DEVELOPMENT OF TRANSITIONAL FLOW MIXING IMPELLER

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ABSTRACT

Many important mixing applications are performed in the transitional flow regime, (i.e. mixing Reynolds number from 20 - 2000, viscosities up to 100,000 cps). When the mixing impeller operates in this regime, some of the liquid volume may be in the laminar flow regime. In many processes, the viscosity changes during the process. Where blending is important, a flow efficient impeller is desired when operating in the turbulent regime as well as the transitional flow regime. This paper will discuss the development of a new mixing impeller (called the A410) which address these issues. The techniques used in its development will be shown.

The impeller performance characteristics were measured with a two-dimensional laser doppler velocimeter (LDV). The flow characteristics were studied in both water and glycerin solutions to cover the turbulent and transitional flow regimes. In order to analyze its process characteristics, blending studies were conducted to observe mixing in all areas of the tank. This is especially important since the laminar regions away from the impeller must also be blended.

Computational fluid dynamics (CFD) was an integral part of the impeller development. The experimental flow characteristics in the transitional flow regime were compared to the calculated velocities of the computational field. Blending calculations using computational fluid dynamics were performed and compared to blending experimental results.

The new A410 impeller produces high flow efficiency in the turbulent regime and possesses unique characteristics in the transitional flow regime. The flow field measured by the LDV agrees well with the computational fluid dynamics calculations. In addition, the blending studies demonstrate the value and insights gained by the use of computational fluid dynamics in mixing studies.

INTRODUCTION

Important mixing applications occur in the transitional flow regime, (i.e. mixing Reynolds number from 20 to 2,000, viscosities up to 100,000 cps). When the mixing impeller operates in this regime, some of the liquid volume may be in the laminar flow regime. In many processes, the viscosity (therefore the Reynolds number) changes during the process. This is especially important in small batch sizes (which account for a large percentage of all mixing applications). Small volumes, requiring small impeller diameters, are more likely to be in the transitional flow regime. If these small batches have a large product value, then it is extremely important that the products are processed efficiently under all conditions. A flow efficient impeller is desired when operating in the turbulent range, as well as, in the transitional flow regime. This paper will discuss the developments of a new mixing impeller (designated the LIGHTNIN A410 Impeller) which address these issues and it will show many of techniques used in its development.

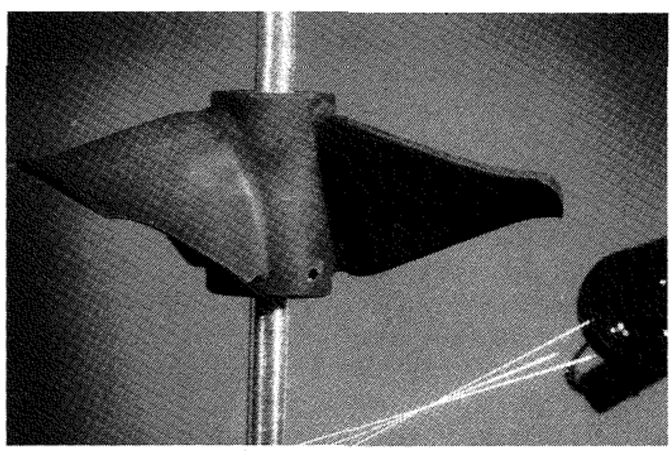

FIG.1 A410 IMPELLER

[A410] TRANSITIONAL FLOW IMPELLER REGIME

The A410 impeller as shown in Fig. 1 has been developed to operate in the laminar or transitional flow regime. As stated above, this is a common and extremely important operating range for small batch size mixers (often called portable mixers). Fig. 2 shows a portable drive mixer incorporating the A410 impeller. This new impeller is made of corrosion resistant, composite plastic materials. The impeller was designed with computer-aided design (CAD), finite element analysis (FEA) and computational fluid dynamics (CFD). In addition, blending studies were done to analyze the particular characteristics in this range.

