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ANALYSIS OF MICROALGAE SUSPENSION FLOW DYNAMICS IN CIRCULAR, HEXAGONAL AND SQUARE SHAPE TUBES

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Abstract-*Microalgae based biofuel is considered as the most sustainable alternative to the fossil fuel. As microalgae are photosynthetic microorganisms, light is one of the limiting factors for their growth. In the closed photo-bioreactor method, the proper light distribution related to the suspension flow inside the tube is not properly investigated yet for different types of tube. In this study, we aim to simulate the flow dynamics inside three different PBR tube such as Circular, Hexagonal and Square shape. The length of each tube is approximately 20.5m with radius 0.05m. From this study, we observed that the hydrodynamics of suspension flow show quite dissimilar inside three different tubes. The straight part shows parabolic shape of the flow in case of circular tube while square and hexagonal resembling different shapes. At the middle of the U-loop fluid distribution haphazardly moving in all directions for all kind of tubes. In case of three tubes, a linear pressure drop from inlet to outlet is found; however in U-loop small fluctuation of pressures are found. By comparing the three tubes we observed that tubular one shows better agreement for less cell damage and proper light distribution than others.*

Keywords: CFD, Biofuel, Photo-bioreactor, Microalgae, Simulation

1. INTRODUCTION

Global warming, CO_2 emission, gradual run out of petro-fuel and the issues regarding the use of alternative fuel make the scientists and researchers all over the world thoughtful about finding a renewable energy [1]. Increasing global energy demand, greenhouse effect and the depleted sources of petroleum fuel have gathered the industrially develop countries to explore a renewable energy source that is eco-friendly and economic. Generally, renewable energy sources such as solar, wind, hydro, geothermal and energy from biomass and wastes are being used by many developed countries to mitigate the pressure on fossil fuel due to rapid industrialization and population growth. A recent study from International Energy Agency (IEA) shows that only combustible renewables and wastes has the highest energy potential among other renewable sources. From that report, combustible renewables and wastes cover 10.0% of the total primary energy supply, whereas hydro 2.2% and others 0.7% (solar, wind, geothermal).So It can be predicted that combustible renewable i.e. biodiesel can play a vital role as an alternative renewable energy in the near future [2].

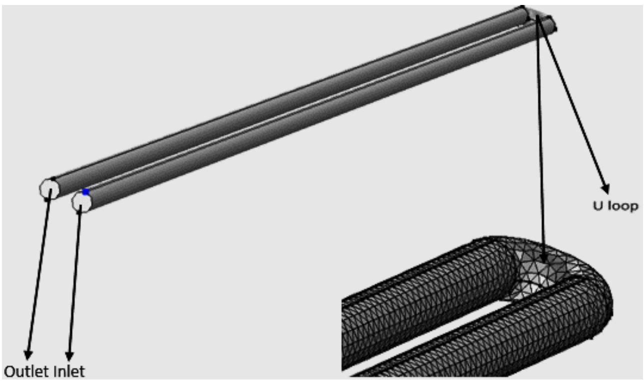
Biodiesel is now drawing a keen interest of the researchers, traders and the countries. The technology of producing biodiesel has been known for more than 50 years [3]. The main advantages of it over fossil fuel that it is non-toxic and biodegradable. Biodiesel production from first generation (soybean, rapeseed, sunflower, palm oil) and second generation (nonedible oil such as oil from corn or sugarcane) have some drawbacks due to economic and environmental limitations. In that case, to overcome those drawbacks microalgae is the most promising source of the third generation biofuels as alternative fuel and foreseen to be the fuel of future [4, 5, 6].

Microalgae are photosynthetic microorganisms that grow rapidly about 100 times faster than terrestrial plants and can make biomass double in one day. Their strains contain lipid inside the cells which can be converted into biodiesel [3]. There exist two major systems in the algae-production industry; one is the open pond system and another is the closed bioreactor system. Traditionally algae are growing in open ponds for a long time because of the low operating cost. This raises numerous anxieties such as difficulties to control growth conditions and contamination risks. These technical and biological limitations have enforced the development of closed systems. The main advantage of photo bioreactors (PBR) is that it permits the growth of single strain culture, in which optimum growth condition is always maintained to ensure high consistency in biomass and lipid productivity. During photo bioreactor design, light regime is considered as one of the most limiting factor as cell growth of microalgae extremely depends on it. An investigation led by Perner showed that bent pipes with large radius of curvature and circular cross area are better than rectangular shapes.

