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Heat Transfer and Hydrodynamic in Internal Jacket Airlift Bioreactor with Microbubble Technology

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Abstract

Integration of laminar bubbling flow with heat transfer equations in a novel internal jacket airlift bioreactor using microbubbles technology was examined in the present study. The investigation was accomplished via Multiphysics modelling to calculate the gas holdup, velocity of liquid recirculation, mixing time and volume dead zone for hydrodynamic aspect. The temperature and internal energy were determined for heat transfer aspect.

The results showed that the concentration of microbubbles in the unsparged area is greater than the chance of large bubbles with no dead zones being observed in the proposed design. In addition the pressure, due to the recirculation velocity of liquid around the draft tube, increased the retention time of microbubbles in the same area.

Thus it was expected that their effect on mass and heat transfer phenomena would be positive for biological applications. For example the gas fraction volume of microbubble in the downcomer region is 0.0063, while with fine bubble diameter of 1 mm, this region was free from any bubble. Furthermore, the velocity of liquid in the center of ring diffuser would be 0.175 m/s, if the sparging system operated with bubble diameter of 100 micrometer, whilst would be 0.035 m/s with fine bubble diameter of 1 mm.

The study also proved the importance of bubble diameter on the heat transfer in gas and liquid phases in the proposed design. Microbubbles gave greater responsiveness to stability and homogeneity in all parts of the bioreactor. Finally, this study concluded the efficiency of the proposed design with the microbubbles technology thermally and hydrodynamically.

Key words: Bioreactor, Microbubble, Airlift, Computational Model

Introduction

Climate change since the last century has become a matter of concern to the researchers [1]. Despite of confirmed evidences that the main reason for this change is the use of fossil fuels as a major energy source, still global demand for this type of sources is rising.

Carbon dioxide, as one of gases that produced from this source, is considered as a driving factor in that observed climatic change [2].

There are many alternatives to address the problems of fossil fuels and environmental friendly as well [3,4]. However, and according to the available scientific possibilities, finding the main alternative to this source in the production of energy may be difficult and unreasonable [5]. In fact, the problem is not in the quality, but in their quantity and high cost of the production.

Fuel produced from the biomass via the microorganisms is a promising source to change this scenario[5], especially if it produced from food waste or inexpensive materials [6-8].

The operational conditions of these biological processes play an important role in improving the productivity such as the temperature [9-12], since the metabolic activities of microorganisms increase with increasing the temperature [12,13]. Thus the temperature has an effective role in enhancing the consumption of organic matter and improving the production of biofuels. Production of clean energy that can be obtained from thermophilic processes is more than obtained from mesophilic process, such as anaerobic digestion process [14-16]. However, the energy required in such a process may be the main impediment to be at the forefront of the promising sources in the production of renewable energy.

In addition, the nature of the biological medium contributes in the complexity of variables during design of bioreactors, since these mediums usually contain solids, liquid and gas in the same time. Each of these phases requires a basic understanding of the mixing patterns to provide a suitable environment for living microorganisms as well as to get their food taking account the operational conditions such as temperature and prevent the problem of thermal stratification.

In summary, success of any biological process depends on the efficiency of the bioreactor in the hydrodynamic, mass transfer and heat transfer aspects.

As known, the airlift bioreactor has operational and economic advantages in biological applications over other conventional bioreactors, such as simple construction with low cost in manufacturing and maintenance, sufficient mixing and lower shear stress to microorganisms cells[17-19].

Although of many attempts in developing this type of bioreactors (as a design or enhancement of operational conditions) [20-22], there still remain a big challenge due to nature of biological mediums.

Thus, a deep knowledge of the fluid flow pattern and heat transfer inside the bioreactor is required for enhancement of metabolic activities of microorganisms or biomass productivity [23-26].

This research is a serious attempt that aims to reduce the energy consumed in bioreactors through the integration of ring diffuser and internal jacket draft tube in the proposed design. This investigation is done by studying the momentum and heat transfer throughout the proposed bioreactor with microbubbles technology.

Computational Model

The modelling of the process was carried out using COMSOL Multiphysics with two-dimension and axial symmetry. Fig.1 shows three-dimension and two-dimension sketch of the suggested design of bioreactor used in the present study.