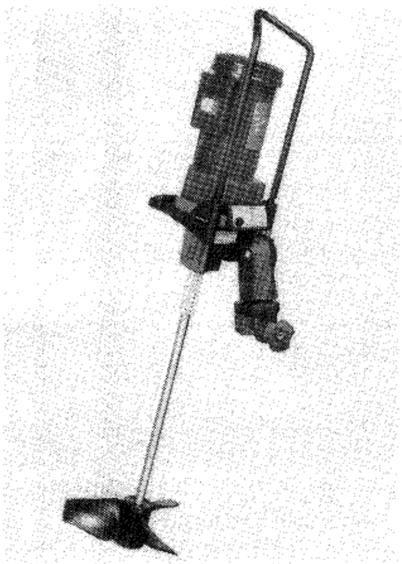

FIG.2 PORTABLE MIXER

BLENDING

Below we will discuss some of the blending attributes in the transitional flow regime. Fig. 3, 4 and 5 show a blending test. Two side-by-side 0.445 m (17.5 inch) diameter tanks were used with a liquid level of 0.457 m (18 inch). A .178 m (7 inch) A410 and a standard marine propeller (A110) were operating at an equal power consumption of 7.9 watts. Both .178 m impellers were located .178 m off the tank bottom. The tests were run at a Reynolds number of approximately 200. An acid or base tracer is injected from a pressurized reservoir that is activated by a Tridak 250 dispenser. The acid (H_2SO_4) tracers and base (NaOH) tracers were mixed with glycerine to minimize density differences between the tracer and the fluid. A 10 ml. tracer was used at a 30% solution. Fig. 3, 4 and 5 were taken at 20, 40 and 60 seconds after the acid tracer was injected. The reduction of color shows (with the phenolphthalein indicator) the areas of decreased pH levels. The photos show a much faster blend time for the A410 impeller (left) compared to the standard marine impeller (right). Also seen in Fig. 5 is a stratified, unmixed layer beneath the marine impeller.

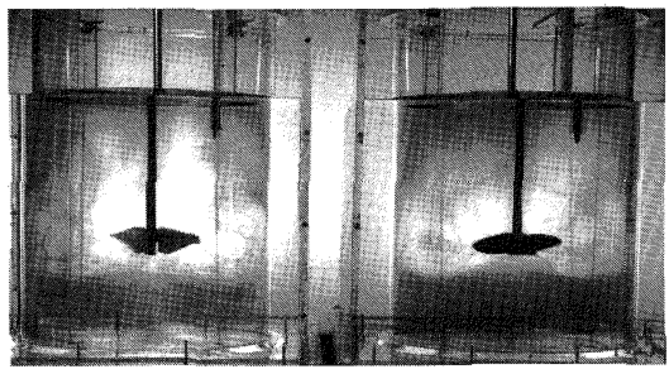

FIG.3 20 SEC.

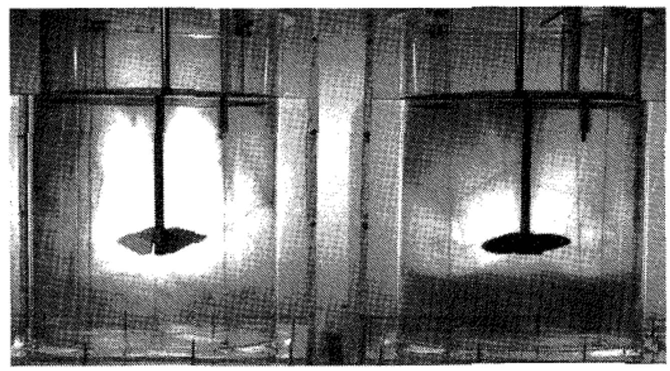

FIG.4 40 SEC.

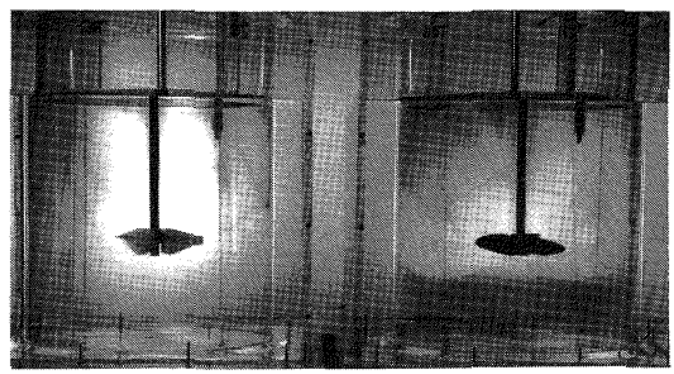

FIG.5 60 SEC.

