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POWER CONSUMPTION AND BLEND TIME OF CO-AXIAL TANK MIXING SYSTEMS IN NON-NEWTONIAN FLUIDS

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Abstract. An experimental and numerical program has been carried out to explore and determine the mixing performance of co-axial agitation systems using Newtonian and non-Newtonian fluids in transitional and laminar regimes. The power consumption and blending performance of two co-axial mixer configurations consisting of a dual set of pitched blade turbines combined with the anchor or Paravisc® as proximity impellers are discussed. The data and analysis indicate that, within the design space investigated, the induced flow of the inner impellers affects the flow field of the proximity impellers, but not vice-versa. However, this effect is distinctly experienced by the proximity impeller due to the differences in primary flow patterns generated by each of these impellers. To compare and assess the blending efficiency of the investigated agitation systems, the blend times are directly compared at constant power input per unit mass and similar fluid properties. Appropriate co-axial mixer design and operating conditions can result in significant reductions in mixing time compared to separate impellers at the same specific power input.

Key words: Co-axial mixers, non-Newtonian, mixing time, power consumption, PARAVISC®

1. INTRODUCTION

Many industrial mixing processes involve highly viscous fluids with complex rheology. Such processes can be found in polymer based industries in the manufacturing and processing of rubbers, plastics, fibers, resins, coatings, sealants and adhesives as well as in the food processing industries, biotechnological operations and in the manufacturing of fertilizers, detergents, propellant, explosives, etc. Although the mixing of highly viscous fluids is widespread, it is a very difficult and complex operation, and it is often considered as the limiting step in chemical processes. The difficulty and complexity vary widely among processes that involve fluids with complex rheology, complex chemistry, and/or fluids that change viscosity during the mixing process. These processes are commonly accompanied with difficult operational problems, like formation of gels and lumps, fouling and build up on surfaces, low heat transfer, too long mixing times, poor dispersion of solids, presence of stagnant zones, etc. The result is that such complex and challenging mixing tasks might not be effectively accomplished in standard agitated tanks and possibly requires the use of more sophisticated mixing systems, such as planetary mixers, non-standard multi-shaft mixers, kneaders [1].

Co-axial impeller systems belong to this class of hybrid mixing systems. They consist of a combination of high speed impellers and a close-clearance impeller and both impellers rotate independently on the same reactor axis. The co-axial mixing system combines the effectiveness of open impellers in the low viscosity range and proximity impellers in the high viscosity range. Co-axial mixers are used in industry but detailed analysis of their performance characteristics have only recently appeared in the open literature. Relevant contributions on the subject have been conducted by Tanguy and co-workers [2-3], focusing on the power consumption and mixing time of co-axial impeller systems composed of an anchor impeller combined with different turbines, such as the Mixel TT impeller, Rushton and sawtooth, rotating modes in laminar and transitional regimes. Also a dual shaft mixer consisting of Paravisc® and an off-centered Deflo disperser were recently investigated [4]. The authors concluded that the power drawn by the inner impeller was not affected by the speed of either the anchor or Paravisc, but the power drawn by the proximity impellers were influenced by the inner dispersing turbines. Besides, they concluded that the co-rotating mode is more efficient than the counter-rotating mode in all investigated configurations. Rudolph *et al.* [5] also concluded that the power consumption of a dual set of pitched blade turbines was not affected by the speed of the anchor impeller, but the speed of the inner impellers affected the power drawn by the anchor in the co-rotating mode. Köhler *et al.* [6] observed that the power consumption of the inner impeller (four-blade paddle) was affected by the speed of the anchor in the transitional and turbulent regime (Re>100) for counter-rotating mode. They also showed that the speed ratio has a stronger influence on power consumption than the diameter ratio. Heiser *et al.* [7] investigated the performance of a co-axial mixer consisting of a helical ribbon and a central screw impeller and concluded that the power consumption of each impeller was affected by the other regardless of the chosen rotating mode.