Laminar flow model was considered to simulate the airlift bioreactor using Navier-Stokes equation:

$$\emptyset_l \rho_l \frac{\partial u_l}{\partial t} + \emptyset_l \rho_l u_l . \nabla u_l = -\nabla P + \nabla . \left[\emptyset_l \eta_l \left(\nabla u_l + \nabla {u_l}^{T} \right) \right] + \emptyset_l \rho_l g \quad \ldots (1)$$

Where $\emptyset_l$, ρ_l , u_l , t, P , η_l ,and g are liquid volume fraction (m^3/ m^3), density of liquid, velocity of liquid phase (m/s), time (sec), pressure (Pa), dynamic viscosity (Pa.s) and the gravity(m/s^2) respectively.

The second model that was used in this current study was heat transfer model:

$$\rho Cp \frac{\partial T}{\partial t} + \rho Cp\, \boldsymbol{u}.\nabla T = -\nabla P + \nabla.(K\nabla T) + Q + Q_{vh} + W_p \quad \dots (2)$$

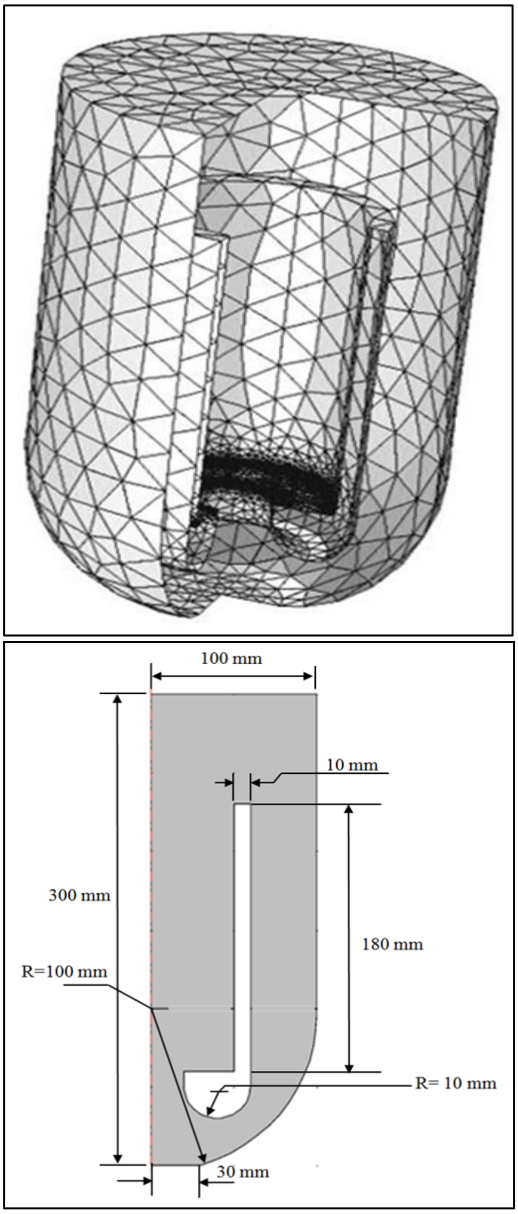

Fig.1, Two and three-dimension sketch of bioreactor that suggested in this study

Where Cp heat capacity [J/(mol K)], Q heat source/sink [W], Q_{vh} heat loss [W], K heat conductivity [W/(m K)], T temperature [K], and W_p pressure work [J].

A time-dependent momentum balance model and heat transfer model were calculated in this model. For low gas concentration, the $\nabla.u_l$ was pointed to zero as considered in the present model.

The equation of gas phase was also used in present model with assumption that no mass transfer occurs between the two phases (gas and liquid). Therefore the equation was equalled to zero:

$$\frac{\partial \rho_g \emptyset_g}{\partial t} + \nabla.\left(\emptyset_g \rho_g u_g\right) = -m_{gl} = 0 \quad \dots (3)$$

Where ρ_g , $\emptyset_g$, and u_g are the density of gas phase (kg/ m^3), gas volume fraction (m^3/ m^3), and velocity of gas respectively.

The liquid volume fraction was calculated by $\emptyset_g = 1 - \emptyset_l$. The gas velocity can be determined as $u_g = u_l + u_{slip}$, since u_{slip} is relative velocity between two-phase fluid (gas and liquid). The u_{slip} was calculated from pressure drag that is balanced with pressure forces according to the following equation [27]:

$$\frac{3Cd}{4d_b}\rho_l\left|u_{slip}\right|u_{slip} = -\nabla P \quad \dots (4)$$

No-slip boundary condition was used on the draft tube and ring diffuser, while slip boundary condition was considered at the top of the liquid. Extra fine mesh with 2141 elements was used in the present model. The general operational conditions that used in this research are illustrated throughout Table 1.

