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THE EFFECT OF IMPELLER DESIGN ON THE MIXING OF NON-NEWTONIAN INTERNAL TYRE LUBRICANT

Abdul Aziz Azoddein[1], Shaliza Ibrahim[2] and Aziz Hassan[3]

[1] TATI, Kampus TATI, Jalan Panchur
24000 Teluk Kalung
Kemaman, Terengganu

[2] Department of Civil Engineering
[3] Department of Chemistry
University of Malaya
50603 Kuala Lumpur
(shaliza@fk.um.edu.my)

RINGKASAN: *Percubaan telah dijalankan untuk menilai beberapa reka bentuk pengaduk jenis klasik, jenis komersil dan jenis tempahan khas, untuk mencampur bendalir kompleks yang bernilai komersial. Berdasarkan aliran bendalir dan keperluan kuasa pengaduk, kajian ini menunjukkan kepentingan nisbah garis pusat pengaduk kepada tangki (D/T) dan geometri pengaduk bagi hasil pencampuran optimum. Walaupun pengaduk jenis pengayuh bersirip yang sedia ada menghasilkan produk akhir yang diingini, hasil yang memuaskan juga diperolehi dengan pengaduk jenis komersial dengan D/T yang lebih rendah, yang boleh menjimatkan kuasa sebanyak 80%.*

ABSTRACT: Experiments were conducted to assess the performance of various classic, commercial and made-to-order impeller designs to mix a rheologically complex fluid of commercial value. This study highlights the importance of impeller-to-tank diameter ratio (D/T) and impeller geometry for optimal mixing results, based on the flow of fluid and impeller power requirement. Although an existing finned-paddle type impeller produced the desired final product, satisfactory results were also obtained with a commercial impeller of smaller D/T, which could lead to 80% power savings.

KEYWORDS: Mixing, impeller geometry, non-newtonian, internal tyre lubricant

INTRODUCTION

Mixing, the inter-penetration of one substance with another, consumes a considerable portion of processing time as material moves through a plant. The preparation of raw materials, maintenance of suitable conditions in a reactor, separation processes and treatment of wastes, often involve mixing. Fluid materials in chemical, pharmaceutical, biochemical, petroleum and mineral industries are commonly mixed in stirred vessels. Comprising a motor-run agitator rotating in a tank, this traditional method is simple yet versatile. The numerous impeller designs available and the flexible capacity that a vessel can hold enable the system to be used for a wide range of mixture properties and operating scale.

It is, however, unfortunate that mixing is sometimes taken for granted and not much consideration is given in optimizing mixing equipment. Improper selection of an agitator can lead to poor mixing or over-mixing where unnecessary excessive energy is being used to accomplish a particular mixing task. The mixing criterion may be based on the final outcome of the product, but overall optimization of the mixing process should include proper monitoring of the material flow pattern and energy consumed during agitation. In practice, these factors are easily overlooked. At industrial scale the agitation power consumption is hardly ever measured, and the vessels are often made of opaque materials such as stainless steel or concrete, which prevent visual observation of the materials being mixed. In a case where a new product is to be mixed, it might be convenient to use existing equipment, but variations in the mixture properties may mean that a readily available agitator is not the most suitable for a new system. It may prove worthwhile to conduct some study at the small scale and to invest on an optimum design before a particular mixing system is used for a long term.

Among the factors that affect the choice of an agitator are the mixture properties, namely liquid viscosity and density, whether it is Newtonian or non-Newtonian, the extent of non-Newtonian behaviour, and properties of gas and/or solid phases, if present. High liquid viscosity and non-Newtonian characteristics such as pseudoplasticity, yield stress and viscoelasticity can alter the basic flow pattern generated by a particular agitator geometry, which in turn affect the mixing performance (Nienow and Elson, 1988; Ibrahim and Nienow, 1995). Extreme pseudoplasticity and yield stress can lead to intense mixing close to the agitator but stagnation in areas further from the agitator. This has to be overcomed with the use of larger agitator-to-tank diameter ratio (Elson *et al.,* 1986). Viscoelastic fluids when agitated can form the rod-climbing "Weissenberg effect" (Elson *et al.,* 1982), which in extreme cases could potentially damage the agitator motor. Thixotropic and rheopectic fluids exhibit characteristics, which are dependent on the duration of shearing, either becoming less or more viscous with time of shearing.