In the transitional flow regime an axial impeller looses its effectiveness to pump in the axial direction. This occurs initially at the hub. It will be described in more detail in the laser doppler velocimeter (LDV) measurements below. Therefore, it is important that the inside of the impeller near the hub pump as much as possible. The way to accomplish this is to have an extremely high twist on the blade, i.e. the difference in blade angle between the tip of the impeller and the blade angle at the hub. The angle of the blade is measured from the chord of the airfoil blade section relative to the horizontal. Fig. 6 shows results of blending experiments conducted as a function of twist angle from the tip to 0.4 radius. It shows a large reduction in blend time as the twist angle increases. Illustrated in Fig. 6 is a sharp reduction (improvement) in blend time from conventional axial flow impellers that have twist angles in the range of 15° compared to a twist angle greater than 30°. Thus, the A410 impeller, with a twist greater than 30°, is able to pump more near the hub than a standard marine impeller. As we'll see later, the A410 impeller still experiences a reduction in axial flow as it approach the laminar region. Even with this reduction, it has sufficient pumping action near the hub to prevent stratification as was seen in the above Fig. 3, 4 and 5.

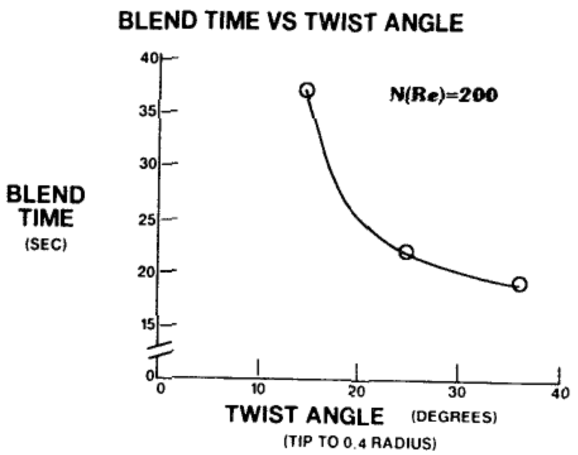

FIG.6

It is extremely important to have a contoured airfoil shaped impeller where complete freedom is available to change the attributes of the blade, i.e. twist, camber, thickness, etc.

In the development of the A410 impeller tufts were used to critically examine the flow and separation on the surfaces of the blade. The tufts or threads on the blades were examined with a Hi Band 8mm video with a 1/2000 shutter speed.

An example of an impeller with high twist that is not a true airfoil shape is called the A210 Impeller. The highly flow efficient A310 impeller with a twist angle of 16° can be compared to the A210 impeller. The A210 impeller has the same flow number as the A310 impeller (0.56) but it has a 0.53 turbulent power number compared to a 0.30 power number for the A310. The A210 impeller has a twist of 45° compared to the A310 twist of 16°. This high twist as well as other airfoil differences requires the A210 to consume 77% more power at the same flow. This example illustrates the need to use extreme care when increasing the twist of an impeller. This paper shows that the A410 has high twist for blending in *the transitional flow regime as well as high flow* efficiency in the turbulent regime. Characteristics of various impellers are described by Weetman, et. al.[1]. Additional discussions on impellers operating in the transition region is discussed in Weetman, et. al.[2].

LDV MEASUREMENTS

Measurements of fluid velocities have been performed using a dual channel laser doppler velocimeter (LDV). Three laser beams shown in Fig. 1 are generated by a Dantec 55X two-color laser doppler velocimeter. It measures two velocity components simultaneously and is mounted on a computer-controlled, three axis traversing mechanism that allows a complete scan of a mixing tank. Measurements are collected via back-scattering, with both receiving and transmitting optics in the same module. This eliminates the need to re-align the receiving optics at each measurement point and allows an automated computer-controlled operation. This laboratory is described in more detail by Weetman[3].