Table 1, operation conditions used in the computation model

Operational Conditions for Computational Model		
Parameter	Value	Unit
Temperature of Gas	20	°C
Temperature of Jacket	50	°C
Pressure of Process	101	kpa
Gas Mass Flux	0.000754	$Kg/m^2.s$

In fact, dealing with these kinds of models with time-dependent requires very high quality processor to complete the task of two dimensions model. Therefore, and to compute these complex models, the present study used an official software package of computational model with a special system and high quality that were provided by the University of Sheffield, UK.

The dead zones in airlift bioreactor have investigated by Al-mashhadani [27]. According to their results, decreasing the bubble size decreases the dead regions. However, reducing the bubble size, in spite of its advantages, may be undesirable in some biological applications because it causing separation of microorganisms or their nutrients by floatation process. Then this will lead to failure of the process. Therefore, 100 microns were considered in the present study. While the bubbles diameter of 1 mm and 0 micrometer were used for compression.

Results and Discussion

Hydrodynamic Study

In the present study, the suggested design was examined through two aspects; hydrodynamic and heat transfer aspects. Gas fractions, velocity of re-circulation liquid and volume of dead regions are main objective variables that were investigated for hydrodynamic study. While the temperature of the liquid, internal heat flux were addressed for heat transfer section.Fig. 2 shows the gas-holdup in the downcomer region of the reactor at the bubble diameter of 100 micron and 1 mm. It can be seen that the existence of bubbles of 100 microns is more than that with 1 mm. For example the gas volume fraction of microbubble in the downcomer region is 0.0063, while with fine bubble diameter is 6.89e-12.

Thus, the retention time of small bubbles increases in this unsparged region, allowing greater exchange between the gas and liquid phases across the interfacial layers depending on the known principles of material-heat transfer.

Fig. 3 shows the snapshots of gas volume fraction at different bubble size after 12 min (i.e after steady state).

This figure demonstrated that bubble size is critical factor in the design of bioreactor. In fact, the weak buoyancy force of small bubble size (i.e 100 microns) is sufficient to present such bubbles in downcomer region.

However, the velocity of liquid circulation around the draft tube of reactor plays an important role in determining the amount of gas in this unsparged region as a result of the competition between the flow force of the liquid to that area and buoyancy of bubbles.

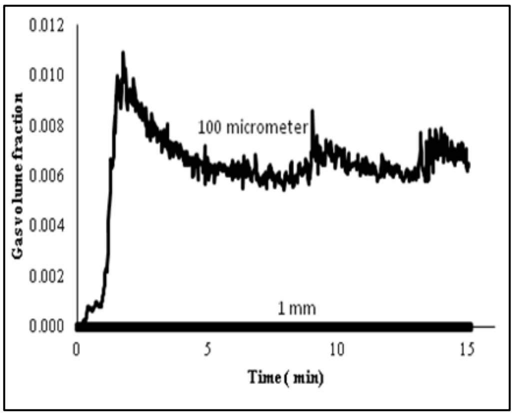

Fig. 2, Gas volume fraction in the down-comer region

Therefore, it is possible to observe that the biggest amount of bubbles present in the down-comer region was in the first 3 minutes, due to the primary velocity of the circulation liquid in the riser region of the reactor and in this time as can be shown in Fig. 4. Then the steady state of gas holdup and velocity of liquid begin.

