Gas-liquid Mass Transfer Performance of Dual Impeller System Employing Rushtons, Concave-bladed Disc (CD-6) Turbines and Their Combination in Stirred Tank Bioreactor

Nurashikin Suhaili, Mohd Shamzi Mohamed, Rosfarizan Mohamad and Arbakariya B. Ariff

Department of Bioprocess Technology, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

Abstract: The degree of oxygenation in stirred tank bioreactor is normally described and characterized by the volumetric gas-liquid mass transfer coefficient ($k_a$). Throughout this study, the gas liquid mass transfer performance of dual impeller stirring system employing either two Rushton turbines (RT), two Concave-bladed disc (CD-6) turbines or the combination of both was comparatively investigated in Newtonian and non-Newtonian fluid systems. Static gassing-out technique was applied in all experimental $k_a$ determinations and subsequent modeling of mass transfer correlations for all configurations were developed by incorporating the effects of power number ($N_D^*$) and superficial velocity ($V_s$) on $k_a$. Ultimately, the use of dual CD-6 stirrers on a mixing shaft improved the oxygen transfer rate (OTR) by about 5-50% and 18-65% higher than the conventional RT-RT system in Newtonian and non-Newtonian systems, respectively.

Key words: Oxygen transfer, volumetric gas-liquid mass transfer coefficient, Rushton turbine, Concave-bladed disc turbine, correlation modeling

INTRODUCTION

An efficient gas-liquid mass transfer process is the key factor in determining a good accomplishment of any chemical or microbial reactions in stirred tank bioreactor. Particularly in aerobic fermentation process, the concern of gas-liquid mass transfer is concentrated on the efficiency of oxygen diffusion within the reaction mixture. The oxygen transfer rate (OTR) in stirred tank bioreactor is mainly governed by the volumetric gas-liquid mass transfer coefficient ($k_a$), in which the relationship is described by Eq. 1:

$$\text{OTR} = k_a (C_e^* - C_e)$$

(1)

Where $C_e^*$ is the equilibrium saturated oxygen concentration (mol L$^{-1}$) and $C_e$ is the actual saturated oxygen concentration (mol L$^{-1}$).

The $k_a$ values in stirred tank reactor are greatly influenced by the tank internals and impeller geometry, physicochemical and rheological properties of the agitated fluid, agitation intensity as well as aeration rate. The interdependency of these terms is typically expressed in a widely referred correlation formerly introduced by Cooper et al.$^{[2]}$:

$$k_a = C_1 \left( \frac{P}{N_D^*} \right)^a \frac{V}{\varepsilon}$$

(2)

It is well accepted that the proportionality constant, $C_1$ and constant $a$ and $\beta$ may differ accordingly due to experimental set up, measurement techniques employed and the variables range tested$^{[3]}$. Thus, optimization of OTR in stirred tank bioreactor in essence would reflects on the optimization of $k_a$ value itself via proper manipulation of all the affecting factors$^{[4]}$.

The application of multiple impellers has been considered as one of the effective approaches to further enhance the rate of oxygen diffusion within the stirred tank bioreactor. Among significant advantages accrued from multiple impeller operation are high dissipation of energy invested from stirring throughout the fluid, a more effective biphasic (gas-liquid) circulation in the vessel, higher gas hold up capability which favorably cater to uninterrupted gas consumption by the reaction processes$^{[5]}$ and maintaining of low shear effect resulting from lower requirement of agitation rate per impeller$^{[4,6]}$.

For over six decades, the flat blades and disc impeller popularly known as Rushton turbine (RT) (Figure 1a) has been the mainstay in stirred tank bioreactor$^{[7]}$. RT is known to generate radial flow field
acclaimed for gas dispersion and able to provide high shear condition required for oxygen traversing the gas-liquid film resistance. Nevertheless, this generic impeller system was later associated with several drawbacks, i.e., low ability of gas handling and high gassed power drop due to the effect of large gas cavities\(^\text{[7,8]}\). Gas cavities are formed as a result of low pressure zone created behind the rotating blades’ faces that accumulate buoyant gas bubbles. At very high gas flow rate operation this may seriously turn into flooding.

