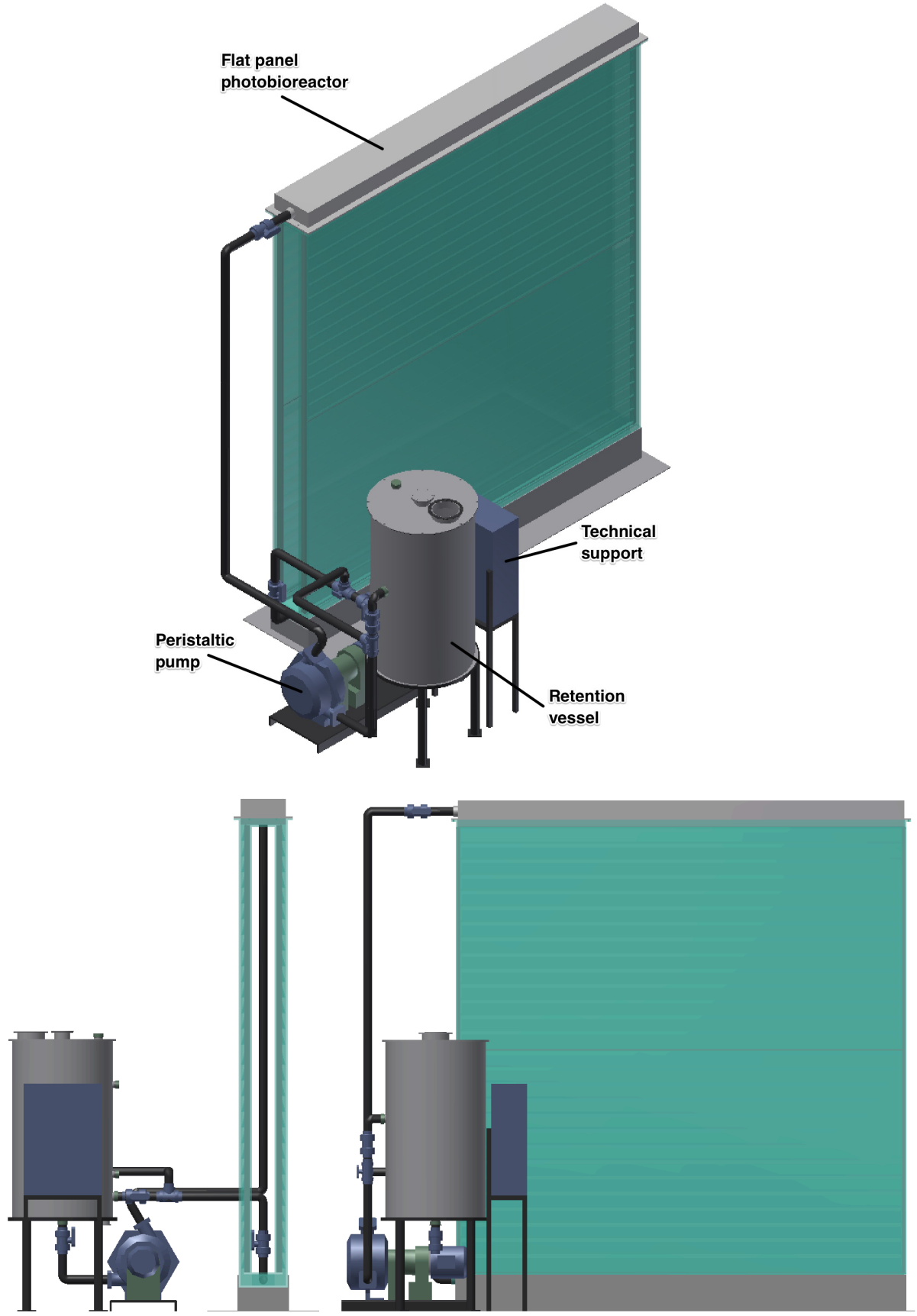

Fig. 46 Flat panel pilot-plant photobioreactor system

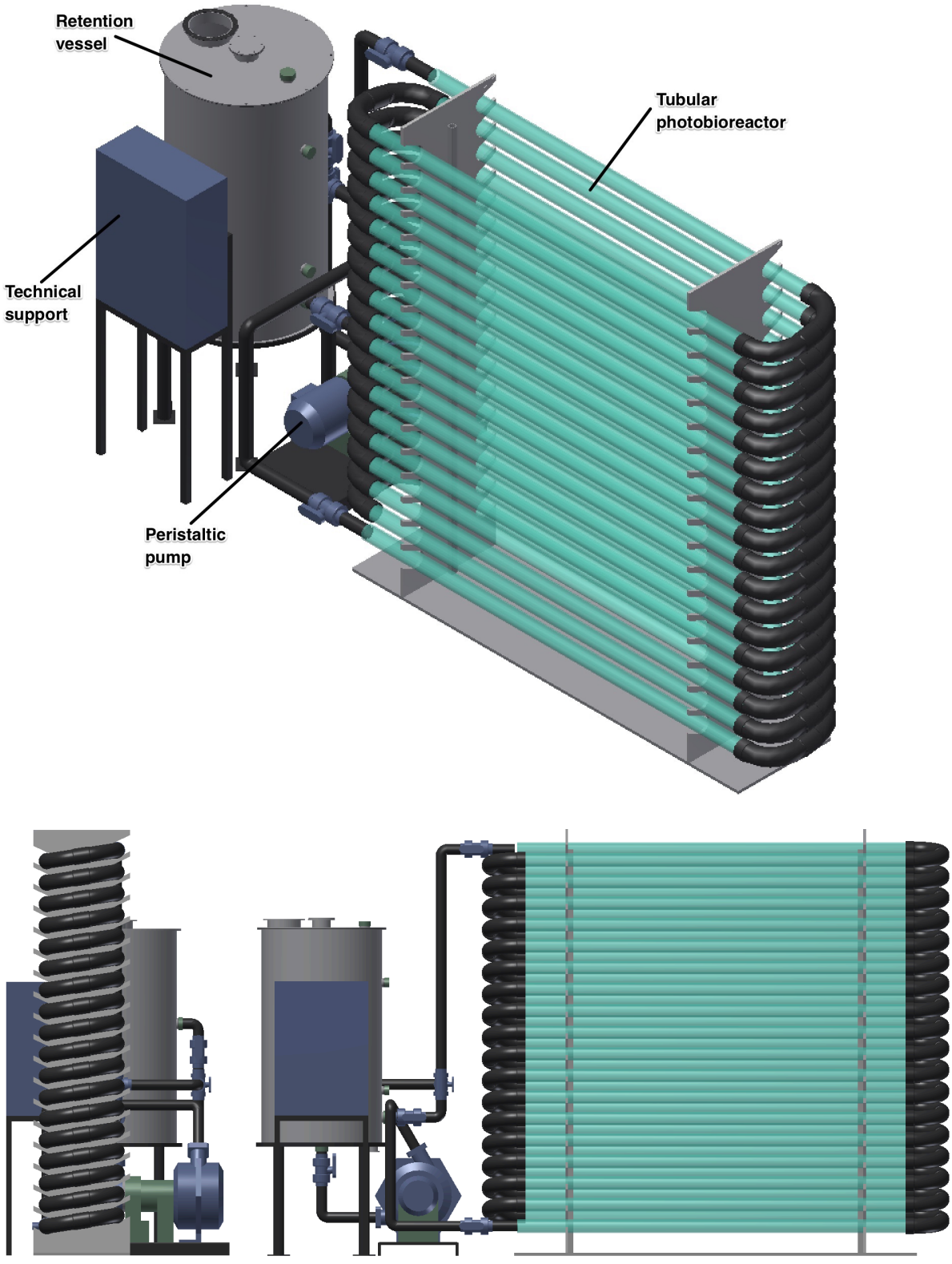

Fig. 47 Tubular pilot-plant photobioreactor system

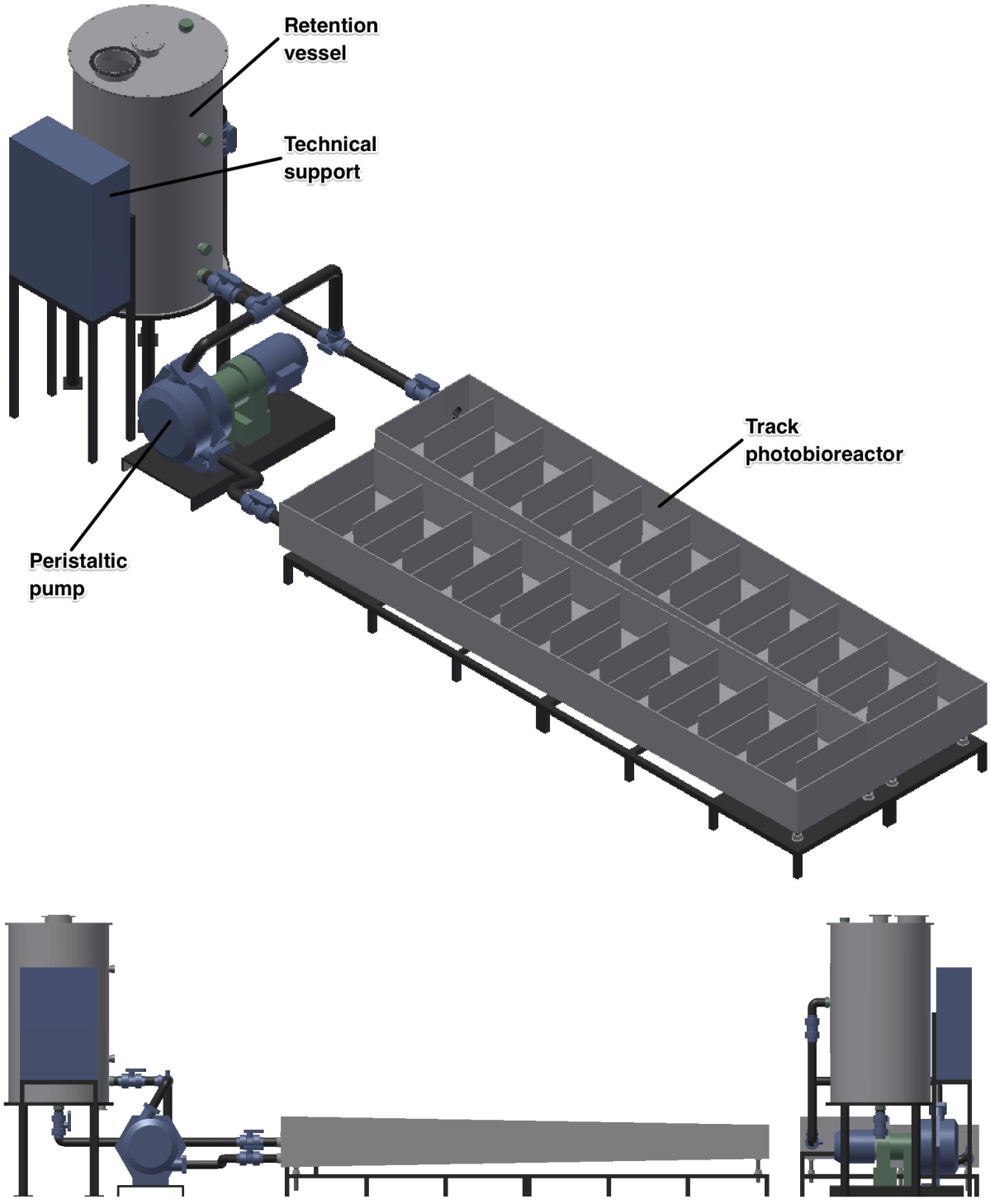

Fig. 48 Track pilot-plant photobioreactor system

In Table 9, an overview of design and operational parameters is shown. The ratio of the irradiated photobioreactor area to the area of the of the laboratory of each photobioreactor shows that the most appropriate is the flat panel photobioreactor. The main drawback of track photobioreactor is low irradiated area and high volumetric flow needs to ensure the same residence time of processed medium in photobioreactor section. On the other hand, it is possible to regulate volume of processed medium in photobioreactor section as well as in the flat panel photobioreactor.