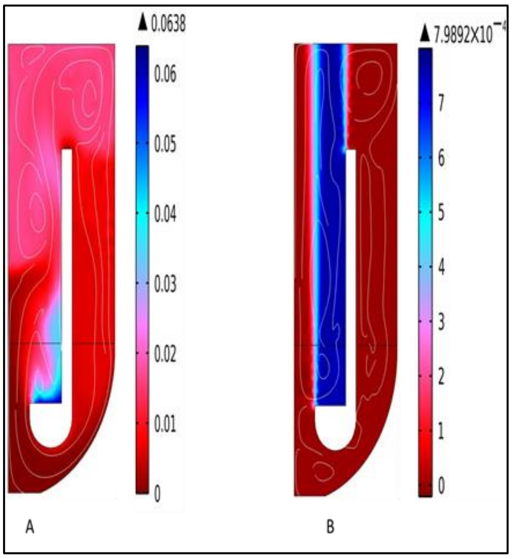

Fig. 3, gas volume fraction at different bubble size A) at 100 micron, B) at 1mm

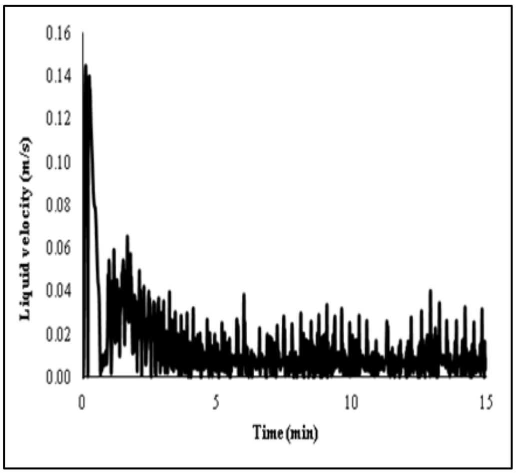

Fig. 4, Liquid velocity in the riser region of bioreactor

Fig. 5 illustrates the fluid flow pattern at 0.1, 2, and 5 min when the bioreactor is sparged with 100 micrometer.

The figure indicates that the change was generated at the first moments of operation, after which, the liquid flow appeared to be stabilized. This stability resulted in homogeneity of the fluid in all parts of the bioreactor, especially after the second minute of simulation time.

In general, the biological processes use domestic and industrial wastes as main biological media. These wastes usually are heavy because they containing the suspended solids. In addition, the biological reactions, naturally, are very slow, thus, sedimentation of these wastes at the bottom of traditional bioreactors is possible. Even if sediments are already not present in the biological medium, the biomass generated by the biological reactions will form a sediment component during cultivation, as in algal cultivation. This will cause inhomogeneity in the temperature and pH as well as the famine in those layers of sediments due to separation from the suspended nutrients.

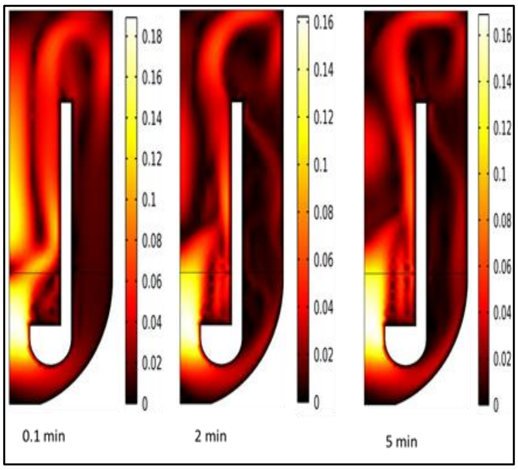

Fig. 5, snapshot of liquid velocity at 0.1, 2, and 5 min

The best solution may be to place the diffuser at the bottom of the reactor, thus preventing the suspended material from precipitation.

But if the waste contains large particles, with time they will cause blockage in the diffuser. Al-Mashhadani [27] has noticed this problem by putting the diffuser at a height of 5 cm from the bottom to ensure that this problem does not occur. However, they reported that the volume dead zoon may be generated at the bottom of the reactor.

The study takes into account the most likely problems by placing the diffuser 5 cm from the bottom of the reactor, but using a circular diffuser instead of disk diffuser and with a specific design as can be shown in Fig. 6 .This construction allows the fluid to flow vigorously in that area to prevent formation of dead areas.

In addition, and although, the present study suggested to use the microbubbles to increase momentum, heat, and mass transfer rate, the potential for foaming and stabilized emulsions in the reactor is a significant negative potential and it is one of the challenges facing the production of microbubbles as well as if is considered undesired property in many applications. Previous studies have addressed this problem, and showed that decrease the bubbles size increases the height of foam [28].