Simple liquid blending is often achieved with large, low-speed agitator such as the paddle or anchor-type agitator. The classic 6-blade disc turbine (6DT) commonly known as the

Rushton turbine produces high shearing action at the tip of each blade as it rotates. This leads to the formation of trailing vortices, which have been shown to be the source of gas dispersion in liquid (van't Riet and Smith, 1973). However, the overall motion from the straight blades of this impeller is in the radial direction, which makes it inefficient for the suspension of solid particles in liquid. The most economical type of agitator to use for solid suspension in liquid are agitators with inclined blades pumping downwards such as the pitched-blade turbine or propeller type impeller (Ibrahim and Nienow, 1996), because inclined blades produce good bulk motion. On the other hand, the angled blades have low shearing action and causes hydrodynamic instability in the presence of gas, thus making them poor gas dispersers (Bujalski *et al.,* 1987).

The preceding paragraphs depict the importance of proper design and selection of mixing equipment before a particular operation is carried out, because an impeller design may only be good for a particular function. Real situations can be more complex because of the numerous possible combinations of rheological characteristics, which sometimes change markedly over the course of a process as reactants are utilized and product concentration increases. Hence, the impeller selected must also be adaptable to the dynamics of the process. Furthermore, many processes require the mixing of solid, liquid and gas, and the impeller has to satisfy such objectives simultaneously.

This paper is concerned with the mixing of an internal tyre lubricant (ITL) produced by a local chemical industry. ITL is produced primarily by mixing various chemical components in a vessel. During the time of this study, the agitator used for the production is of a non-conventional design, made largely by trial-and error. Starting with a flat four-blade paddle-like structure, small vertical and horizontal projections were progressively added to the main blades, presumably to reach areas not covered by the simple paddle. The final design, which is referred to as the "finned-paddle" in this paper may have produced the desired results but this study is to show that a much better outcome could be achieved with a ready made commercial impeller.

The objective of this work is to compare the performance of the existing impeller to more conventional and new commercial designs with the intent of finding the optimum geometry to be used for the ITL system.

MATERIALS AND METHOD

The ITL is a non-Newtonian water-based fluid containing at least 50% active material including xanthan gum, which is known to be viscoelastic, soy lecithin, and mica powder to give good lubricity properties and mica tackifying (tackness). Hence, it is really a fine solid-liquid aqueous suspension with a tendency to separate if left stationery for some period of time. It has a specific gravity of 1.32 and an apparent viscosity of 0.045 Pa s at a shear rate of 503 s^{-1}, torque 7.06 mNm and shear stress 29.7 Pa.

The viscosity was measured using a Mettler Rheomat RM180 concentric cylinder viscometer. *Apparent viscosity* is a term used to describe the viscosity of a shear-dependent fluid, at a particular shearing condition. The viscoelastic and thixotropic properties of ITL could not be quantitatively defined due to the lack of sophisticated analytical instruments.