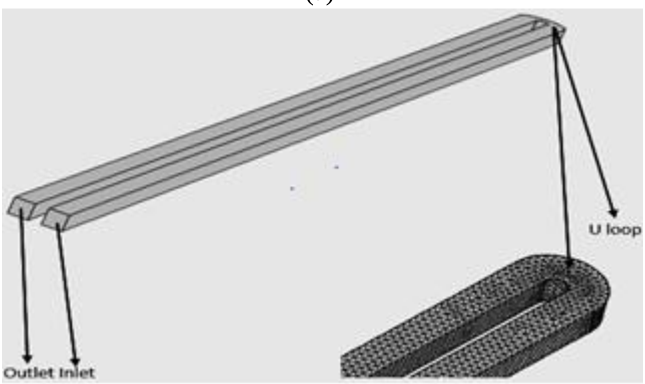
In this study, three types of photo bioreactors such as tubular, square and hexagonal shape tubes with a bent portion of 0.4 meter of radius of curvature for microalgae culture has been considered and made a comparison among them so that it is easy to understand which one is the most conforming to less cell damage while microalgae cell are cultivated.

2. MATHEMATICAL MODEL

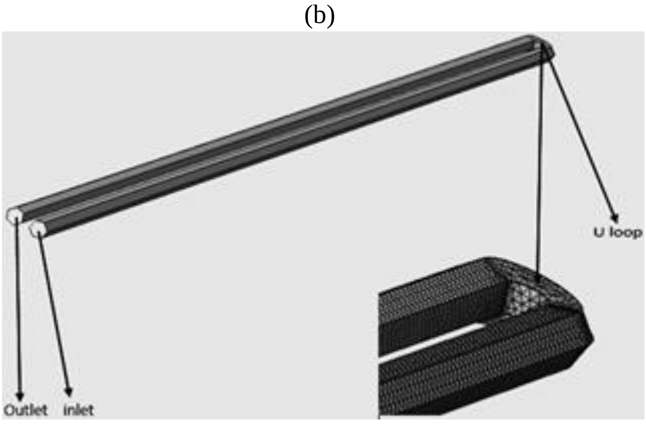
The ultimate goal of this study is to make clear understanding about the performances of different types of photo bioreactors regarding microalgae cultivation. Here we considered three types of PBRs made of acrylic plastic tubes. The microalgae suspension flow inside the tubesis considered as incompressible single phase Newtonian and laminar fluid flow. The density of microalgae suspension culture is taken 1020 kg/m^3.



(a)



(b)



(c)

Fig. 1: The computational domain and normal mesh design of U-loop portion for tubular (a), square(b) & hexagonal(c).

2.1. Computational Domains and Meshes

The three types of photo bioreactor that we considered here, each of them have radius of 0.025m and length is 20.4m. The surface area and working volume for three PBRs' are in Table1.

Table1: Surface area & volume of the PBRs

PBR's Shape Type	Surface area(m^2)	Working volume(m^3)
Tubular	6.351	0.1567
Square	8.124	0.2026
Hexagonal	7.036	0.1755

For simulation study, we use normal mesh for square and hexagonal but for tubular normal as well as coarse mesh is used to make comparative study which one shows better performance for time dependent study. Table 2 shows the comparison of elements between normal and coarse mesh for circular PBR and table 3 shows the mesh parameters for each PBR for normal mesh.

Table 2: Comparison between normal and coarse mesh

Mesh type	Total elements	Minimum quality	Average quality	Mesh volume,m^3
Normal	153526	0.1506	0.6948	0.1551
Coarse	53189	0.06733	0.5986	0.1519

From the comparison of mesh design in table 2, we can see that mesh quality and elements both are better in normal mesh. The goal is to check the grid sensitivity in our simulation which is discussed later.

Table 3: Mesh parameters of the PBRs

Photo bioreactors	Vertex Elements	Edge Elements	Boundary Elements
Tubular	12	1825	28472
Square	16	2416	19158
Hexagonal	24	5145	30746

2.2 Governing Equations

Microalgae suspension is considered as an incompressible Newtonian fluid and the flowproblem islaminar, the governing equations are the continuity equation and Navier-Stokes equations as follows:

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{g} \quad (2)$$

where,**u**denotes the velocity of the suspension, ρ represents the density, $\boldsymbol{\sigma}$ is the stress tensor and **g** denotes the gravity. $\boldsymbol{\sigma}$ can be expressed as

$$\boldsymbol{\sigma} = -P\mathbf{I} + 2\eta \mathbf{D}(v) \quad \mathbf{(3)}$$

where, η is the viscosity of the fluidand $\mathbf{D}(v)$ is the rate of deformation of the tensor. The viscosity $\eta(t)$ in equation (3) related to the water viscosity $\eta_0(t)$ is determined by:

$$\eta(t) = \eta_0 \eta_r(t). \quad (4)$$

The Einstein's relative viscosity relating to the concentration is then used and determined by

$$\eta_r(t) = 1 + \varepsilon C(t) \quad \textbf{(5)}$$

where ε is the Einstein's coefficient [7].Based on the experiment conducted by Hon-nami and Kunito[8], the concentration *C(t)* in equation (5) is given by the logistic equation (6).