The present work addresses the blending of viscous and non-Newtonian fluids in co-axial agitation systems in transitional and laminar regime. The presentation of the data in dimensionless form, which is essential to generalize the results for scale-up and design, is very challenging, because results are influenced by the presence of two impellers interacting in the system and parameters related to both impellers. None of the published correlations so far could be applicable to fit our experimental power consumption and mixing time data into a single master curve. In the author's opinion, there is still a lack of a general approach to describe the performance of co-axial mixers. For industrial applications, it is important to characterize the agitation systems in terms of power consumption and mixing time. The most efficient mixer is the one that can achieve the lowest mixing times at minimum power input. The mixing times in this work are presented in terms of a direct comparison for the investigated agitation systems at constant power input and non-Newtonian fluids.

2. EXPERIMENTAL DETAILS

2.1 Apparatus

The experimental mixing tank is illustrated in Figure 1. The geometrical dimensions are in mm. The cylindrical tank is made of Plexiglas™ with a dished bottom in DIN torispherical shape. The fluid volume is 86-liter. The tank is equipped with two electric drive-motors of 3 kW and 1.5 kW; one drives the inner impellers and the other the outer impeller, respectively. The co-axial combination of impellers could be realized by using a combination of a hollow and a solid shaft.

Two co-axial design configurations using a dual set of pitched-blade turbines as open impellers in combination with a proximity impeller at different operating conditions were investigated. Two proximity impellers were employed in this investigation, the standard anchor and a modified helical ribbon known as PARAVISC® (Ekato Rühr- und Mischtechnik

GmbH). The mixing system was instrumented to measure continuously the torque, and rotational speed of the inner impellers and power and rotational speed of the proximity impeller. The measured total power consumption for the outer impeller was corrected by subtracting the measured power from a calibration curve, which includes the motor friction losses.

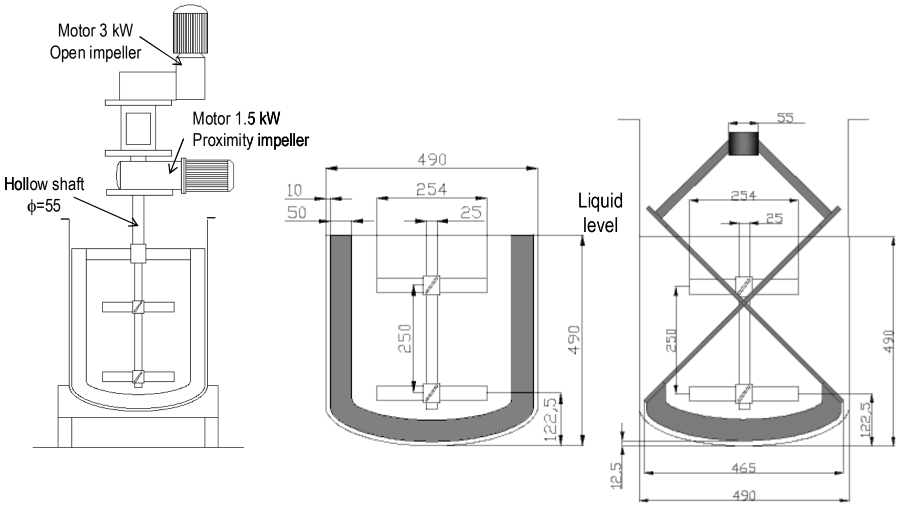

Figure 1: Experimental Setup

2.2 Test Fluids

Two polymer solutions were employed as non-Newtonian fluids in the experimental program, the hydroxyethyl cellulose (HEC), or CELLOSIZE™ HEC QP300 and sodium carboxymethyl cellulose (CMC), or WALOCEL® CRT 20000, both products of Dow Wolff Celullosics. The non-Newtonian test liquids were prepared by thickening water with the cellulosics product at different weight concentrations. Rheological measurements for hydroxyethyl cellulose (HEC) solutions were conducted in a cylinder rotation viscometer (Searle-Type). The rheological behavior of the HEC solutions can be described by the Ostwald-de Waele viscosity model (Table 1).

Table 1: Rheological parameters of power law model for HEC solutions at 25°C

HEC Concentration weight %	Consistency index k [Pa s ^{n}]	Shear-thinning index n [-]
3	2.64	0.71
5	29.2	0.51
7	101.2	0.44
8	154.8	0.42

Although HEC aqueous solutions at the selected concentrations exhibit shear-dependent viscoelastic properties, their effect on the power consumption measurements of the co-axial mixer was not investigated. It was assumed to be negligible in the laminar regime at rotational speeds from 0-200 rpm. No Weissenberg effect (i.e. liquid climbing up the rotating shaft) was observed during the power curves measurements.