Fig. 7 shows velocity vectors in the RZ plane for the A410 composite impeller. These measurements were taken in a 0.445 m (17.5 inch) diameter tank with a 0.457 m. (18 inch) liquid level. The impeller diameter is 0.178 m (7 inch). The velocity vectors emanate from the horizontal and vertical scan lines. The axes in the figures are the tank centerline and the bottom half of the tank. The vertical line near the tank wall represents the width of the four baffles. The off-bottom height of the impellers is 0.178 m (7 inch). In Fig. 7 the flow diagrams were measured in the turbulent range, i.e. Reynolds number = 2.2 x 10^5. The Reynolds number, the ratio of inertia forces to viscous forces, for mixing impellers is calculated as:

VELOCITY VECTORS IN R-Z PLANE

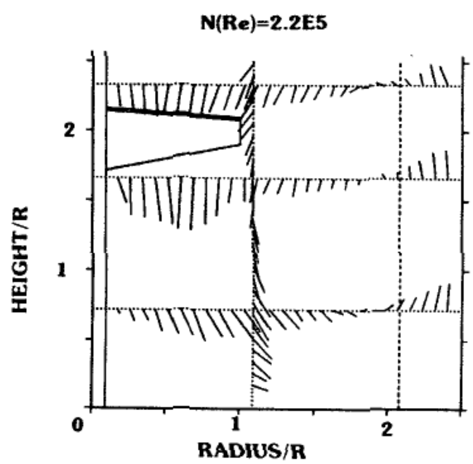

FIG.7

$$N_{Re} = \rho \; ND^2/\mu$$

D = Impeller Diameter (m)
N = Impeller Speed (rps)
ρ = Density (Kg/m^3)
μ = Dynamic viscosity (Ns/m^2)

As the Reynolds number decreases, the fluid resistance to flow increases causing the axial impellers' discharge flow to become more radial. In the limit of laminar flow, the discharge flow from an axial impeller is radial. Examining Fig. 8 and 9, the progression of axial to radial flow of axial flow impellers is shown. Fig. 8 shows the flow discharge angle at a Reynolds number of approximately 700 and Fig. 9 shows it at a Reynolds number of approximately 200.