$$C(t) = C_0 + \frac{a}{1 + be^{-\mu t}} \quad \textbf{(6)}$$

where, μ is the constant growth rate of microalgae cells, C_0 is the initial concentration of the suspension and *a* and *b*are constants.

2.3. Boundary and Initial Conditions

For our simulation we considered no slip boundary condition on the wall of the tube and zero normal stress at the outlet for all the three domains, as follows:

$$\boldsymbol{u} = 0, \quad (7)$$

$$[-p\boldsymbol{I} + \eta(t)(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T)]\boldsymbol{n} = 0 \quad (8)$$

3. SIMULATION AND NUMERICAL RESULTS

The main goal of this study is to develop in-depth knowledge of fluid behaviour for three different types of PBRs. We run our simulation using the COMSOL Multi physics version 4.2a package.

3.1 Parameters

The input parameters and their corresponding values for simulation are given in table 4.

Table 4: Parameters value using for simulation

Name	Value	Description
g	9.8m/s^2	Gravity acceleration
eta_0	0.001[Pa*s]	Water viscosity
C_0	0.55	Constant parameter
B	200	Constant parameter
A	1	Constant parameter
mu1	0.063[1/h]	Maximum growth rate

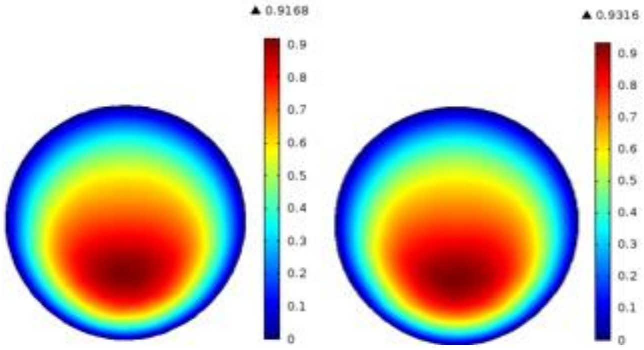
3.2 Variables

The variables are assumed c and mu and their expressions are c0+1/(a+b*exp(-mu1*t)) and eta_0*(1+2.5*c) respectively. The inlet velocity is u=0.5 m/s^{-1}.

3.3 Numerical Results

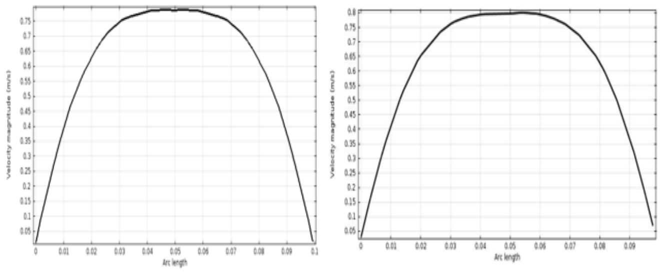
During simulation, the solver was configured as time dependent and the range was (0, 1, 50).For the output of results, in every case we select the last time condition.

In case of accuracy of numerical simulation mesh size plays a vital role. Satisfactory computational accuracy can be achieved by continuously changing the mesh until the results from two trials lead to very close to each other [9]. As we previously discussed about the mesh quality to make comparison between normal and coarse mesh in case of tubular, some results regarding velocity profile are shown in figure 2 and figure 3. From legend bar it is clear that the velocity magnitude differs slightly between them and higher value is found in normal mesh than in coarse mesh.



(a) (b)

Fig.2: Velocity at the middle of U-loop of tubular PBR for (a) coarse mesh (b) normal mesh



(a) (b)

Fig.3: Velocity profile at straight portion of tubular PBR for (a) coarse mesh (b) normal mesh