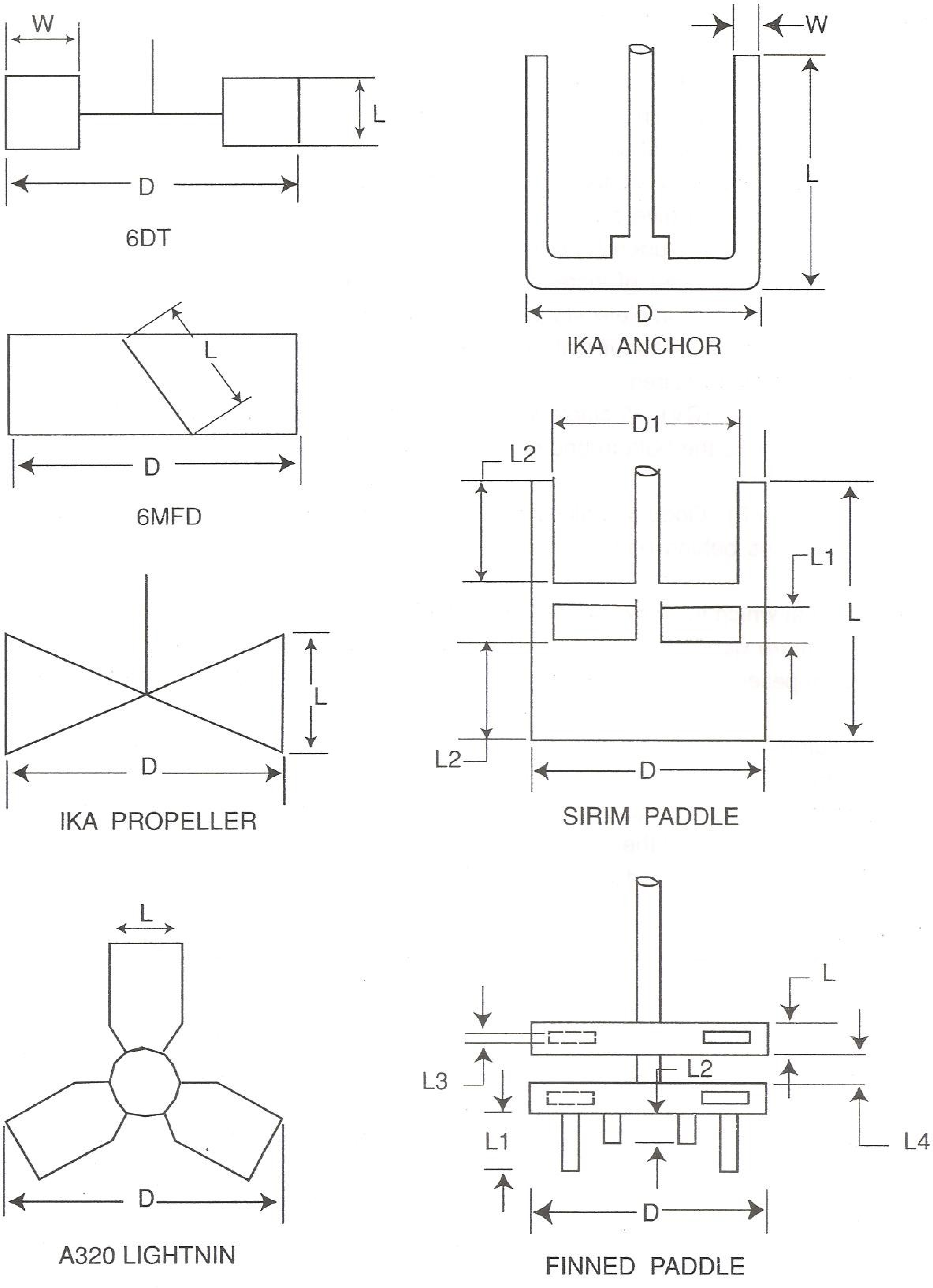
Mixing was conducted in a 19 cm diameter (T) cylindrical Perspex tank, with a dish-shaped base, open top and standard baffles (strips T/10 wide along the wall on each quadrant of the vessel). The impeller is 6.33 cm from the base of the vessel, mounted on a shaft which is centrally and vertically positioned, and motor-driven from the top. The motor and power-measuring device is a Lightnin Labmaster SI Series Mixer unit. Speed control and measurement from 0 to 1000 rpm were available with the unit, but the runs only went up to a maximum of 450 rpm, as this was sufficient to make comparisons of the performance of all the impellers. The power data reported are averages of three values for each run.

