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# An experimental method to evaluate global pumping in a mixing system: Application to the Maxblend™ for Newtonian and non-Newtonian fluids

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## HIGHLIGHTS

- ▶ Use of a decolorization method to evaluate the global flow number of an impeller.
- ▶ Maxblend™ impeller most efficient in the transitional regime for Newtonian fluids.
- ▶ No impact of the rheological behavior in the transitional regime for the Maxblend™ impeller.
- ▶ Appearance of pathological mixing situations in the laminar regime with the Maxblend™ impeller.

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## ABSTRACT

This work introduces an experimental method to determine the global pumping capacity of an impeller in a transparent vessel using a decolorization method. Contrary to commonly used experimental methods such as Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV), this new inexpensive and easy-to-use method can be employed to quickly fill the lack of data in the literature about the impact of impeller geometry on the pumping efficiency. The new method was first applied to three well-known mixing systems and a Newtonian fluid to assess its reliability and accuracy: a six-blade Rushton turbine (RT), a pitched blade turbine (PBT) with four 45° blades, and a three-blade hydrofoil propeller (HP). It was then applied to evaluate the global pumping capacity of the Maxblend™ impeller in the case of Newtonian and non-Newtonian fluids. The results obtained show that, for the Newtonian fluid, the Maxblend™ impeller performs better than the other three impellers in the transitional regime, and it has a similar pumping capacity than that of the PBT and the RT in the complete turbulent regime. In this case, it was also noticed that the HP is outperformed by the other tested impellers over the entire range of Reynolds numbers. Moreover, it was observed that the extreme shear-thinning behavior of the non-Newtonian fluid used does not significantly affect the pumping generated by the Maxblend™ impeller in the transitional regime, that is for Reynolds number larger than 80. A global flow number, normalized by the power draw, is also introduced. Based on this criterion, the HP is shown to perform the best in the fully turbulent regime. Mixing times evaluated by means of the decolorization method also reveal that the Maxblend™ impeller is the most efficient for all regimes.



## 1. Introduction

Three important parameters are commonly used to characterize impeller performance: the power consumption, the mixing time and the pumping capacity. The power consumption is the amount of energy necessary to rotate an impeller at a given speed in a fluid. The mixing time is the time needed to achieve a certain degree of homogeneity in a stirred tank. The pumping capacity measures the ability of an impeller to discharge a fluid in a stirred tank. There are many experimental techniques available to determine power consumption and mixing time. The pumping capacity is more difficult to evaluate because measuring the flow field is not straightforward. Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV) have been used for this purpose [1], but these techniques remain expensive and rather difficult to setup and utilize.

Flow fields can also be obtained using computational fluid dynamics (CFD). Impellers have specific shapes and impart characteristic flow patterns. Therefore, methods have been developed to calculate their pumping capacity. One common technique is to create an envelope around the impeller and calculate the amount of flow exiting (or entering as both amount are equal) this envelope [2]. Another method is to consider the flow going through

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**Nomenclature**

| | |
|---|---|
| $a$ | Carreau–Yasuda parameter (–) |
| $c$ | bottom clearance (m) |
| $D$ | impeller diameter (m) |
| $H$ | tank height (m) |
| $m$ | consistency index (Pa s$^n$) |
| $M$ | mixing index (%) |
| $n$ | power law parameter (–) |
| $N$ | rotational speed (rotations s$^{-1}$) |
| $P$ | power (W) |
| $Q$ | flowrate (m$^3$ s$^{-1}$) |
| $t$ | time (s) |
| $T$ | tank diameter (m) |
| $M_m$ | measured torque (N m) |
| $M_r$ | residual torque (N m) |
| $w$ | baffle diameter (m) |

*Greek letters*

| | |
|---|---|
| $\dot{\gamma}$ | shear rate (s$^{-1}$) |
| $\mu$ | Newtonian viscosity (Pa s) |
| $\eta_{(\dot{\gamma})}$ | generalized non-Newtonian viscosity (Pa s) |
| $\eta_0$ | zero-shear rate viscosity for the Carreau–Yasuda model (Pa s) |
| $\lambda$ | relaxation time for the Carreau–Yasuda model (s) |
| $\rho$ | density (kg m$^{-3}$) |
| $\omega$ | vorticity (s$^{-1}$) |

a horizontal and circular plane close to the impeller [3,4]. A third technique is to use a vertical and cylindrical surface around the impeller. This surface can be at a given distance between the wall of the tank and the edge of the mobile [5], or moving between them, the maximum flow value being then used to calculate the pumping capacity of the impeller [6]. Finally, when close clearance impellers are used, such as a helical ribbon or the Maxblend™, the flow can be investigated by means of a set of horizontal planes placed along the height of the tank, and the pumping can be quantified using this information [7,8].