VELOCITY VECTORS IN R-Z PLANE

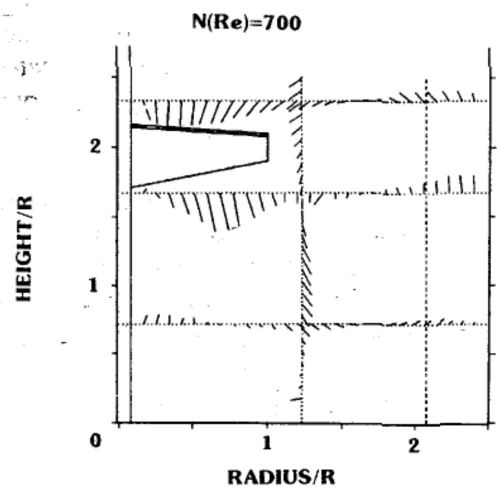

FIG.8

VELOCITY VECTORS IN R-Z PLANE

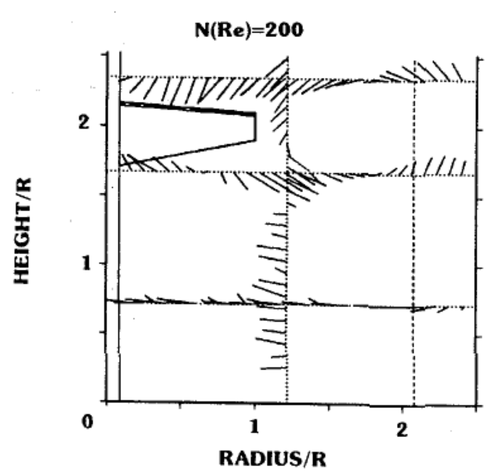

FIG.9

The test measurements at the lower Reynolds numbers (700 and 200) were conducted in glycerine, while tests at the higher Reynolds numbers were done in water. Care is needed to obtain good measurements in higher viscosity materials like glycerine. To obtain quality signals from the LDV, the glycerine needs to be kept free of contaminates. Obviously, with glycerine's viscosity sensitivity to temperature, a tight control of temperature also needs to be maintained. The power number and flow number versus Reynolds number for the A410 are shown in Fig. 10. The power number curve has the classical shape of a flat minimum in the turbulent range and then increases as the Reynolds number decreases (or with increasing viscosity). A change (increase) in power number in the transition region is also observed with a change (decrease) in flow number as shown in Fig. 10. As the load on the impeller increases due to the viscous nature of the fluid, the fluid velocity entering the impeller decreases. This causes an increase in angle of attack to the blade and therefore the power number will increase. *Also, increased viscous drag on the blades* contributes to a further increase in power number. As the flow around the impeller blade becomes laminar, the airfoil characteristics of the blade that produce lift is diminished. With the decreasing lift (or thrust) the axial flow decreases as observed in the flow numbers.

Np & Nq vs REYNOLDS NUMBER

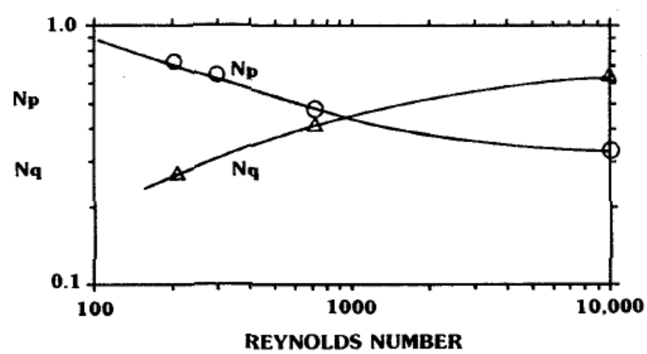

FIG.10

It is difficult to compare different impellers that have different shapes in the transition region. Fig. 9 shows that the outlet flow is beyond the impeller diameter. This is because the outlet flow has a radial and an axial component in the transitional flow regime. When comparing different impellers, care is required in measuring the outlet flow number. A larger (diameter and/or height) impeller occupies more effective volume in the tank. Therefore, the flow number alone may not accurately describe its process performance. It may be necessary to measure *the flow at the same* relative position on the tank. The flow numbers in Fig. 10 include the radial as well as the axial outlet flow.

CFD RESULTS AND LDV COMPARISONS

Computational fluid dynamics is one of the tools used in the development of the A410 transitional flow mixing impeller. Background on the commercial code used and on some of the techniques employed are described by Hutchings et. al.[4]. The program used is FLUENT by creare.x, Inc. Presented here are velocity fields from the CFD computations for the turbulent flow conditions and for a Reynolds number of 200.

The results obtained at a Reynolds number of 2×10^5 are presented in Fig. 11 through 14. These are for the same conditions that were discussed previously for a 0.445 m (17.5 inch) diameter tank. Fig. 11 shows the velocity vectors for the entire tank and these compare favorably with those of Fig. 9. Obviously, the advantage of the CFD is that one is able to obtain other comparisons after one has obtained the solution of the velocities. As shown in Fig. 12, 13 and 14, the streaklines, kinetic energy contours and turbulent energy dissipation are presented respectively. These results are based on the k-ε turbulent model for the Navier-Stokes Equations. These analyses are three-dimensional with the input for the impeller from the outlet velocity profile as measured by the LDV. The input using the maximum values of the velocity components in the flow field that occur at the impeller outlet is advantageous.