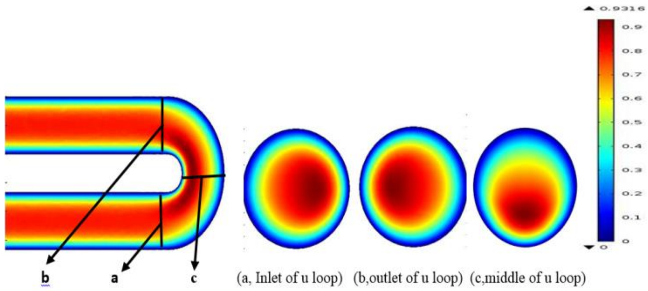


Fig.4: Velocity magnitude at different cross section of U-loop of tubular PBR

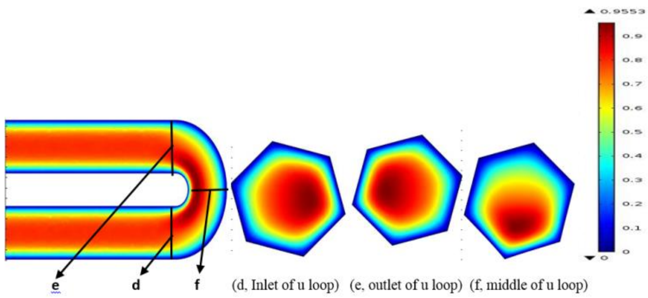


Fig.5: Velocity magnitude at different cross section of U-loop of hexagonal PBR

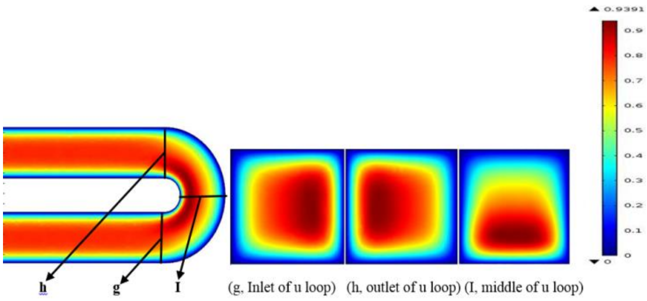


Fig.6: Velocity magnitude at different cross section of U-loop of square PBR

From Fig. 4, Fig. 5 and Fig. 6 we can observe the velocity magnitudesof a single phase flow along the U-loop portions in case of three PBR types. In all cases, by analysing the cross sections from fig. 4(a, b, c), fig. 5(d, e, f) and fig. 6(g, h, I), it is found that there are quite similarities in velocity magnitude for three PBR's. The velocity magnitude is higher near the inner wall of U-loop portionthan any other portionfor every PBR. The rate of flow in case of the hexagonal shape PBR is a bit higher compared to the tubular and the square which we can found from the legend.

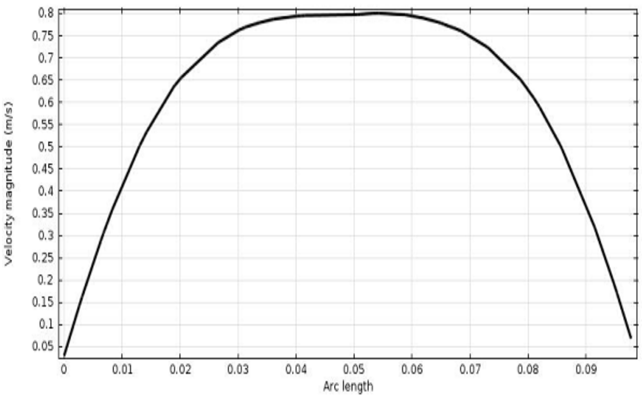


Fig.7(a): Velocity profile at the straight part of the tubular PBR.

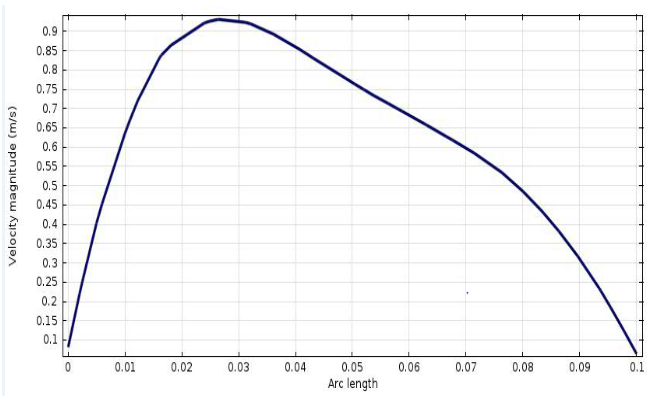


Fig.7(b): Velocity profileat themiddle of the U-loop of the tubular PBR.