The purpose of this paper is to propose a versatile, inexpensive and global technique to measure experimentally the pumping capacity of an impeller. This technique, which relies on a decolorization method, considers the whole volume of the tank. Therefore, it is not dependent on the location of observation planes or envelopes as in the case of the above-mentioned techniques. The method, which is fully described in the next section, is first assessed for its reliability and accuracy using results obtained for three common impellers (a six-blade Rushton turbine, a pitched blade turbine with four 45° blades, and a hydrofoil propeller) and a Newtonian fluid. Next, using the same conditions, the global pumping capacity of the Maxblend™ impeller is compared to that of the other three impellers. Note that the Maxblend™ impeller has more than a thousand applications in the Asian chemical industry. It is known to be a versatile agitator that maintains excellent performance over a wide range of viscosities [9,10]. A quantitative comparison with more conventional impellers is then of interest. Afterwards, the experiments with the Maxblend™ are repeated with a highly non-Newtonian fluid and the results are then compared with that of the Newtonian case. Finally, mixing times for these four impellers are evaluated with the decolorization method and compared for the sake of completeness.

## 2. Materials and method

### 2.1. Equipment

The four mixing systems used are depicted in Fig. 1. Experiments involving the Maxblend™ (wedge model) were conducted in a cylindrical two-baffled 35.4 L tank with a semi-ellipsoidal bottom and an open top. A cylindrical fully-baffled flat-bottom 3.6L vessel was used for the RT, PBT and HP experiments. These two tanks are made in polycarbonate. The dimensions of these mixing systems are given in Table 1.

### 2.2. Fluids

Both Newtonian and non-Newtonian fluids were used in the experiments. Three Newtonian fluids were employed: aqueous solutions of glucose (Glucose Enzone 62DE, Univar, viscosity from $\mu$ = 32 to 0.1 Pa s) and aqueous solutions of Glycerol (Univar, viscosity from $\mu$ = 1 to 0.02 Pa s), which covered the laminar and transitional regimes, as well as water to reach the turbulent regime. The rheological properties of theses fluids were measured using viscosimeters with integrated temperature control (Bohlin Visco88 and TA-Instruments AR2000). The solution densities were obtained by weighing 10 mL of each solution (APX 402 scale, Denver Instrument).

An aqueous solution of 24–26 wt% ammonium laureth sulfate (Steol CA-230-D) was used as the non-Newtonian fluid. It is highly shear-thinning and a four-parameter Carreau–Yasuda model can be used to characterize its rheological behavior:

$$\eta(\dot{\gamma}) = \eta_0[1 + (\lambda\dot{\gamma})^a]^{\frac{n-1}{a}}, \quad (1)$$

where $\eta_0$ is the zero-shear rate viscosity, $n$ the power-law slope, $\lambda$ the characteristic time of the fluid such that $1/\lambda$ represents the shear rate value at which the transition between the zero-shear rate viscosity and the power-law region begins, and $a$, a parameter that adjusts the breadth of this transition.

The rheological properties of this fluid can be chemically modified by adding sodium chloride. The rheogram in Fig. 2 shows the effect of the sodium chloride concentration on the shear viscosity while the corresponding Carreau–Yasuda parameters are grouped in Table 2. The salt concentration does not affect the power law index, which remains constant at $n$ = 0.05. However, increasing the salt concentration exponentially raises the zero-shear rate viscosity ($\eta_0$), the characteristic time of the fluid ($\lambda$) and the breadth of the transition (a). The operating shear rate ($\dot{\gamma}$) range of the Maxblend™ impeller extends from 2.5 to 30 s$^{-1}$, as estimated by the product of the Meztner–Otto constant ($K_s$) and the Maxblend™ rotational speed (10–120 rpm) [11]. A $K_s$ value of 15 was estimated by Fradette et al. [12] for a power-law fluid with an index equal to 0.1. This value is used here because the $n$ values are in the same range. It can be seen in Fig. 2 that, within this operating range of $\dot{\gamma}$, the higher the salt concentration, the more significant the shear-thinning effects. Note that small amplitude oscillatory shear test described in previous work [13] revealed that these solutions can be considered inelastic.

Finally, both Newtonian and non-Newtonian solutions were prepared and poured in the tanks at least 24 h before the experiments to ensure that the solutions were bubble-free.

### 2.3. Methods

In mixing, the power consumption, the mixing time and the pumping capacity are represented in a dimensionless manner as a function of the Reynolds number. The Reynolds number