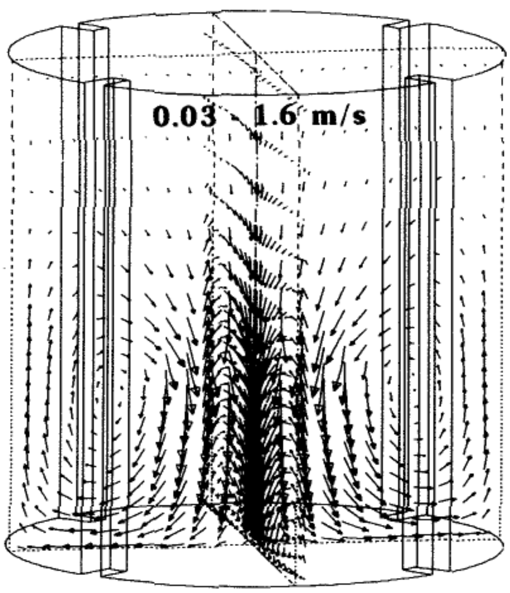

FIG.11 VELOCITY VECTORS NREY=2E5

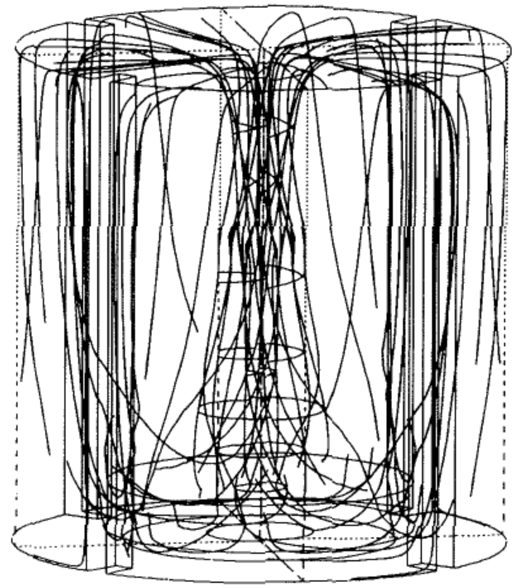

FIG.12 STREAKLINE NREY=2E5

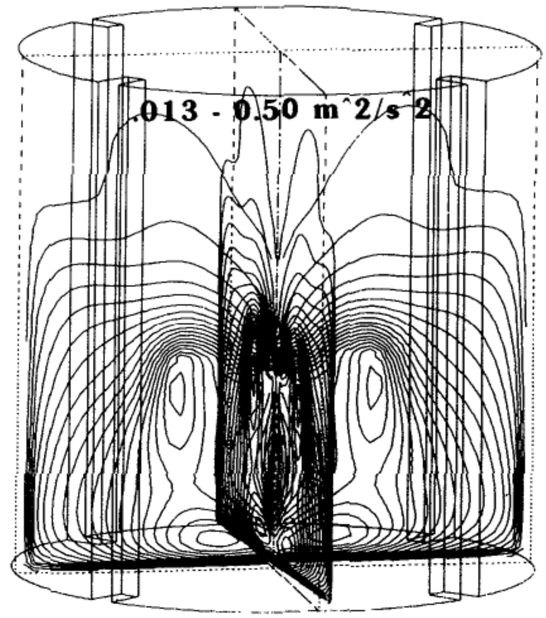

FIG.13 KINETIC ENERGY NREY=2E3

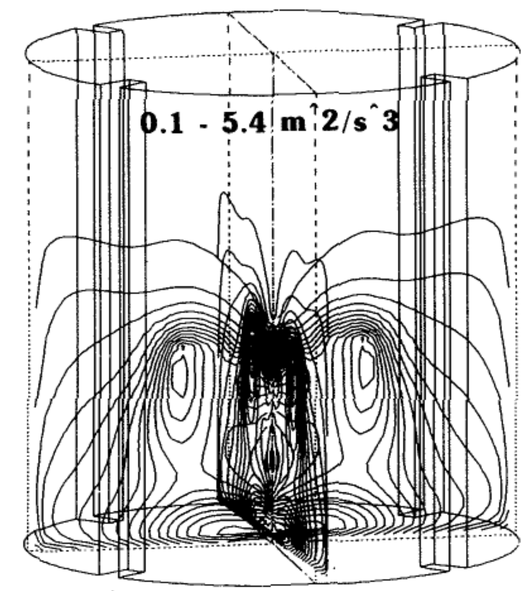

FIG.14 EDDY DISSIPATION NREY=2E5

The results obtained at a Reynolds number of 200 are shown in Fig. 15 and 16. These figures show the velocity vectors and streaklines for the A410 Impeller. Here again the input into this three-dimensional model is from the LDV velocity data underneath the impeller. The streaklines showing the two circulation patterns are shown in Fig. 16. These are contrasted to the streaklines in the turbulent condition shown in Fig. 12.

A model of the blending experiment where the dye tracer was injected at .383 m off bottom, .146 m radius and 0.68 radians into the tank was calculated with the CFD. Fig. 17 through 19 show the progression with time of the contours of mass fraction of the tracer or interjected specie. The times from injection are 10, 30 and 60 seconds.