Figures 49 and 50 show the attachment of photobioreactors in CTU laboratory

	Flat panel	Tubular	Track
Maximal medium volume in irradiated area V_{PBR} [L]	220	100	220
Irradiated area A_{PBR} [m^2]	8	8.01	1.76
Laboratory area occupied by photobioreactor A_{PBR} [m^2]	0.45	0.63	1.76
$\frac{A_{PBR}}{A_{PBR\_lab}}$	17.8	12.7	0.97
Construction material	Polyethylene terephthalate	Polymethylmethacrylate	Polyethylene terephthalate
Equipment weight m_{PBR} [kg]	140	55	40
Residence time in photobioreactor section t_{PBR} [s]	255		
Volumetric flow $\dot{V}_{PBR}$ [$L\ s^{-1}$]	0.64	0.3	0.86

Table 9 An overview of design and operational parameters

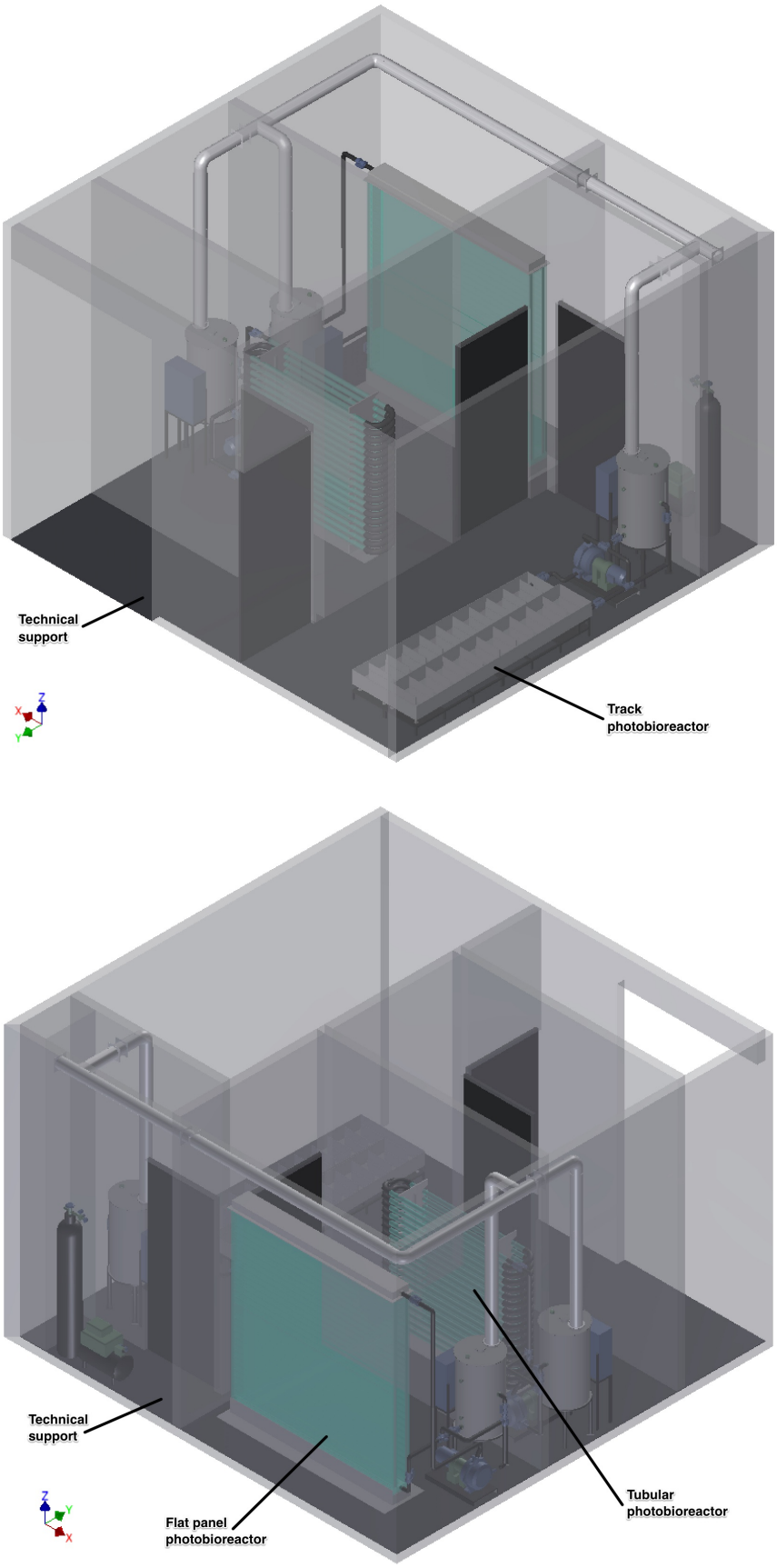

Fig. 49 UPC laboratory with attached equipments

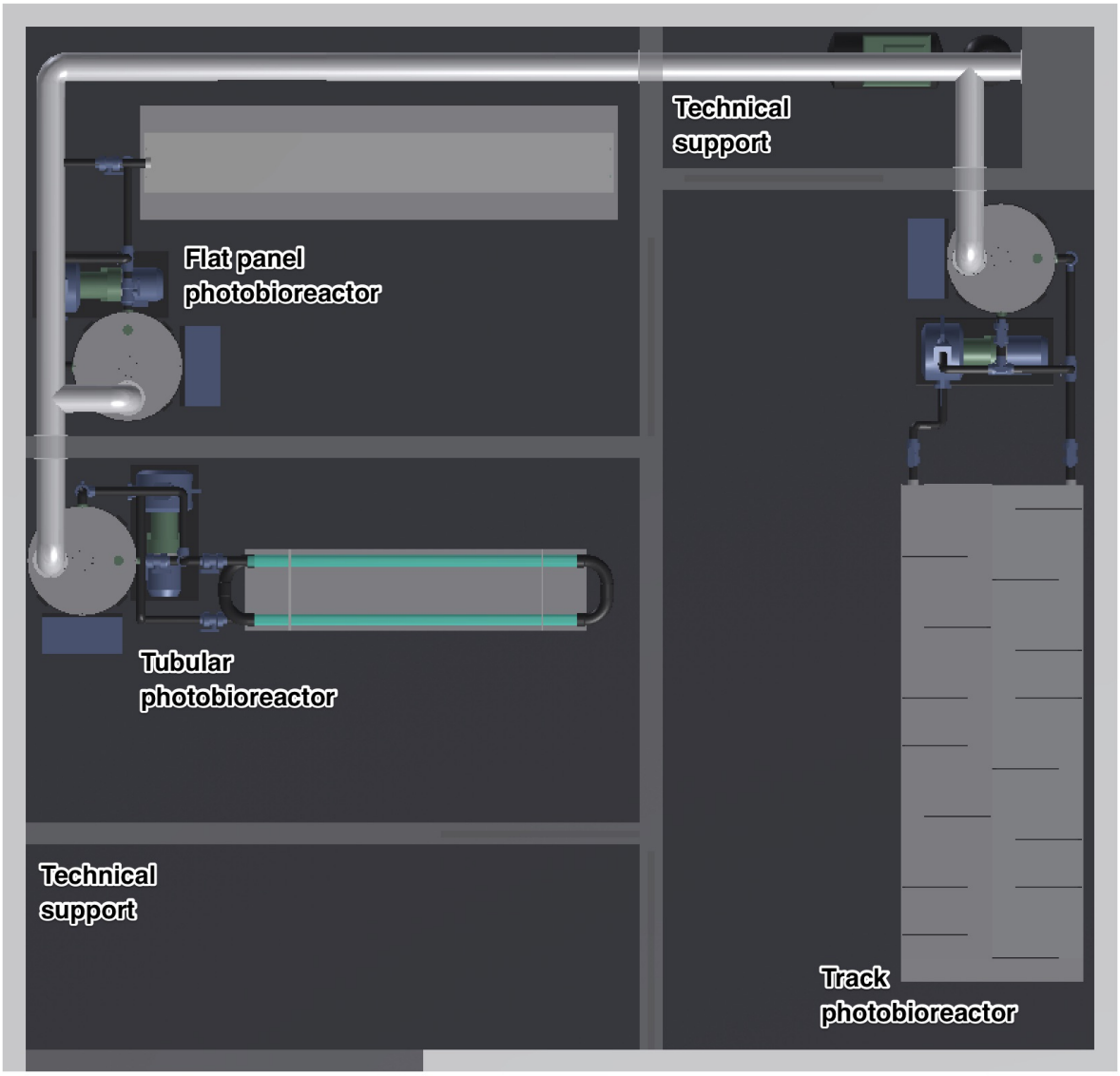

Fig. 50 UPC laboratory top view

6. Conclusions

Algae biomass is classified as a third generation feedstock and it has a potential for biofuel, food, feed and chemical production. However, challenges to commercialize the production at large scale need to be solved. The aim of the theoretical part of this diploma work was to provide an overview of algae application and existing design alternatives for algae cultivation and biofuel production.

- Different algae life cycles and product range of algae biomass have been described. Algae biomass cellular structure and possibility of components optimization have been described. The comparison of algae with other biodiesel feedstocks and conversion process of algae biomass is shown.