The rheological behavior of the solutions of CMC was measured in the rotation rheometer Bohlin CVO120 using a cone-plate configuration. The fitting parameters of the Ostwald-de Waele model was found to be k=41.34 (in Pas ^{n}) and n=0.39 for CMC with 2% weight concentration at 20°C. The density of CMC and HEC solutions is 1000 kg/m^3.

The use of aqueous solution of acid and base to measure the mixing time caused a continuous dilution of the test fluid in the tank. In order to account for the alteration in the viscosity due to the dilution, the HEC and CMC concentration in the tank was tracked, and the viscosity corrected for each experiment. Additionally, after a number of experiments, the test fluid was thickened with a certain amount of HEC or CMC to return to the set concentration.

Aqueous solutions of glucose syrup C*Sweet (SWE) from Cerestar GmbH and Glucomalt (GLU) from Tate&Lyle Europe were used as the Newtonian fluid. The viscosity range is from 4 to 50 Pas and the density is 1415 kg/m^3 for SWE and from 92 to 175 Pa·s and 1400 kg/m^3 for GLU. The mixing time measurements caused a continuous dilution of the syrup as well, which required the adjustment of the viscosity after a number of experiments.

2.3 Mixing Time Measurement

A non-intrusive technique based on direct visualization of a color change, DISMT method “Determination of Mixing Time through Color Changes” [8], was applied for measurements of the mixing time. DISMT is a visualization method that makes use of two pH sensitive indicators. The range of color change of both indicators overlaps so that three colors can be distinguished depending on the pH. With a clear mixing vessel, an observer may see distinct red and blue regions, as well as the later emergence of yellow regions. The present experiments using the investigated test fluids, CMC and HEC, demonstrated that the DISMT was also suitable for these aqueous polymer solutions. CMC solutions demonstrated, however, better suitability for this method in comparison to HEC solutions, due to their clearness in neutral pH.

3. RESULTS

3.1 Power Consumption Analysis

The interactive effects in the investigated co-axial mixers for Newtonian and non-Newtonian fluids operating in co-rotating mode are analyzed. The power curves of the co-axial mixer consisting of an anchor impeller and a dual set of pitched blade turbines (PBT) are plotted in Figure 2 and Figure 3. The Reynolds number for the non-Newtonian fluids was calculated using Metzner-Otto constants, as previously reported by Rudolph *et al.* [5]. It can be concluded that the power draw of the inner impellers is not affected by the anchor speed, but the power consumption of the anchor impeller reduces as the tip speed ratio increases (i.e. inner impeller speed increases). Analogous analysis was carried out for the co-axial mixer using Paravisc as proximity impeller. Figure 4 shows the power curves of the dual set of pitched blade turbines calculated using the characteristic length and speed of the inner impellers and varying the tip speed ratio. Similar to the co-axial mixer with the anchor, a single characteristic power curve for the inner impellers was obtained regardless of the Paravisc impeller speed. Therefore, the Paravisc impeller rotation does not affect the power of the inner impeller in the given configuration. Using a proximity impeller other than anchor, i.e. the Paravisc impeller, which generates a different flow pattern, the power consumption of the pitched blade turbines remains the same as if the inner turbines were rotating alone in the vessel.

Figure 5 shows the power curves of the Paravisc impeller for different tip speed ratios. The dimensionless numbers are now related to the proximity impeller Paravisc. The experimental data for Newtonian and non-Newtonian fluids follow curves with a slope of -1 in laminar regime. The variation of the power constants K_P versus the tip speed ratio is summarized in Table 2. The experimental data indicate that the power drawn by the Paravisc impeller decreases with increased speed of the inner impellers when both impeller types are rotating in the same direction. In co-rotating mode, the pitched blade turbines induce a flow that drags the proximity blades, consequently decreasing the power consumption. As the tip speed ratio increases (i.e. increasing the rotational speed of the inner impeller), the additional shear field induced by the central impellers significantly influences the flow field around the proximity impeller and consequently the power consumption. However, the rotation of the inner impellers affects the power consumption of each proximity impeller differently, as shown in Table 2.