Evolution of RT geometric features towards enhancement of gas dispersion characteristic was first initiated by Smith in 1980s and further continued by several others with major modification made on the original 90° angle to blades of different degree of curvature, leading to the so-called Concave-bladed Disc turbine (CD-6) (Figure 1b). The innovation of concave blade shape is mainly to resemble the contour of gas cavity during agitation. CD-6 reportedly minimizes the drawbacks of RT by decreasing the gas cavities dimension as well as reducing gassed power drop with its improved gas handling performance\(^\text{[7,8]}\). Both the RT and CD-6 eject fluid radially and in the case of dual impeller system, the supposition is that two radial flow fields would provide more efficient mixing and gas dispersion performance than a single configuration.

Albeit numerous development on mass transfer correlations utilizing various types of impellers were extensively reported in the literature, there are still limited information concerning direct comparative assessment of multiple impeller system comprising of RT, CD-6 or a combinatorial of both turbine in one mixing system. The present work investigates the gas-liquid mass transfer performance of dual impeller system under Newtonian and non-Newtonian fluid conditions. Distilled water and viscous carboxymethylcellulose sodium salt (CMCNa) solution were chosen to represent both systems, respectively. The rheological characteristics of \textit{Aspergillus flavus} culture for kojic acid production is of specific interest in this work and at 0.35% (w/v), the aqueous CMCNa solution matches quite comfortably with that of \textit{A. flavus} culture to sufficiently simulates the fungal broth hydrodynamics during stirred tank mixing.

**MATERIALS AND METHODS**

**Experimental Set up:** All the experiments were carried out in a 2-L ellipsoidal-bottom cylindrical vessel of internal diameter, \(D_i = 0.13\) m equipped with four baffles of width, \(J = 0.0095\) m and height, \(B_j = 0.13\) m. Working volume was fixed at 1.5 L. Figure 2 illustrates the schematic diagram and dimensions of stirred tank bioreactor (Biostat B, B. Braun, Germany) used in this study. Two impellers installed on a common shaft comprised of six bladed RT \((D_i/D_o = 0.4, L = 15\) mm, \(W_r =10\) mm) and CD-6 \((D_i/D_o = 0.4, L = 17\) mm, \(W_r =13\) mm). Turbine arrangements tested were classified as RT-RT, CD6-CD6, RT-CD6 and CD6-RT with the first and second notation denotes bottom and top impeller, respectively. The bioreactor was equipped with a polarographic dissolved oxygen (DO) probe (InPro 6900, Mettler Toledo, Switzerland). In all experiments the vessel temperature was controlled at 30°C and stirring carried out at revolution between 150 to 900 rpm (2.5 to 15 \(\text{s}^{-1}\)). Compressed air was introduced 15 mm below the bottom impeller through a ring-type sparger distributor. Airflow rate was varied from 1.0 to 3.0 L min\(^{-1}\) (correspond to \(V_a\) of 1.256 \(\times 10^{-3}\) to 3.768 \(\times 10^{-3}\) ms\(^{-1}\)). Deoxygenation of medium was then performed using oxygen-free nitrogen (OFN). Aqueous simulant solutions used consist of distilled water and high viscosity grade CMCNa (BDH, USA).

**Determination of Probe Time Constant, \(k_p\):** Determination of probe time constant \((k_p)\) is imperative based on the fact that every DO probe has an inherent delayed response or lag signal time which inevitably affect the accuracy of transfer rate measurement. In order to determine \(k_p\), DO probe was first immersed in a beaker containing distilled water completely desorbed of oxygen content. Once the \(pO_2\) reading was stabilized at 0%, probe was swiftly transferred to the reactor vessel filled with distilled water at 100% saturation. The abrupt rise of \(pO_2\) reading from 0% to 100% was monitored and recorded at 5 sec time interval. Probe time constant, \(k_p\), was obtained from the linear regression of Eq. 3 as described by Brown\(^\text{[9]}\).

\[
\ln \left( \frac{C_L}{C_L^* - C_p} \right) = k_p t
\]  
(3)

Where \(C_L^*\) is the equilibrium concentration of dissolved oxygen in liquid (mol L\(^{-1}\)) and \(C_p\) is the measured dissolved oxygen concentration by the probe (mol L\(^{-1}\)).