The impeller specifications are summarized in Table 1 and the schematics are shown in Figure 1. The 6DT has a disc in the center and 6 blades projecting straight outwards. The 6MFD is also a 6-blade turbine but the blades are inclined around 45°, without a central disc. The Lightnin A320 is a 3-blade impeller of hydrofoil design. The blades are inclined in a gradual manner, where the angle decreases with increasing distance from the hub.

Table 1. Impeller Specifications

Impeller	**Diameter, D (m)**	**D/T**	**L/D**	**W/D**	**Others**
6DT	0.100 0.127	0.526 0.668	0.20 0.25	0.25 0.30	
6MFD	0.100 0.127	0.526 0.668	0.20 0.25	N/A N/A	
IKA Propeller	0.100	0.526	0.20	N/A	
Lightnin A320	0.127	0.668	0.20	N/A	
IKA Anchor	0.090	0.474	1.22	1.11	
SIRIM Paddle	0.090 D1=0.040	0.474	1.44	0.278	L1=0.050 cm L2=0.025cm
Finned Paddle	0.140	0.737	0.178		L1=0.050 cm L2=0.025 cm L3=1.000 cm L4=4.500 cm

D Impeller diameter
T Tank diameter
L Blade width
W Blade length
L1, L2 Blade dimensions/segments of blade width as defined in Figure 1


6DT

IKA ANCHOR

6MFD

SIRIM PADDLE

IKA PROPELLER

A320 LIGHTNIN

FINNED PADDLE

Figure 1: *Different impeller diesigns used in the experimental work*

RESULTS AND DISCUSSION

The opacity of the fluid used in this study did not allow visual observation of the flow in the bulk of the vessel although a transparent tank was used. Hence, the quality of mixing was assessed based on flow observations of the liquid surface from the top of the vessel. Since the impeller was placed at one third of the liquid height from the tank bottom, flow characteristics on the surface should give an indication of the fluid movement in the lower region of the vessel. Realizing the crudeness of this assessment method, observations were made only for the following, in order of increasing mixing efficiency:

(i) No Flow (NF): Complete stagnation of the surface. Not desired.
(ii) Partial Flow (PF): About half of the surface moves while a substantial portion is still stagnant. Not desired.
(iii) Central Vortex (CV): A single vortex forming in the center causing the liquid surface to dip towards the bottom and resulting in a swirling action rather than chaotic mixing. Not desired.
(iv) Full Flow (FF): Good overall fluid motion as observed from the surface except for small dead zones behind baffles. Required.

The speed at which full flow is first observed, coupled with the impeller power consumption, provide a more quantitative comparison of the impeller performance. Figure 2 shows the range of impeller speed and power requirement under full flow condition.

Table 2 summarizes the experimental data. The impellers in Groups A1 and A2, namely the 6DT, 6MFD, IKA Propeller and Lightnin A320 are usually used as high-speed impellers at D/T less than or equal to about 0.5. But the results here show that at D/T=0.526 (large for these impellers), none of the impellers produced full flow on the surface. For 6DT and 6MFD the larger D/T=0.668 fared better with full surface flow at 300 rpm, although the power