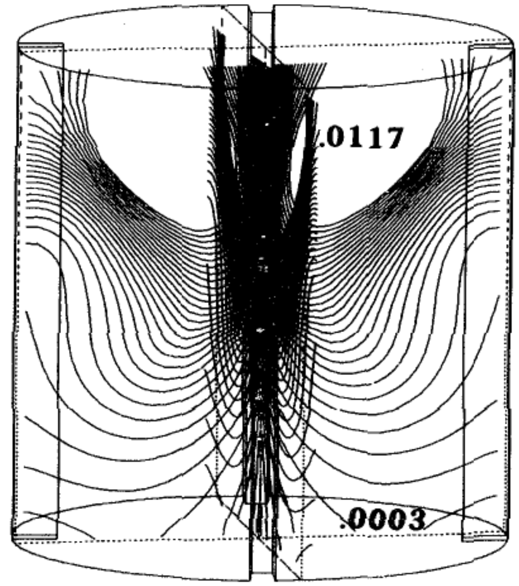

FIG.17 MASS FRACTION 10 SEC.

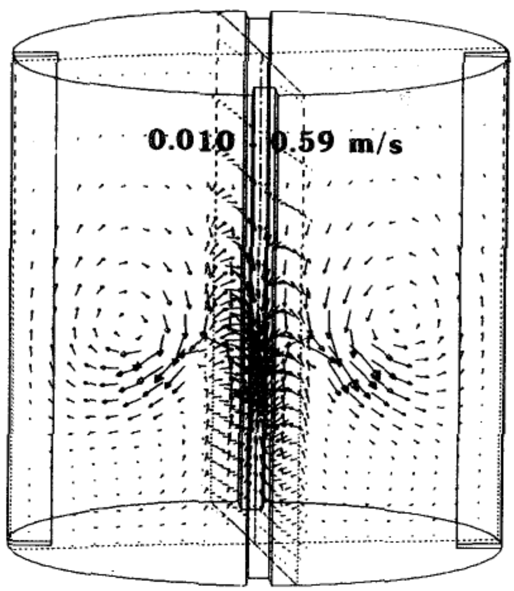

FIG.15 VELOCITY VECTORS NREY=200

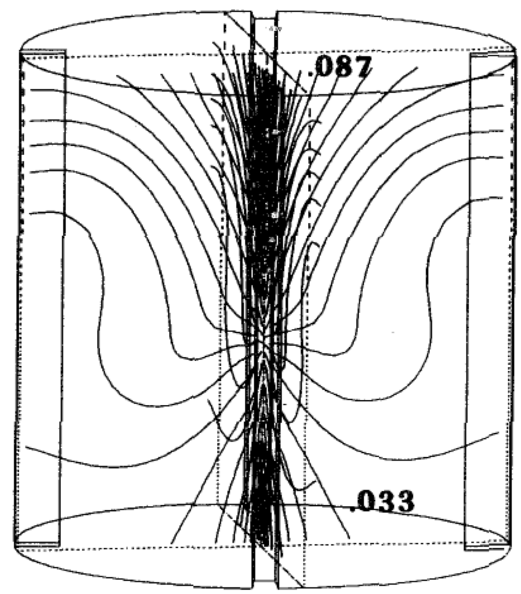

FIG.18 MASS FRACTION 30 SEC.