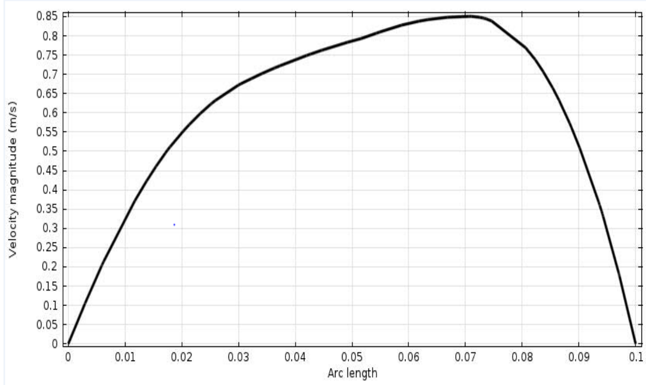


Fig.7(c): Velocity profile at the entrance of the U-loop of the tubular PBR.

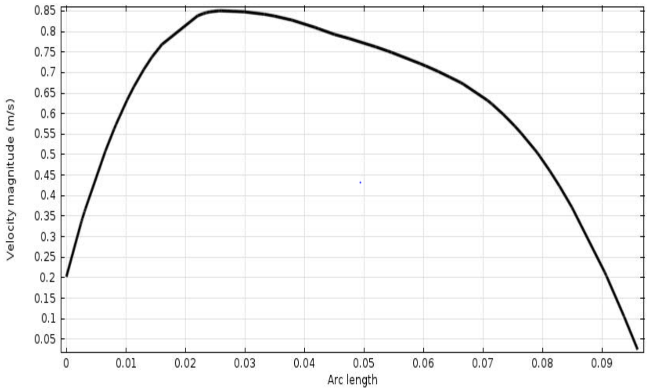


Fig. 7(d): Velocity profile at the exit of the U-loop of the tubular PBR.

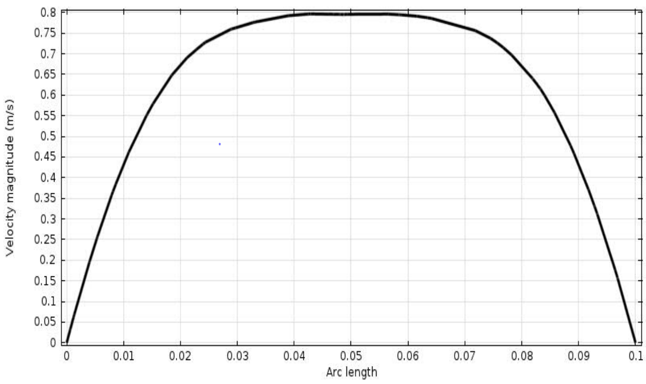


Fig.8(a): Velocity profile at the straight part of the square shape PBR.

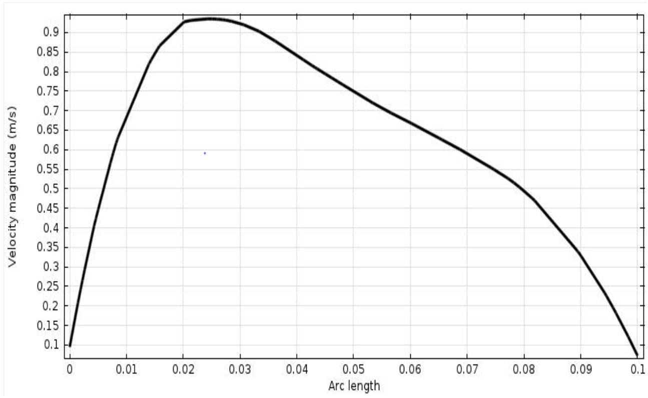


Fig.8(b): Velocity profile at the middle of the U-loop of the square PBR.

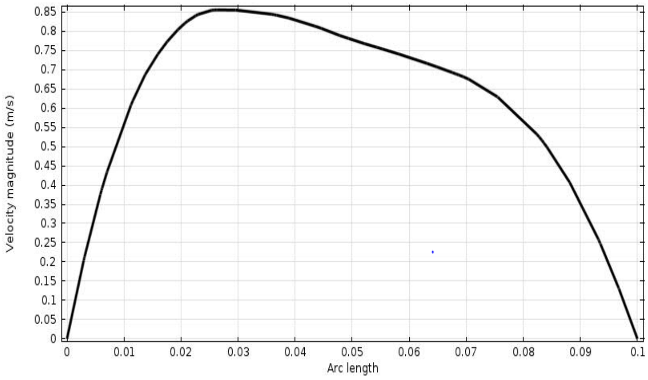


Fig.8(c): Velocity profile at the entrance of theU- loop of the square shape PBR.