- An overview of algae cultivation and influence of properties and factors have been described. The ration of dependence is strictly connected with the type of algae species. For the selection of the proper cultivation system, it is necessary to define operational parameters, which most affect the function. Light, temperature, CO_2 absorption, nutrients, pH and agitation of processed medium are the most important factors affecting algae cultivation.
- According to weather conditions in the Czech Republic, use of artificial source of light for algae irradiation seems to be the best option. In electricity consumption and operation stability terms, LED light source appears as appropriate.
- Some algae species tolerate a broad range of temperatures between 15 and 45 °C. For this reason, it is appropriate to use closed indoor system due to its easier temperature control.
- Utilization of CO_2 by algae for its growth can be divided into two main stages: absorption of CO_2 by mass transfer and fixation of CO_2 by photosynthesis. The aim of the absorption is to reduce the mass transfer resistance. The ways for increasing transfer area are bubbling or absorption in packed bed. However, the mechanism must be suitable for O_2 production from algae as well, because high presence of O_2 around algae cells is undesirable. The source of CO_2 may be surrounding air at a CO_2 concentration of about 0.035 %. To intensify growth can be used flue gas with concentration ranges between 0.035 and 15 %.

- Algae require two major nutrients for proper growth: nitrogen and phosphorus. Both of them play a significant role in controlling growth rates and lipid production.
- The pH of the medium is connected to the concentration of CO_2 and because pH is so influential it is necessary to control pH value during the growth. The optimal pH of most cultured algae species in in the range of 7-9.
- Agitation is important feature for proper algae cultivation. It is necessary to prevent sedimentation of algae cells and ensure that all cells will have uniform average exposure time to light and nutrients.
- Algae production could have significant influence on environmental impact. Direct mitigation method is used to capture CO_2 directly from atmosphere and indirect mitigation is used to reduce CO_2 emission from production. The pathway for the removal of nutrients such as nitrogen and phosphorus and also chemical and organic contaminants has been described.
- And overview of existing design alternatives for algae cultivation has been elaborated. Autotrophic production is the only method which is currently economically and technically feasible for scale-up production of algae biomass.
- Design alternatives have been divided into the three main groups: open pond system, closed photobioreactor systems and hybrid photobioreactors. According to this groups, main cultivation systems has been described and and pros and cons have been specified.
- The comparison overview of open pond systems and closed photobioreactor systems for algae cultivation and all characteristics and operational parameters, which most affect the function, have been elaborated.
- According to design alternative study, three designs have been selected: raceway pond system, flat panel photobioreactor and tubular photobioreactor.