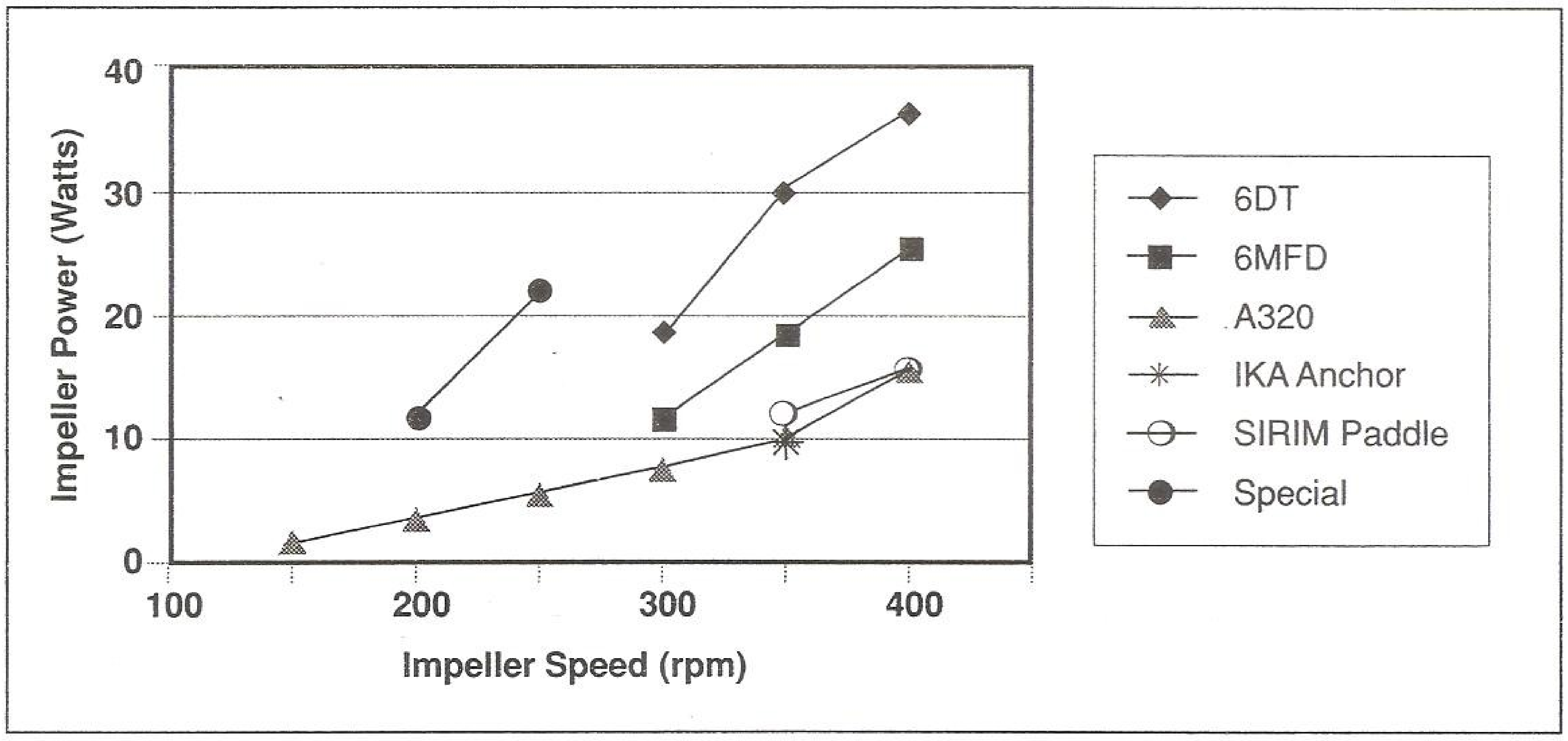


Figure 2: *Comparing Impeller Speed and Power at Full Surface Flow*

Table 2: Liquid Surface Characteristics and Impeller Power Requirement for the Mixing of ITL