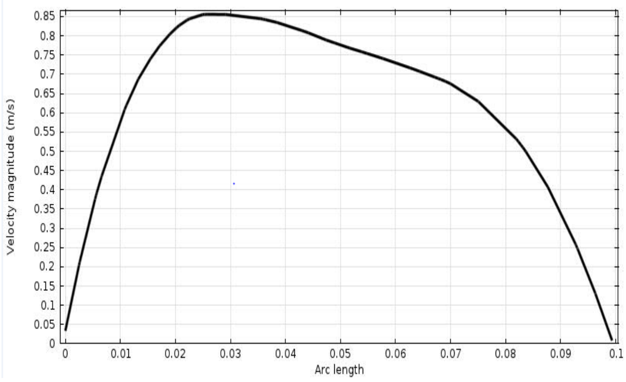


Fig.8(d): Velocity profile at the exit of the U-loop of the square shape PBR.

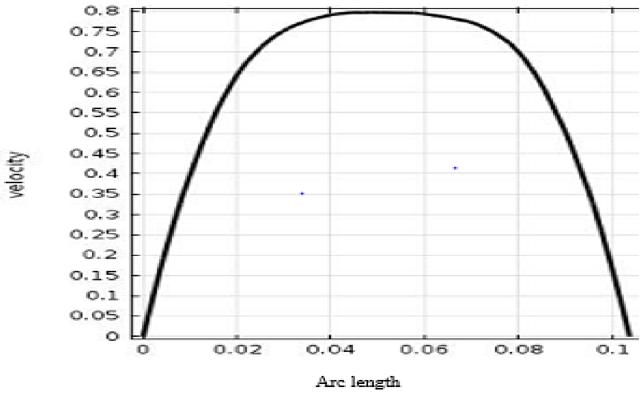


Fig.9(a): Velocity profile vs. arc length at straight part of hexagonal shape PBR.

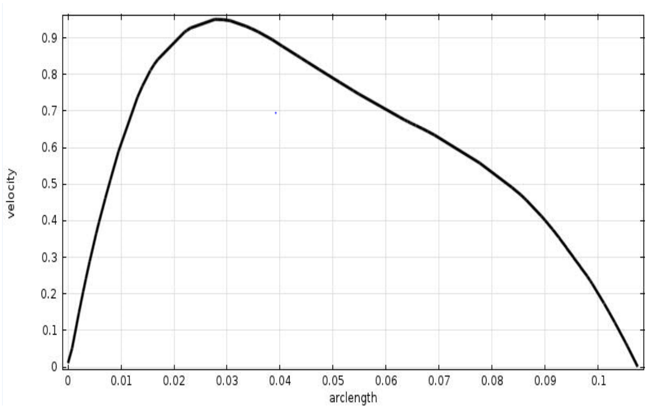


Fig. 9(b): Velocity profileat the middle of the U-loop of the hexagonal shape PBR.

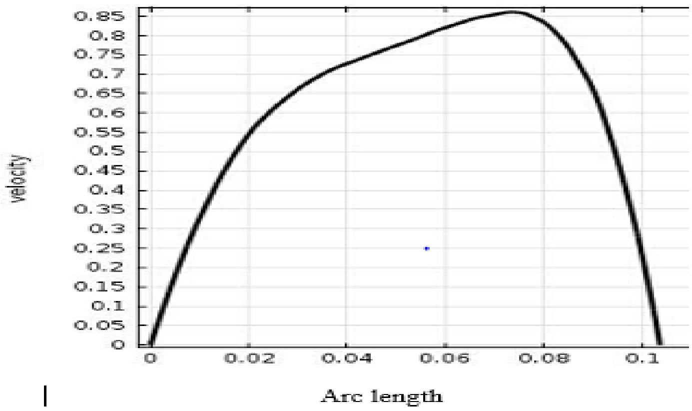


Fig.9(c): Velocity profileat the entrance of the U-loop of the hexagonal shape PBR.

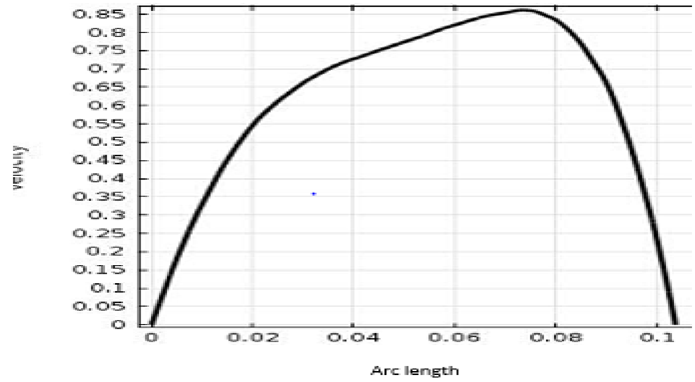


Fig.9(d): Velocity profile at the exit of the U-loop of the hexagonal shape PBR.