The aim of the design part was to obtain three design variants of pilot-plant photobioreactors that could be further compared. Comparing aspects have been specified and according to this, basic operational and design conditions have been selected.

- The retention vessel is used as the external equipment, which should ensure the same CO_2 absorption condition and easier temperature control for each cultivation system.
- Retention vessel, flat panel photobioreactor, tubular photobioreactor and track photobioreactor have been designed. Design drawing and equipment 3D model have been elaborated for each cultivation system.
- The scheme of laboratory layout with dimensional disposition and laboratory 3D model have been elaborated.
- The piping and instrumentation diagram for each cultivation system has been provided and technical support equipments have been specified.
- The 3D model of laboratory with attached photobioreactors and technical support equipment has been elaborated.

7. Notations

Nomenclature

$\dot{\mathbf{V}}$	$[\mathrm{m}^3\ \mathrm{s}^{-1}]$	Volumetric flow
$\Delta\mathbf{p_1}$	[Pa]	Head loss
$\Delta\mathbf{p_2}$	[Pa]	Minor head loss
$\Delta\mathbf{p}$	[Pa]	Total loss
$\mathbf{A}$	$[\mathrm{m}^2]$	Irradiated area
$\mathbf{b}$	[m]	Distance between panels
$\mathbf{d}$	[m]	Diameter
$\mathbf{D}$	[m]	Characteristic dimension
$\mathbf{g}$	$[\mathrm{m\ s}^{-2}]$	Gravitational acceleration
$\mathbf{h}$	[m]	Panel height
$\mathbf{I}$	$[\mu\mathrm{E\ m}^{-2}\mathrm{s}^{-1}]$	Irradiance
$\mathbf{k}$	[m]	Roughness
$\mathbf{l}$	[m]	Length
$\mathbf{m}$	[kg]	Weight
$\mathbf{n}$	$[-]$	Quantity
$\mathbf{P}$	$[\mathrm{g\ m}^{-2}\ \mathrm{day}^{-1}]$	Productivity
$\mathbf{p}$	[Pa]	Pressure
$\mathbf{S}$	[m]	Cross-section
$\mathbf{t}$	[s]	Residence time
$\mathbf{V}$	$[\mathrm{m}^3]$	Volume
$\mathbf{v}$	$[\mathrm{m\ s}^{-1}]$	Velocity
$\mathbf{w}$	[m]	Panel width

Greek letters

$\boldsymbol{\lambda}$	$[-]$	Darcy friction factor
$\boldsymbol{\mu}$	$[\mathrm{Pa\ s}]$	Dynamic viscosity
$\boldsymbol{\nu}$	$[\mathrm{m^2\ s^{-1}}]$	Kinematic viscosity
$\boldsymbol{\xi}$	$[-]$	Loss coefficient
$\boldsymbol{\rho}$	$[\mathrm{kg\ m^{-3}}]$	Density

Subscripts

a	Areal	**PBR**	Photobioreactor
abs	Absolute	**PBR_lab**	Photobioreactor lab
b	Bend	**rel**	Relative
ex	External	**RV**	Retention vessel
f	Friction	**T**	Tube
FPP	Flat panel photobioreactor	**TP**	Tubular photobioreactor
FPP_lab	Flat panel photobioreactor lab	**TP_lab**	Tubular photobioreactor lab
in	Internal	**TR**	Track
K	Knee	**TRP**	Track photobioreactor
P	Panel	**TRP_lab**	Track photobioreactor lab
p	Pump	**w**	Water

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9. Appendixes

Appendix 1: Design drawing, FLAT PANEL PHOTOBIOREACTOR: VB01 – 01.0001

Appendix 2: Design drawing, TUBULAR PHOTOBIOREACTOR: VB01 – 02.0001

Appendix 3: Design drawing, TRACK PHOTOBIOREACTOR: VB01 – 03.0001

Appendix 4: Design drawing, RETENTION VESSEL: VB01 – 04.0001

Appendix 5: Data sheet, PERISTALTIC PUMP: VB01 – 05.0001

Appendix 6: Data sheet, AIR OIL-FREE COMPRESSOR: VB01 – 06.0001