**Determination of Volumetric Oxygen Transfer Coefficient, \(k_{a,i}:** Static gassing-out method was adopted in determining the \(k_{a,i}\). Initially, the dissolved oxygen in test liquid medium was purged with nitrogen gas. Once \(pO_2\) readout stabilized at 0%, compressed air was sparged in and the gradual rise of \(pO_2\) was monitored and recorded at 5 sec interval until equilibrium saturation was achieved.

A graph of \(\ln (C_L^* - C_p)\) over time, \(t\), was plotted and \(k_{a,i}\) value was obtained from the slope of the plot. Considering the effect of response time of DO probe used, this rather “uncorrected” \(k_{a,i}\) would serve as the
preliminary guess value input to commence the non-linear regression fitting of Equation (4) to the experimental data until a new optimized \(k_a\) value is reached through the use of Gauss Newton algorithm (MATLAB R2008a, MathWorks, USA).

In lieu of correlating the \(k_a\) with volumetric power input \((P/V)\) and superficial gas velocity \((V_g)\), alternatively, by examining the dimensionless impeller Power number relationship, it is also possible to equate the term \((P/V)\) with the expression \((N^3D^3)\) in the original mass transfer correlation based on their linearity as forwarded by several investigators\(^{10-15}\). This has resulted in the alteration of Eq. 2 conforming to the following mathematical relationship.

**Modeling of Gas-liquid Mass Transfer Correlation:**

\[
k_L a = C_1 \left( \frac{N^3 D^3}{V_g} \right)^a \tag{5}
\]
Where \(N\) is agitation speed (s\(^{-1}\)) and \(D\) represents diameter of impeller (m). This approach is useful as it eliminates fluctuation and imprecision of measuring stirring power input delivered to the agitator\(^{[15]}\).

In approaching the mathematical modeling, Equation (5) in its power law form was linearized beforehand by introducing natural logarithmic function to the equation,\(^{[16]}\) thus leading to a more simplified linear polynomial form of Eq. 6.

\[
\ln(k_{L}a) = \ln(C_{L}) + \alpha \ln\left(\frac{N^2D^2}{\rho g L^{2}}\right) + \beta \ln(V_{e})
\]  

(6)

Fitting Eq. (6) to the collection of experimental data and solving for the unknown correlation indices of the interaction terms would then require the capability of MATLAB multiple linear regression analysis module.

**RESULTS AND DISCUSSION**

3.1 Effects of Agitation Speed and Impeller Geometry on \(k_{L}a\): The replacement of \(P/V\) with \(N^2D^2\) has led to the dependence of \(k_{L}a\) on agitation speed and impeller geometry. Figure 3 demonstrates the trends exhibited by different configurations of RT and CD-6 in distilled water system and 0.35% (w/v) CMCNa aqueous solution.

There is a proportional relationship between \(k_{L}a\) and agitation speed and this trend was exhibited by every impeller configuration in both fluid systems. The reason behind this interdependency is that as the agitation speed increases, higher dissipation of energy would arise which later increases the efficiency of bubble break up and consequently enhance the rate of oxygen absorption into the liquid.

Generally, the profiles of \(k_{L}a\) as a function of \(N^2D^2\) at all airflow rates tested in this study are more or less consistent. In distilled water system, at 2 L min\(^{-1}\), dual CD-6 turbines gave the highest range of \(k_{L}a\) values of between 0.009 and 0.0745 s\(^{-1}\) with superiority over other impeller configurations of about 30%. Furthermore, dual CD-6 system was revealed to give 5 to 49% higher rate of oxygen transfer than that achieved by conventionally used RT-RT system within the abovementioned range of agitation speed and airflow rate.

Similar observations were also found in the case of non-Newtonian fluid where 0.35% (w/v) CMCNa aqueous solution was used. CD6-CD6 combination dominated over others where higher gas-liquid mass transfer performance was shown in most of airflow rates tested. At 2 L min\(^{-1}\), the highest range of \(k_{L}a\) achieved in dual CD-6 system was 0.0018 to 0.0263 s\(^{-1}\), which gave significant difference of 18 to 65% than that attained by the standard dual RT system. While combination of RT and CD-6 under one mixing system was found to perform slightly better than two RT, the difference was not significantly shown, making them just about comparable with each other.