Group	D/T	Impeller	100 rpm		150 rpm		200 rpm		250 rpm		300 rpm		350 rpm		400 rpm		450 rpm	
			Flow	Power (Watt)	Flow	Power (Watt)	Flow	Power (Watt)	Flow	Power (Watt)	Flow	Power (Watt)	Flow	Power (Watt)	Flow	Power (Watt)	Flow	Power (Watt
A1	**0.526**	**6DT**	NF	0.4	NF	0.7	NF	1.7	NF	3.1	NF	5.2	PF	9.4	PF	13.9	PF	19.1
		6MFD	NF	0.3	NF	0.	NF	1.3	NF	2.2	PF	2.9	PF	4.0	PF	5.4	PF	7.3
		IKA Propeller	NF	0.3	NF	0.5	NF	1.0	NF	1.8	NF	2.4	NF	3.2	PF	4.6	PF	6.4
A2	**0.668**	**6DT**	NF	1	NF	2.5	PF	5.7	PF	11.1	FF	18.6	FF	29.6	FF	36		
		6MFD	NF	1.1	NF	2.2	NF	4.1	NF	7.8	FF	12.1	FF	18.1	FF	24.5		
		Lightnin A320	NF	0.7	FF	1.5	FF	2.8	FF	4.5	FF	6.4	FF	10.7	FF	15.2		
B1	**0.474**	**IKA Anchor**	PF	0.6	CV	1.2	CV	2.4	CV	4.1	CV	5.6	FF	9.6				
		SIRIM Paddle	PF	0.7	CV	1.5	CV	3.2	CV	5.9	CV	8.8	FF	12.1	FF	15.5		
B2	**0.737**	**Special**	PF	2.9	CV	6.2	FF	11.9	FF	22.2								

consumption increased 3 to 4 times. But at D/T=0.668 the A320 shows outstanding performance with full flow occurring at a speed of only 150 rpm and power consumption only about 10% of the power of the other two impellers.

Group B1 comprises of what are generally known as large, low speed impellers - anchors and paddles. These are used here at D/T=0.474. Both produced full flow at 350 rpm, indicating that they may be better than the 6DT and 6MFD or IKA propeller since their D/T is less. Figure 2 shows that their power consumptions at full flow are comparable to that of the A320 at the same speeds. But the A320 can be used at much lower speeds with less power consumption to achieve full flow. A problem encountered with the paddle and anchor impellers is the formation of a central vortex at intermediate speeds. A central vortex is not desired in a mixing operation as its swirling action defies the mixing objective of chaotic motion, and the liquid surface may to dip right into the impeller blades and ingest air from the atmosphere.

Group B2 is the specially made finned-paddle impeller that has the largest diameter of 0.737. The minimum speed for full flow, observed at 200 rpm is close to that of A320, but the power draw of 11.9 watts is 8 times more. Although this impeller has been used in the production of ITL, the results of the other more conventional impellers (with exception of the 6DT) indicate that they could have worked just as well with slightly lower power in some cases. The reason that the finned-paddle worked is most probably due to the large D/T and the projections of blades on it. However, these extra blades may also well be the reason for the high power requirement due to shearing action.

CONCLUSIONS AND RECOMMENDATIONS

The experiments performed in this study have shown that:

(i) At D/T=0.526 none of the turbines and the propeller produced full flow for the range of speeds studied.

(ii) For the 6DT and 6MFD, a larger D/T of 0.668 was better able to mix the ITL, and the 6MFD consumed less energy than the 6DT for full flow.

(iii) The SIRIM paddle at D/T=0.474 is comparable to the 6MFD in terms of energy consumption, while the IKA Anchor demanded less power under otherwise similar conditions. These low speed SIRIM and IKA impellers have better potentials than the classic turbines for mixing the ITL since full flow was achieved with lower D/T.

(iv) The hydrofoil A320 is by far the most superior impeller for this work, requiring only 16% of the power of the IKA Anchor (the next most efficient impeller) and 13% of the special made-to-order impeller power currently used for full scale ITL production. Figure 2 clearly shows the greater efficiency of this impeller compared to the other geometries tested in this work; in terms of both the speed and power required to achieve full surface flow.

The above findings suggest that it might be worthwhile investing in the A320 for this process as it would be more economical in the long term due to substantial savings in operating costs. Prior to that, however, further studies should be conducted to determine the optimum D/T for the A320, and whether the quality of final product obtained meets the desired specifications. Trial runs should also be performed at the actual operating scale to see if the outcome is as expected.

Although the work done here was for a particular type of ITL, the observations may also be applicable to other commercial fluid of similar properties.

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