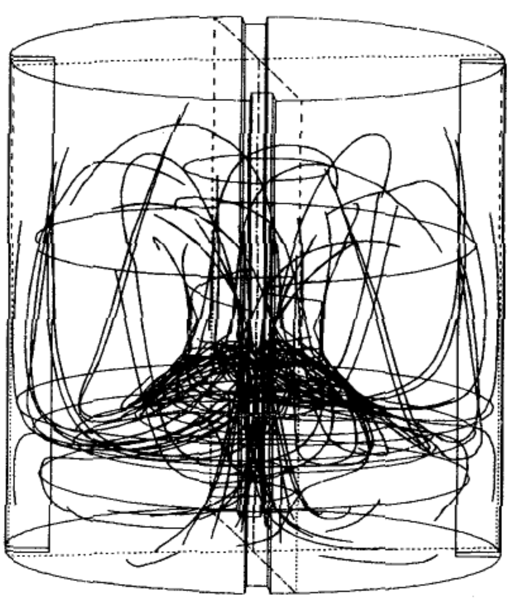

FIG.16 STREAKLINES NREY=200

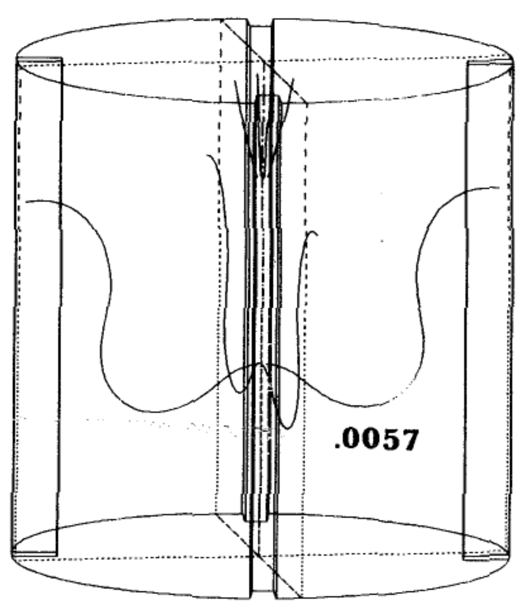

FIG.19 MASS FRACTION 60 SEC.

The progression shows over-saturation at the top of the tank followed by spreading out of the contours. The mass fraction contour lines are at 0.0006 intervals. Three locations in the tank were noted and the tracers for the mass fraction versus time was plotted in Fig. 20. The three positions were at 11, 70 and 383 mm from the bottom of the tank, at a radius of 15 mm and at an angle of .05 radians. Fig. 20 shows the overshoot of the highest position (383 mm) at the top of the tank compared to the other two positions. As seen in this figure, the three positions are almost at the same concentrations at 60 seconds. This is in good agreement with the blending study noted earlier that obtained uniformity in approximately 60 seconds.

CONCLUSIONS

This paper presents the effectiveness of the new A410 impeller in the transitional and turbulent flow regimes. Results show the blending time reduction using a high twist which enables the impeller to pump effectively near the hub. Care is required in incorporating a large twist on the impeller blade.

Results from LDV measurements showed the different flow characteristics of the A410 in the turbulent and transitional flow regimes. Also presented were blending studies showing the characteristics of blending in the transitional flow regime where laminar regions are required to be mixed. The advantages of using CFD computations to examine the entire flow field were received. Good agreement was obtained between the CFD computations and the LDV measurements for both the flow measurements and the blending experiments.

MASS FRACTION VS TIME

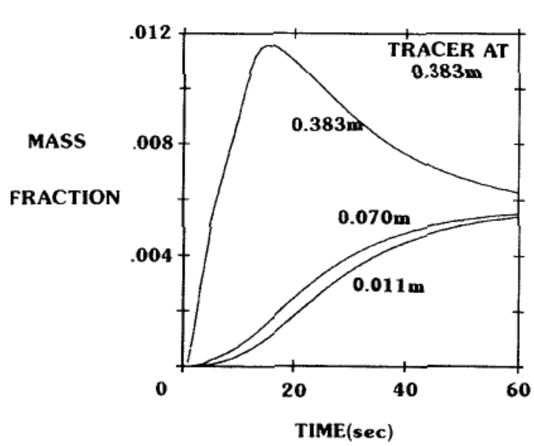

FIG.20

NOMENCLATURE

A110	= Marine 1.0 Pitch Impeller
A210	= High Twist Impeller
A310	= Fluidfoil Impeller
A410	= Fluidfoil Composite Impeller
C	= Impeller Off-Bottom (m)
D	= Swept Impeller Diameter (m)
N	= Impeller Speed (rps)
N_Q	= Q/ND^3
N_P	= $P/\rho N^3D^5$
N_{Re}	= $\rho N D^2/\mu$
Q	= Outlet Flow (m^3/s)
P	= Power (W)
T	= Tank Diameter (m)
H	= Liquid Height (m)
ρ	= Density (kg/m^3)
μ	= Viscosity (Ns/m^2

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