Oxygen transfer rate in 0.35% (w/v) CMCNa solution for all impeller configurations was found to reduce drastically to about 65-81% from that in distilled water. CMCNa solution which is categorized as pseudoplastic fluid exhibits notable change of its apparent viscosity whenever the level of impeller shearing action changes, whereas the viscosity is always remained unaffected in the case of Newtonian fluid. The presence of viscous force in non-Newtonian fluid has led to the lowered rate of mass circulation within the fluid and therefore decreases hydrodynamics alteration of the bubbles break up than the one encountered in Newtonian fluid.\(^{[17]}\)

Based on similar pseudoplastic behaviour shared by both CMCNa solution and real fermentation broth, the trend of oxygen transfer rate in \(A.\ flavus\) culture could be approximated from this study involving 0.35% (w/v) CMCNa solution.

Different impeller types and configurations also exerts a notable effect on power number which is represented by the term \(N^2D^2\). The higher mass transfer performance produced by dual CD-6 system is mainly contributed by the improved physical features. Besides reducing the trail of gas cavities as well as gassed power drop, CD-6 promotes better gas dispersion through its downward fluid pumping and this is quite the opposite to RT that produces somewhat upward flow direction. Contrary to upward flow pumping, downward fluid motion by CD-6 enables better bubbles distribution throughout the lower parts of the vessel.\(^{[19]}\) When two CD-6 were combined on the same shaft, as expected, the merged would further enhance the gas liquid mass transfer performance significantly and this could probably explain the superiority of dual CD-6 over other configurations tested in this study.

3.2 Effects of Aeration Rate on \(k_{L}a\): The relationship between \(k_{L}a\) and \(V_{e}\) characterizes the influence of aeration rate on gas-liquid mass transfer performance in systems investigated. Comparison of \(V_{e}\) effect on \(k_{L}a\) by different impeller configurations for both systems are depicted in Figure 4.

The dominance of dual CD-6 system in terms of its oxygen transfer rate over other configurations is indicated in both fluid systems with average percentage difference with other impeller configurations of up to 30%. In distilled water system, for the range of airflow rate used in this study, the augmentation of \(k_{L}a\) values in dual CD-6 system is from 0.0447 to 0.068 s\(^{-1}\) while...
Fig. 3: Effect of N'D^2 on k_a for different dual impeller configurations of RT and CD-6 at 2 L min\(^{-1}\) in (a) Newtonian system: Distilled water system; (b) non-Newtonian system: CMCNa aqueous solution. (○) RT-RT; (■) CD6-CD6; (▲) RT-CD6; (●) CD6-RT

in CMCNa aqueous solution the range of k_a measured is from 0.0135 to 0.0159 s\(^{-1}\). On the other hand, k_a profile of the generic dual impeller system of RT did not differ considerably with the other two configurations employing both RT and CD-6.

General profiles of all configurations demonstrate linear dependency of k_a with air flow rates in both test fluids. When air was introduced during agitation and passes through impeller regions which are known to be the most turbulent parts in the vessel, collision of bubbles would occur and led to formation of smaller bubbles, making the gas liquid interfacial area, a, wider and thus increases the overall oxygen transfer rate. The rate of bubble breakup however is greatly influenced by the degree of agitation and dispersion capability possessed by the impeller used. Basically, more tiny bubbles would be produced at higher turbulence and shear stress near the impeller region. Even so it is reported elsewhere in the literature that CD-6 produces lower shear stress level than RT\(^{[20-21]}\) the results from this study somehow found that combination of two CD-6 in one system performed much higher rate of gas liquid mass transfer than RT-RT system or even configuration with at least one RT installed. This is supported by other studies pertaining to single system of RT and CD-6\(^{[8, 22]}\) which concluded better mass transfer capability of CD-6 over RT. Furthermore, a simulation study on local bubble size distribution by Gimbun et al.\(^{[19]}\) suggested that better circulation of gas bubble could be achieved by the substitution of RT with CD-6.