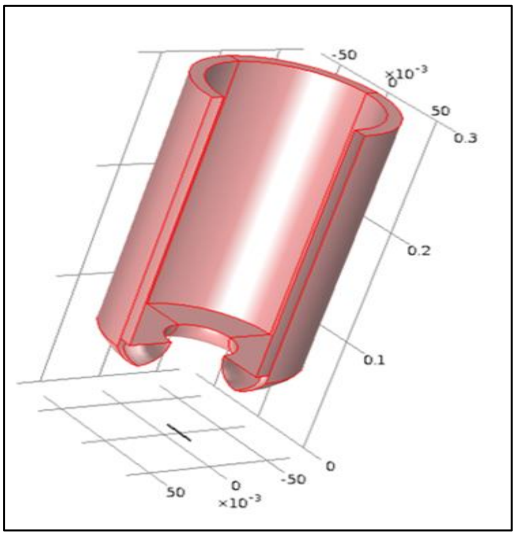

Fig.6, schematic of integration of ring diffuser and internal Jacket draft tube

The current study also took into account these problems and it sought to get an appropriate design to help using advantage of the microbubbles and reduce the problems resulting from the use of such technology.

Effect of foam, for example, can be reduced through increasing the circulation of the liquid around the draft tube in the bioreactor. Although, the velocity of the liquid may be somewhat slow in the upper part of the downcomer of reactor it is unable to address the problem as can be seen in Fig.7. This velocity increases as the liquid moves down the reactor. In fact, the proposed geometry of current reactor has greatly contributed in improving the liquid speed at the bottom. This Figure shows the velocity of the liquid at different areas of the reactor. It can be observed that there is a significant increase in fluid velocity.

This result will greatly contribute to move the biological sediments formed at the bottom of the reactor with great uniformity in temperature and pH.

Therefore, and according to these figures, the dead areas will be very few if not vanished in this suggested design.

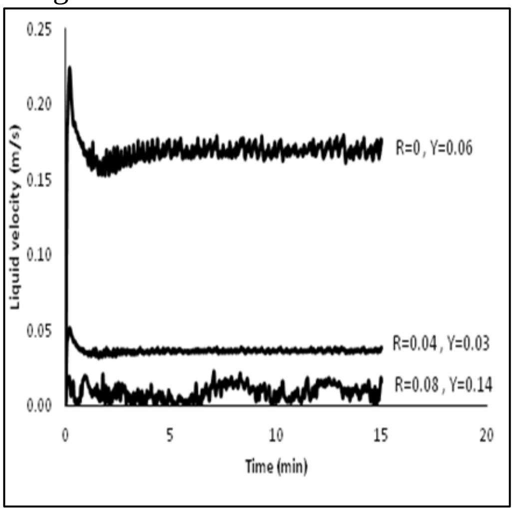

Fig. 7, liquid velocity at different positions of reactor, a) in the downcomer (0.08, 0.14), b) in the bottom of reactor (0.04, 0.03), in the center ring of diffuser (0, 0.06)

However, the microbubbles size can play an important role in determining liquid velocity, the increase in the central velocity of liquid during the reactor's length is observed in Fig. 8.

This behaviour is due to the high momentum of the microbubbles to push the liquid up or down causing a decrease in the pressure and density of the mixture, which helps in generating high flux of the fluid due to momentum transfer between gas and liquid.

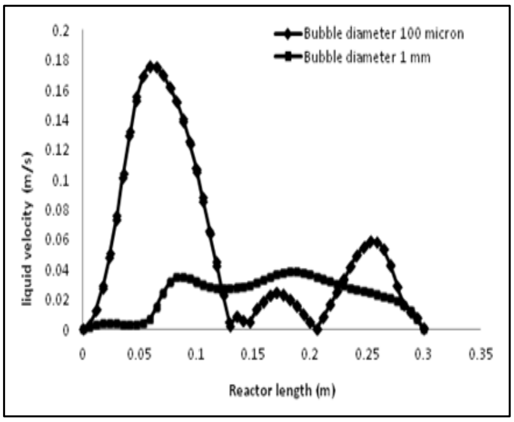

Fig. 8, liquid velocity along the bio-reactor

Heat Transfer Study

The effect of bubble size on the suggested design in heat transfer aspect was also investigated in this section.

This factor represents the fundamental step in increasing the metabolic processes of microorganisms. Traditional heating methods for biological processes have some disadvantage such as formation different thermal layers in the same reactor, and thus will affect the microorganisms. The current design is radically different from what was done in these attempts through Fig. 6, which shows schematic diagram of suggested part in bioreactor by integrating the ring diffuser with internal draft jacket.