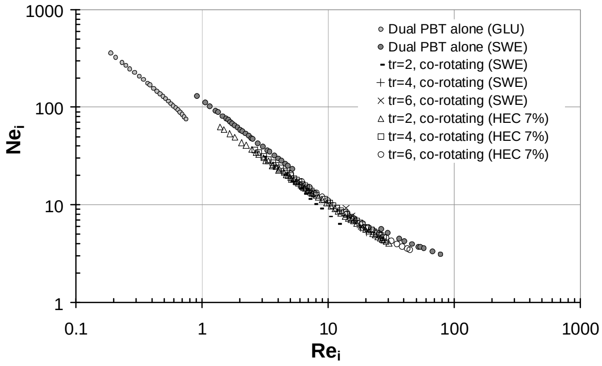

Figure 2: Power curves of PBT in co-axial mixer using anchor as proximity impeller

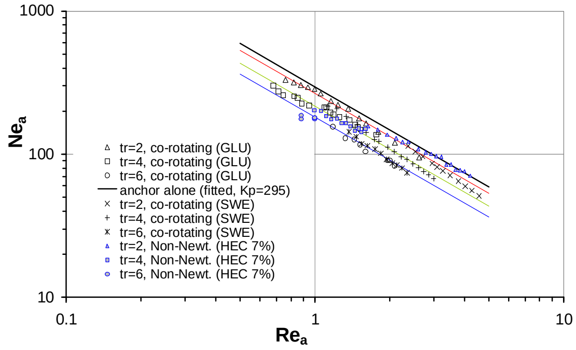

Figure 3: Power curves of anchor in co-axial mixer

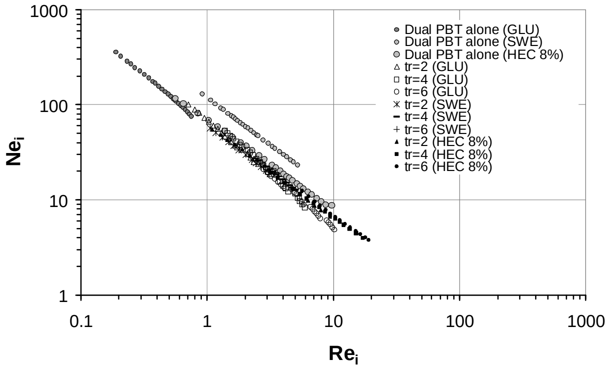

Figure 4: Power curves of PBT in co-axial mixer with Paravisc as proximity impeller

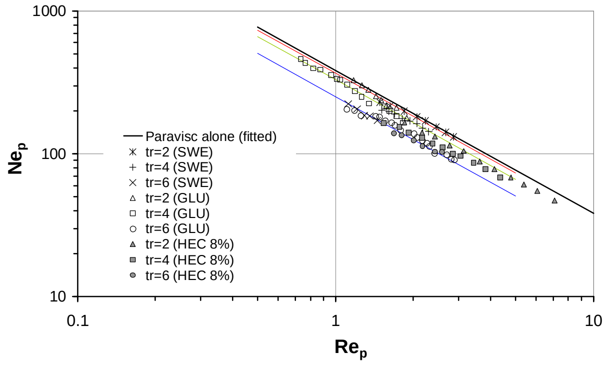

Figure 5: Power curves of Paravisc in co-axial mixer

Table 2: Variation of K_P of the proximity impellers for different tip speed ratios (co-rotating mode)

Tip speed ratio (tr)	K_P Anchor	K_P Anchor Decay	K_P Paravisc	K_P Paravisc Decay
0	295	-	385	-
2	266	10%	366	5%
4	216	27%	330	14%
6	182	38%	252	35%