Efficiency of bubble size disintegration is closely related to the flow pattern created by the impeller thus good selection of impeller type and configuration must be taken into consideration in enhancing mass transfer potential of a reaction\(^{[19]}\).
3.3 Development of Gas-liquid Mass Transfer Correlation: Correlations for gas-liquid mass transfer under different dual impeller configuration of RT and CD-6 were established based on the form of Eq. 5. Multi regression analysis was applied in solving the coefficients of mass transfer correlation (C, α and β) simultaneously. Values of the unknown constants for all impeller configurations in both systems are presented in Table 1. Correlation of mass transfer proposed for each impeller configuration was plotted well within the determination coefficient, $R^2$, values ranging from 0.93 to 0.97 and with mean error of less than 20% (Figures 5 and 6). Experimental data for all combinations fitted accordingly to their respective models with error limits of approximately within ±25%

As pointed out in Figures 3 and 4, dual CD-6 system could be regarded as the more superior impeller configuration in this study due to its highest performance of gas-liquid mass transfer in Newtonian and non-Newtonian system. The following correlation (Eq. 7) was derived for dual CD-6 system in distilled water with determination coefficient ($R^2$) of 0.93.

$$k_L a = 0.1393 \left( \frac{N^3 D^2}{V_g} \right)^{0.4093} \left( V_g \right)^{0.2972} \quad (7)$$

Likewise, correlation for dual CD-6 system in 0.35% (w/v) CMCNa aqueous solution with $R^2$ of 0.96 was established and written as in Eq. 8,
Table 1: Values of mass transfer correlation constants of different impeller configurations of RT and CD-6 in Newtonian and non-Newtonian systems

<table>
<thead>
<tr>
<th>System</th>
<th>Impeller configuration</th>
<th>Mass transfer coefficient $k_a = C_{ij}(V_j)^\alpha (V_i)^\beta$</th>
<th>Mean Error (%)</th>
<th>Coefficient of determination ($R^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newtonian system: Distilled water</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RT-RT</td>
<td>0.1048</td>
<td>0.3473</td>
<td>8.21</td>
<td>0.9721</td>
</tr>
<tr>
<td>CD6-CD6</td>
<td>0.1393</td>
<td>0.4093</td>
<td>7.87</td>
<td>0.9346</td>
</tr>
<tr>
<td>RT-CD6</td>
<td>0.0811</td>
<td>0.3928</td>
<td>11.40</td>
<td>0.9658</td>
</tr>
<tr>
<td>CD6-RT</td>
<td>0.0651</td>
<td>0.4010</td>
<td>9.85</td>
<td>0.952</td>
</tr>
<tr>
<td>Non-Newtonian system: CMCSu Na aqueous solution</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RT-RT</td>
<td>0.0053</td>
<td>0.4591</td>
<td>15.59</td>
<td>0.9474</td>
</tr>
<tr>
<td>CD6-CD6</td>
<td>0.0231</td>
<td>0.4744</td>
<td>10.35</td>
<td>0.9643</td>
</tr>
<tr>
<td>RT-CD6</td>
<td>0.0072</td>
<td>0.4645</td>
<td>12.38</td>
<td>0.9534</td>
</tr>
<tr>
<td>CD6-RT</td>
<td>0.0071</td>
<td>0.5366</td>
<td>19.57</td>
<td>0.9644</td>
</tr>
</tbody>
</table>

![Graph (a)](image_url)  
![Graph (b)](image_url)
Fig. 5: Comparison between experimental $k_{\alpha}$ and calculated $k_{\alpha}$ for different dual impeller configurations of RT and CD-6 in Newtonian system: Distilled water system. (a) RT-RT; (b) CD6-CD6; (c) RT-CD6; (d) CD6-RT
Fig. 6: Comparison between experimental $k_{i\alpha}$ and calculated $k_{i\alpha}$ for different dual impeller configurations of RT and CD-6 in Non-Newtonian system: CMCNa aqueous solution. (a) RT-RT; (b) CD6-CD6; (c) RT-CD6; (d) CD6-RT
In terms of $\alpha$ and $\beta$ values, a slight change was observed when the fluid system was switched from distilled water to viscous non-Newtonian. Notable distinction is also observed on the values of $C_i$ obtained for two different systems which determine the profound difference of oxygen transfer rate. In general, $C_i$ for Newtonian fluid was about six times higher than the values obtained in non-Newtonian sample.

The values of exponents obtained from this work with literature data for both Newtonian and non-Newtonian systems are summarized and compared in Table 2. The range of $\alpha$ and $\beta$ values obtained for Newtonian system, which is between 0.35-0.41 and 0.24-0.3 respectively are generally in a reasonable range with the formerly proposed data. On the other hand for non-Newtonian fluid, information on $k_a$ correlation with $N_D^2$ is not as widely available as opposed to correlation of $k_a$ with $P/V$. Thus in this study, comparison was only made with $P/V$ from the literature. Comparing $\alpha$ values obtained for non-Newtonian fluid in this present work with $\alpha$ values from the literature somehow show that there is a good agreement between both data. However, there was a slight deviation for $\beta$ values obtained in this study with those revealed earlier by previous researchers. This could be possibly explained by dissimilarity of various factors, including wide rheological property of non-Newtonian test fluid applied or the exclusion of probe response determination.