From this integration, the moving of the gas and liquid upwards generates driving force in inner side of jacket draft tube. This force has sufficient power to remove the thermal thin layers, which are generated on the internal jacket during heat transfer process, thus, reduces the formation of the thermal resistance in this part of reactor. Removing this layer creates an environment suitable for more heat transfer rate. In other words, decreasing the thermal layer thickness increases the heat transfer rate if the process was under sparging system.

Fig. 9 shows simple schematic diagram of removal and generation of thermal layer during sparging system. At time equal zero (no bubbling system), the thermal layer is already generated. When the sparging system starts, the created layer will be removed. Thus more heat will transfer due to decreasing the thermal resistance.

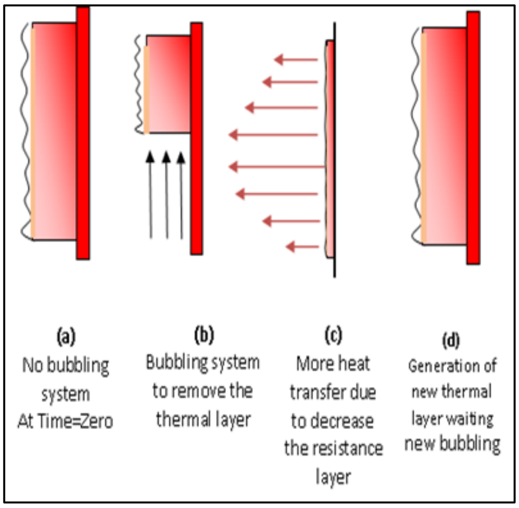

Fig.9, schematic diagram of removal the thermal layer by bubbling system

The influence of the bubble sizes on the heat transfer rate in the current design was also considered. Fig. 10 displays the temperature response in the two reactor areas (downcomer and riser region) for 12 min until the steady state is achieved.

It is noted that the temperature in the first zone is higher than that in the second zone as well as the fastest up to the steady state. The main reason for this change is the amount of internal heat transferred from the riser region to downcomer region as a result of the momentum transfer generated by sparging process. This behaviour demonstrates a real integration between air bubbles and the liquid that work together in heat transfer process.

Therefore it is a significant delay in the temperature response in the downcomer region due to delay the recirculation of the liquid and gas between the two areas. Figure 11 shows snapshot of transfer of internal energy from the riser region to downcomer region at 0.1 min, 5 min and 8 min.

However, determining the temperature difference between these two regions depends largely on the diameter of the micro bubbles. Figure 12 shows that the temperature and speed of access to the steady state is almost very simple change between the two regions, while with no bubbling process, there was no observed change in temperature at any region.

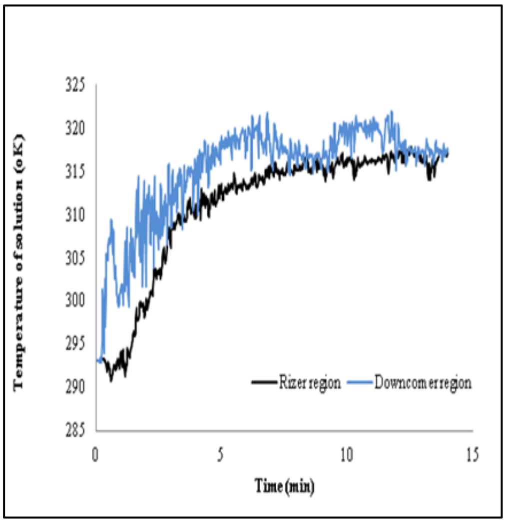

Fig.10, temperature profile in riser and downcomer region at 100 micron bubble size

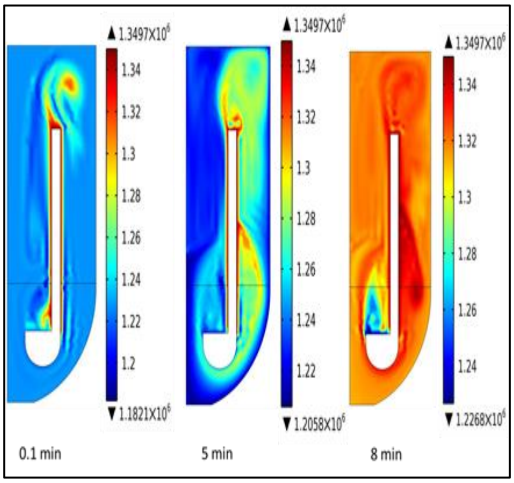

Fig. 11, internal energy in the suggested bioreactor at different simulation time; 0.1, 5, and 8 min. the last number was taken as value at steady state situation