In Fig. 7(a), Fig. 8(a) and Fig. 9(a) the velocity profiles are found to be parabolic but the shape is gradually distorting from its regular shape from the entrance of the U-loop to the exit of the U-loop. In the middle of the U-loop the distortion is severe due to the highest velocity magnitude at the closest to the inner wall for all PBR's. Though there is no significant different, but the velocity profile is comparatively smoother in tubular PBR among the three. It is known that movement of fluid particles incur a shear stress on the boundary of the domain. So the shear distribution rate is also an important factor for analysing the flow in the PBR's to determine which one is most conforming to flow phenomenon.

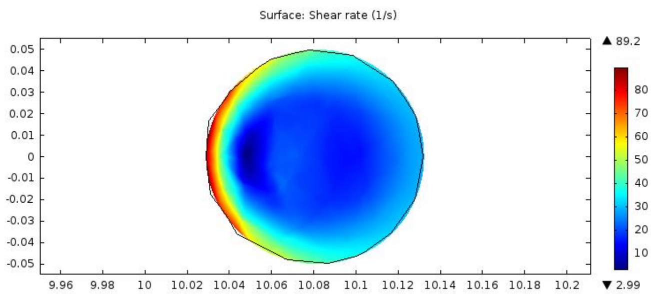


Fig.10: shear rate profile at the middle of the bending portion of tubular PBR

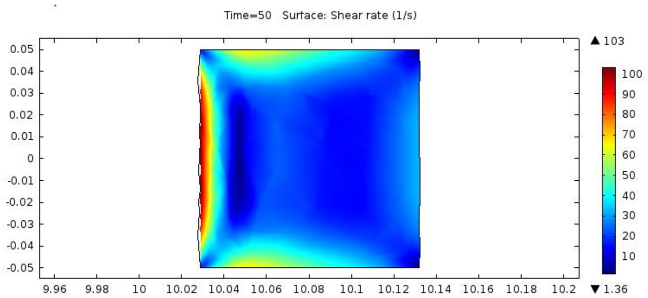


Fig.11: shear rate profile at the middle of the bending portion of square PBR.

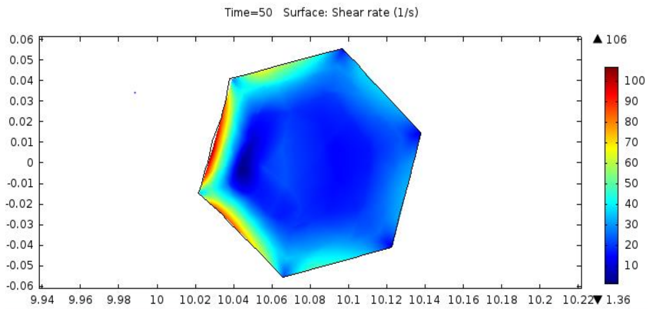


Fig.12: shear rate profile at the middle of the bending portion of hexagonal PBR.

From Fig.10, Fig.11 and Fig.12, we observe that shear rate distribution is high on the inner wall of the U-loop of each PBR. The legend bars with every shear rate profile show that the highest values of shear rate are 89.2, 103 & 106 for tubular, square and hexagonal shape PBR's respectively. So the shear rate is the lowest in case of tubular compared to square and hexagonal from which it is conspicuous that tubular is the most suited to the culture of microalgae.

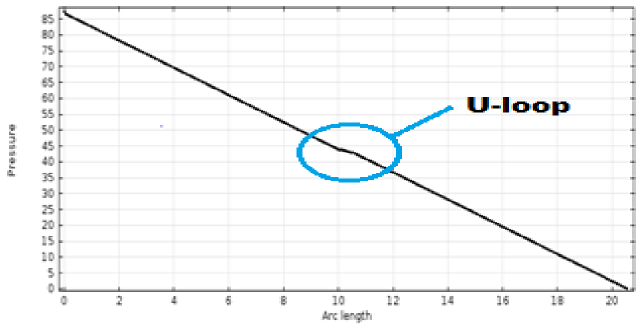


Fig.13(a): Pressure profile along the tubular PBR from inlet to outlet

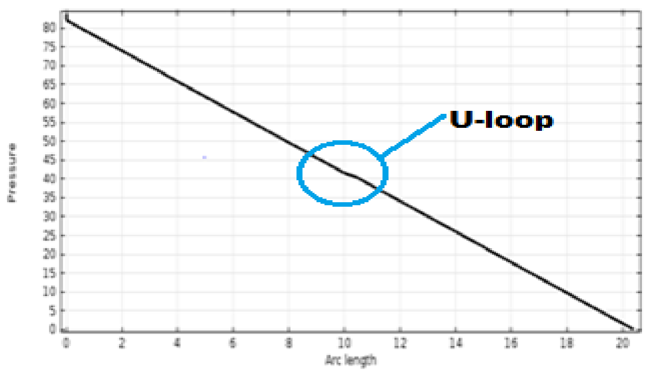


Fig.13(b): Pressure profile along the square PBR from inlet to outlet.