It is noteworthy to consider that several reported exponent values of mass transfer correlation found in literature were determined by considering single effect of operational variable on $k_a$ which is insufficient and rather unrealistic in real application where combined effects of various affecting factors could not be neglected.

Development of mass transfer correlation for a specific bioreactor design thus provides us with useful insights in optimizing variables affecting process $k_a$ such as agitation speed, aeration rate and impeller geometries/configurations to enhance the oxygen transfer. Such knowledge may be used to further improve the productivity of aerobic $A. flavus$ fermentation using stirred tank bioreactor.

**Conclusion:** Different dual impeller configurations employing RT and CD-6 have been assessed in term of their mass transfer performance in Newtonian and non-Newtonian fluids. Dimensional mass transfer correlations for the four different impeller configurations in Newtonian and non-Newtonian fluid were derived expressing the effects of $N_D^2$ and $V_e$ on $k_a$. The dual impeller system of CD-6 significantly improved gas-liquid mass transfer performance efficiently in both types of fluid tested. The range of $k_a$ values obtained with these turbines for Newtonian fluid ($0.0076-0.0952$ s$^{-1}$) and non-Newtonian fluid ($0.0016-0.0273$ s$^{-1}$) was about 0.9 to 2.9 times higher than those obtained in conventional RT-RT system. Reliability of $N_D^2$ in replacing commonly used $P/V$ in mass transfer correlation was also evaluated throughout this study.

$$k_a = 0.0231 \left( N_D^2 \right)^{0.4744} \left( V_e \right)^{0.2354}$$  \hspace{1cm} (8)

<table>
<thead>
<tr>
<th>System</th>
<th>Impeller type / combination</th>
<th>Exponent of $N_D^2(\alpha)$</th>
<th>Exponent of $P/V(\alpha)$</th>
<th>Exponent of $V_e(\beta)$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newtonian fluid: Distilled water</td>
<td>Single RT</td>
<td>0.42</td>
<td>-</td>
<td>0.6</td>
<td>Ozbek and Gayik$^{[15]}$</td>
</tr>
<tr>
<td></td>
<td>0.16 - 0.37</td>
<td>0.4 - 1.0</td>
<td>0.3 - 0.48</td>
<td>Aksak$^{[14]}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.37</td>
<td>-</td>
<td>0.67</td>
<td>Hortacsu$^{[13]}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.43 - 0.68</td>
<td>-</td>
<td>-</td>
<td>Yoshida et al.$^{[11]}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.74</td>
<td>-</td>
<td>-</td>
<td>Yagi and Yoshida$^{[12]}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>0.62</td>
<td>0.49</td>
<td>Orvalho et al.$^{[9]}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>0.17</td>
<td>Hyman and Van Der Bogaerde$^{[4]}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Single CD6</td>
<td>-</td>
<td>0.63</td>
<td>0.57</td>
<td>Orvalho et al.$^{[5]}$</td>
</tr>
<tr>
<td></td>
<td>Dual RT, Dual CD-6</td>
<td>0.35-0.41</td>
<td>-</td>
<td>0.24-0.3</td>
<td>Present work</td>
</tr>
<tr>
<td>Non-Newtonian fluid: CMC Na aqueous solution</td>
<td>Single RT</td>
<td>-</td>
<td>0.94</td>
<td>0.4</td>
<td>Linek et al.$^{[23]}$</td>
</tr>
<tr>
<td></td>
<td>Dual RT</td>
<td>-</td>
<td>0.80</td>
<td>0.3</td>
<td>Yagi and Yoshida$^{[12]}$</td>
</tr>
<tr>
<td></td>
<td>Dual RT, Dual CD-6</td>
<td>0.46-0.54</td>
<td>-</td>
<td>0.07-0.24</td>
<td>Arjunwadkar et al.$^{[22]}$</td>
</tr>
</tbody>
</table>

243
REFERENCES