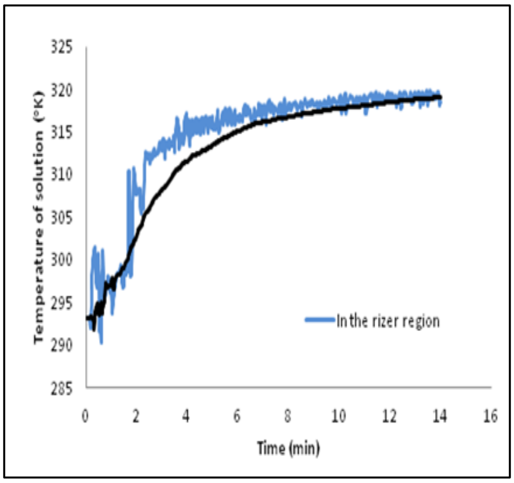

Fig. 12, temperature profile in riser and down-comer region at 1mm bubble size

Figure 13 illustrates temperature profile in unsparged area (downcomer region) at different bubble size; 1mm, 100 and 0 micrometer. It can be seen from this figure that the flow, whatever its velocity is better than the flow without a bubbles, due to improved temperature, speed and homogeneity.

However, microbubbles give great heat efficiency compared to large bubbles, not by the high speed of heat transfer alone but with improving the features of the hydrodynamic.

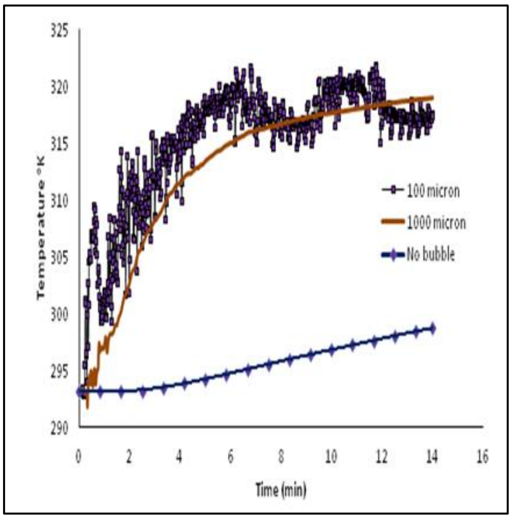

Fig. 13, temperature profile in downcomer region at 1 mm, 100, and 0 micron bubble size

Conclusions

Current research addressed the hydrodynamic and heat transfer study of the proposed reactor design using laminar bubbling flow model and heat transfer model in internal Jacket airlift bioreactor. Through the integration of these two models, the results indicated the importance effect of microbubbles on the main variables in biological processes such as retention time and mixing system. This will harmonize with the operating conditions in the process to get the equitable distribution of nutrients and prevent the formation of dead areas. In terms of the study of heat transfer, bubbles are important factor in the efficiency of heat transfer.

However, reducing the bubble diameter increases the frequency of the temperature response and reaching the steady state quickly.

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Nomenclature

Cd	Viscous drag coefficient (dimensionless)	W_p	Pressure work [J]
Cp	Heat capacity [J/(mol K)],		
D	Diameter of the bioreactor (m)		
d_b	Bubble diameter (m)	u_l	Velocity of liquid phase (m s^{-1})
g	Gravity (m s^{-2})	u_g	Velocity of gas phase (m s^{-1})
K	Heat conductivity [W/(m K)]	$\emptyset_l$	Liquid volume fraction (m^3 m^{-3})
Q	Heat source/sink [W]	$\emptyset_g$	Gas volume fraction (m^3 m^{-3})
Q_{vh}	Heat loss [W]	ρ_l	Density of liquid phase (Kg m^{-3})
M_w	Molecular weight of the gas bubble	ρ_g	Density of gas phase (Kg m^{-3})
m_{gl}	Mass transfer rate (kg m^{-3}.s^{-1})	η_l	Dynamic viscosity of liquid (Pa.s)
P	Pressure (Pa)		
u_{slip}	Relative velocity between two phases fluid (gas and liquid).		
T	Temperature (K)	**Subscript**	
t	Time (sec)	ALR	Airlift reactor
		CFD	Computational Fluid Dynamics

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