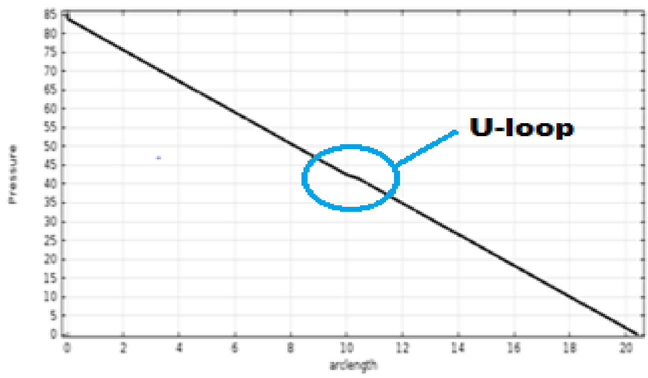


Fig.13(c): Pressure profile along the hexagonal PBR from inlet to outlet.

A similar uniform pressure drop is observed from the inlet to the outlet of the PBR's but slightly fluctuates at the U-loop due to increase of resistance to flow which is observed in Fig. 13(a), Fig. 13(b) and Fig. 13(c).

4. CONCLUSION

A Computational Fluid Dynamics based mathematical model for microalgae culture is developed and analysed the flow dynamics for three different geometries of PBR here to compare which one is the best suited to cultivate the microalgae culture. In this study, the numerical results of the velocity magnitudes, the shear rates and the pressure profiles have been obtained from single phase microalgae suspension flow in the three different types of PBRs. It is noted that both the velocity magnitude and the shear rate are less fluctuating in case of tubular PBR than square and hexagonal shapes PBR and may become as the most promising for the growth of microalgae. From the light distributional point of view, by comparing the geometrical shapes of three tubes tubular is the best choice as it has smoother shape than other two. As the sun moves from the east to the west in a semi-circular shape, thus the tubular shape absorbs more sun light among the tubes because it's smooth geometric surface.

5. ACKNOWLEDGEMENT

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6. REFERENCES

[1] S. karthikeyan, "A critical review: Microalgae as arenewable source for biofuel production", International Journal of Engineering Research and Technology, vol-1issue 4, 2012.

[2] M. k. Lam and K. T. Lee, "Microalgae biofuels: A criticalreview of issues, problems and the way forward", Biotechnol Adv, doi: 10.1016/j.biotechadv.2011.11.008, 2011.

[3] Y. Chisti, "Biodiesel from microalgae", *Biotechnology Advances* 25, pp.294-306, 2007.

[4] J.P. Bitog, I.-B. Lee, C.-G. Lee, K.-s. Kim, H.-S. Hwang, S.-W. Hong, I.-H. Seo, K.-S. Kwon and E. Mostafa, “Application of computational fluid dynamics for modelling and designing photo bioreactors for microalgae production: A review”, *Computers and Electronics in Agriculture*, 76, pp. 131-147, 2011.
[5] A. M. Kunjapur and R. B. Eldridge, “Photo bioreactor Design for Commercial Biofuel production from Microalgae”, *Ind. Eng. Chem. Res.* Vol. 49, No. 8, pp.3516-3526, 2010.
[6] U. K. Deb, K. Chayantrakon and B. Wiwatanapataphee, “Mathematical Model of Microalgae Flow in the HLTP”, *Proceeding at “International Conference for Mathematics and Applications”*, Bangkok, Thailand. 17-19 Dec., 2011, pp. 139-145
[7] A. Einstein, *“Ann. de. Phys.”,* 19, pp. 289-306, 1906.
[8] K. Hon-nami and S. Kunito, “Microalgae cultivation in a tubular bioreactor and utilization of their cells”*China Journal of Oceanology and Limnology*, Vol.16,pp.75-83, 1998.
[9] U.K.Deb, K.Chayantrakon and Y.Lenbury,”Comparison of Single-phase and Two-phase Flow Dynamics in the HLTP for Microalgae Culture, *”International journal of mathematics and computers in simulation”,* vol. 6, pp. 496-503, 2012

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