The data indicate that the design and consequently the generated flow patterns of the proximity impeller have a significant influence in the flow field interactions between the impellers and therefore in the overall co-axial mixing performance. Figure 6 shows a sketch of typical flow pattern produced by standard axial (left) and radial (right) pumping impellers. This should aid in the understanding of the flow field interactions in co-axial mixers. It can be also understood as primary flow patterns produced by the pitched blade turbines in turbulent (left) and laminar regime (right). For high Reynolds numbers, a multi-staged axial pumping impeller like PBT provides ideally a single flow circulation loop through the vessel as indicated on the left side of Figure 6. The situation is different for radial pumping open impellers, or pitched blade turbines in laminar regime – on the right side of the vessel in Figure 6. The discharge flow is directed radially outward towards the cylindrical wall of the vessel where it splits into two circulation loops, one above the impeller plane and one below. If the proximity impeller produces dominantly tangential flow like the anchor, a weak flow field displacement regardless of the rotation mode is expected. As a result, it would be expected that the axial pumping ability remains the same as it is in the single impeller system using the two pitched blade turbines. On the other hand, if the proximity impeller induces an axial flow component like the Paravisc, the flow produced by the inner impeller near the wall of one of the circulation loops is in the opposite direction to the induced flow by the Paravisc impeller (indicated by the thicker arrows). As a result, stronger flow field displacement in the co-axial mixer with Paravisc would be expected as well as a portion of the power drawn by the Paravisc to overcome this opposite flow. The collaborative effect of proximity and inner impellers rotating in the same direction is enhanced in both investigated co-axial mixer configurations, as the power consumption data indicate (Table 2).

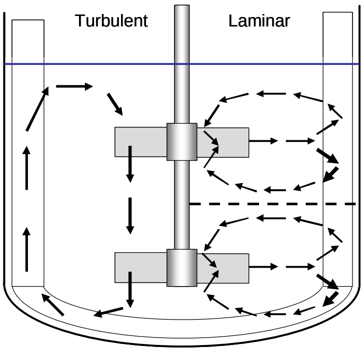

Figure 6: Sketch of flow pattern produced in turbulent and laminar flow by axial pumping impellers

Figure 6 also indicates that in cases, where a dual set of the inner impellers induces a pure radial flow pattern, two distinct zones can exist in the vessel with little exchange between them. On the sketch, the border between those two zones is indicated by the dotted line. As one can see, velocity vectors are parallel in this plane, resulting in a limited axial exchange of a transport property and segregated flow. Segregated flow was observed in the experimental trials using anchor and a dual set of pitched blade turbines combined co-axially. The neutralizing agent was added from the top and mixed relatively fast in the upper zone of the vessel. It takes significantly longer to transport the agent into the lower half of the vessel. The border line between the two zones could clearly be seen.

3.2 Mixing Time

The mixing time measurements were carried out in different non-Newtonian fluids. The co-axial mixers were operating at three tip speed ratios (tr=2, 4 and 6). To compare and assess the blending efficiency of the investigated agitation systems, the blend times are directly compared at constant total power input per unit mass and similar fluid properties. Figure 7 shows the measured blend times as function of the power input in aqueous solutions of CMC of 2% weight concentration for the co-axial mixers anchor and Paravisc combined with a dual set of PBT. The mixing time obtained in the stirred tank with PBT alone (anchor as baffles) are plotted for comparison. As expected, the mixing time of all investigated agitation systems decreases with increased power input. The data indicate that the configuration co-axial Paravisc with PBT showed the best performance regardless of the tip speed ratio and total power input. The anchor combined with PBT exhibits lower performance in comparison to the single impeller system (PBT alone) at low energy input regardless of the tip speed ratio. The performance of the co-axial mixer anchor with PBT increases at higher total power input (e.g. 3W/kg), but only for high speed ratios. At tip speed ratio tr=6, the inner impellers rotates 11 times faster than the anchor and it seems the mixing task is mainly contributed by the inner impellers. It is relevant to point out that the flow regime in CMC 2% is transitional (Reynolds number calculated using the inner impeller parameters). The good performance of the Paravisc with PBT can be explained by the enhanced axial pumping ability of both impellers, since Paravisc pumps upwards and the inner impellers pump downwards. The PBT alone in CMC 2% showed better performance than the co-axial configuration using the anchor for almost all operating conditions. It seems that the anchor impeller does not contribute significantly to the bulk blending.

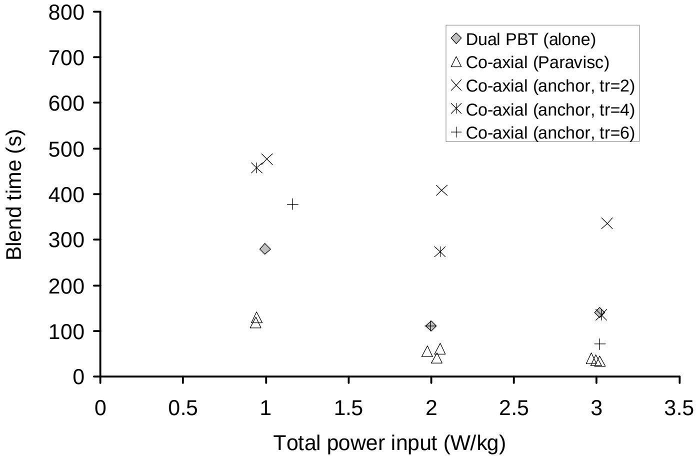

Figure 7: Measured 95% mixing time versus total power input in non-Newtonian fluid CMC (transitional)

The situation changes when the flow regime is laminar. The measured blend times in HEC of 7% wt. concentration as function of the total power input per unit mass are plotted in Figure 8. The efficiency of the single impeller systems compared to the co-axial mixing systems is lower to blend this fluid, with exception of the Paravisc at total power input 1W/kg. The axial pumping capacity of the PBT impellers decreases significantly in laminar flow, as previously discussed. The co-axial mixer using Paravisc as proximity impeller gives the shortest mixing times at the investigated power inputs, but not for all tip speed ratios.

4. CONCLUSIONS

An experimental program using pilot-scale co-axial agitation systems was carried out to explore and determine their design and mixing performance characteristics. In this work, power consumption analyses for different co-axial mixing configurations in co-rotating mode are reported. The investigated co-axial mixers consist of a dual set of PBT combined with a proximity impeller. Two proximity impellers (anchor and Paravisc impeller) that generate different flow patterns were used and compared. The power consumption of the inner impeller is not influenced by the rotation of the proximity impeller, but the power drawn by the proximity impellers is reduced as the inner impellers rotate. However, the magnitude of the reduction is distinct for each of the employed proximity impellers. This might be explained by the individual flow patterns generated by the impellers and the interactions.

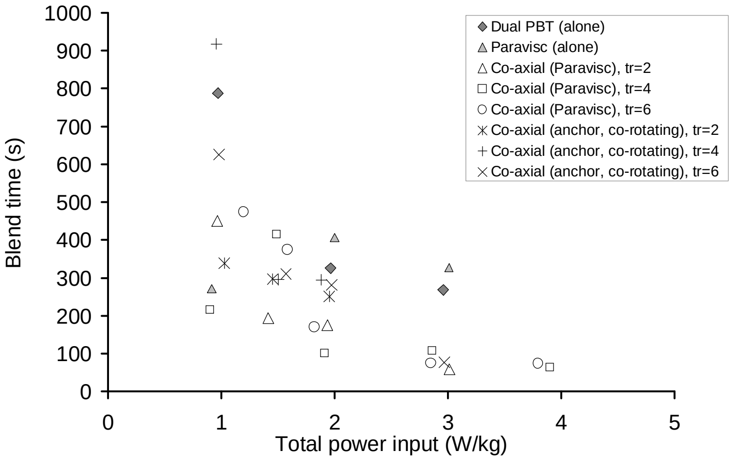

Figure 8: Measured 95% mixing time versus total power input in non-Newtonian fluid HEC 7% (laminar)

The mixing time analysis shows that appropriate co-axial mixer design and operating conditions can result in significant reductions in mixing time compared to single impellers at the same specific power input. In the transitional regime, a co-axial mixer using an anchor as the proximity impeller does not seem to be a good option for blending tasks, since the inner impellers alone (a dual set of pitched blade turbines) exhibit an equivalent or better performance. The features of the mixing time data indicate a high degree of complexity of the flow in the co-axial mixing system. The complex flow is currently under investigation with computational fluid dynamics modeling.

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