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Energy consumption to achieve macromixing revisited

A. Liné[a,b,c,*]

[a] Université de Toulouse, INSA, LISBP, 135 Avenue de Rangueil, F-31077 Toulouse, France
[b] INRA UMR792 Ingénierie des Systèmes Biologiques et des Procédés, Toulouse, France
[c] CNRS, UMR5504, F-31400 Toulouse, France

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ABSTRACT

In this paper, macromixing of Newtonian fluids is analyzed. Mixing time and power number are commonly used to compare different blending systems in terms of macromixing. In this paper, the concept of mixing time energy consumption, defined by the product of the power consumption times the mixing time, is revisited since this concept seems appropriate to compare different mixers as far as macromixing is considered. In addition, different expressions of circulation and diffusion mixing times in laminar and turbulent regimes are considered. Finally, mixing time energy consumption is applied to data issued from Houcine et al. (2000), who compared different mixing systems in terms of power versus mixing time in the turbulent regime.

1. Introduction

Mixing in mechanically agitated tank can be analyzed at different scales: a macroscopic scale, related to macromixing or blending of different species, without chemical reaction and a microscopic scale, related to micromixing in the case of chemical reactions with rapid kinetics. The macromixing is in correlation with the total volumetric flow rate of agitated liquid (Fořt et al., 2007). It is controlled primarily by overall bulk or convective flow consisting of large scale motions and secondly by turbulent diffusion that may contribute to reduce heterogeneities. Micromixing is related to smallest scales of turbulence and molecular diffusion. The micro-mixing is out of the scope of this paper.

In this paper, blending of liquids of equal density and viscosity is considered, involving neither chemical reaction nor interphase mass transfer. The goal of mixing is thus to minimize non-uniformities within the vessel. The flow characteristics of mixing tank affect the rate of homogeneization of the liquid (Grenville and Nienow, 2003; Fořt et al, 1971; Fořt and Jirout, 2011). As far as blending efficiency is concerned, blending time plays a key role (Prochazka and Landau, 1961); thus mixing time approaches will be reviewed. Mixing time is usually measured in two steps: (i) a passive scalar is injected locally and during a short time and (ii) starting from the injection time, measure the time required to achieve a certain degree of spatial homogeneity of concentration in a whole vessel. The quality of mixing will depend on the shape of the tank and the choice of the impeller as well as its speed of rotation.

The comparison of different kinds of mixers used to achieve macromixing is usually based on mixing time t_M (s) and power consumption P (W). Many correlations were proposed in the literature to express dimensionless mixing time and power number N_P. In textbooks on mixing, these two parameters are mainly considered to compare the different mixing systems in terms of macromixing. However, if considered independently these two parameters may be inadequate. The goal of this paper is to revisit the concept of energy consumption E (kW h) for macromixing. The energy consumption E is defined by the product of the power consumption P times the mixing time t_M. Such a parameter makes sense since it quantifies the power needed to achieve

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[*] *Corresponding author at*: Université de Toulouse, INSA; LISBP; 135 Avenue de Rangueil, F-31077 Toulouse, France. Tel.: +33 561559786.
E-mail address: alain.line@insa-toulouse.fr

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Nomenclature

C	instantaneous concentration (concentration unit)
$\langle C \rangle$	spatially averaged concentration (concentration unit)
C_L	coefficient (dimensionless)
C_μ	coefficient (dimensionless)
C^*	concentration ratio (dimensionless)
D	impeller diameter (m)
Diff	diffusivity ($m^2\,s^{-1}$)
E	mixing time energy (J)
H	liquid height (m)
k	turbulent kinetic energy ($m^2\,s^{-2}$)
L_0	characteristic length scale of circulation loop (m)
M	mass of liquid (kg)
N	impeller rotational speed (rps)
N_P	power number (dimensionless)
N_Q	discharge flow number (dimensionless)
P	power (Watt)
Pe	Péclet number (dimensionless)
Q	flow rate discharged by the impeller ($m^3\,s^{-1}$)
Re	impeller Reynolds number (dimensionless)
t	time (dimensionless)
T	tank diameter (m)
t_C	circulation time (s)
t_M	mixing time (s)
t_{MD}	diffusive mixing time (s)
U_0	circulation velocity associated to this large scale mean motion ($m\,s^{-1}$)

Greek symbols

$\langle \varepsilon \rangle$	averaged dissipation rate of kinetic energy ($m^2\,s^{-3}$)
$\dot{\gamma}$	rate of strain (s^{-1})
Λ	macro length scale (m)
μ	molecular dynamic viscosity (Pa s)
ν	molecular kinematic viscosity ($m^2\,s^{-1}$)
ν_t	turbulent kinematic viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
θ	dimensionless time (dimensionless)
T_Λ	macro time scale (s)
ϑ	volume of liquid (m^3)

macromixing, accounting for the mixing time duration. This energy consumption seems thus appropriate to compare different blenders as far as macromixing is considered.

In this paper, only well mixed tanks are considered, both in laminar and turbulent flow patterns. The very low Reynolds numbers corresponding to weak secondary circulation flow are out of the scope of this paper.

1.1. *Mixing time*

The mixing time is the time between the local and instantaneous injection of a volume of passive tracer until the vessel content has reached a "certain" degree of uniformity, in terms of tracer concentration. Many empirical correlations of mixing time were published in the literature. Most of the correlations are based on non-dimensional mixing time defined as $t_M\,N$, where, N is the impeller speed (s^{-1}), and are expressed as:

$$t_M\,N = A\,Re^a \qquad Re = \frac{\rho N D^2}{\mu} \tag{1}$$

given the Reynolds number of the mixing tank Re, where, D is the impeller diameter and ρ and μ are the density and dynamic viscosity of the Newtonian fluid. In turbulent regime (low viscosity liquids, $Re > 10^4$), the exponent is close to 0, whereas in intermediate regime the exponent may be close to -1 ($10^4 > Re > 10^3$); however, the exponent is again close to zero in laminar regime (high viscosity liquids, $Re < 10^3$ (see Harnby et al., 2000, Fig. 8.9, p 153). The product $t_M\,N$ is close to 1–2 in turbulent flow and close to 3–4 in laminar flow.

Novak and Rieger (1975) were proposed to compare homogenization efficiency of various impellers for mixing of viscous liquids in terms of correlation:

$$\frac{P\,t_M^2}{\mu\,D^3} = f\left(\frac{D^2\,\rho}{\mu\,t_M}\right) \tag{2}$$

Grenville and Nienow (2003) proposed a correlation for blending time to reach 95% homogeneity in turbulent flow and batch stirred tank, as:

$$N_P^{1/3}\,t_M\,N\left(\frac{D}{T}\right)^2 = 5.2 \tag{3}$$

Indeed, the correlation proposed by Novak and Rieger can easily be transformed in the form of Grenville and Nienow expression.

Generally speaking, as previously established by van de Vusse (1955a,b), the mixing time in a stirred tank is the sum of the time of mixing by convection, related to large circulation loops associated to the transport by the mean flow plus the time of diffusion, related to molecular diffusion in laminar flow or turbulent one in turbulent flow.

1.1.1. *Circulation time t_C*

The circulation time is defined as the ratio of the volume of fluid ϑ in the vessel divided by the flow rate Q discharged by the impeller ($t_C = \vartheta/Q$). The circulation flow rate Q can be determined by the discharge flow number N_Q of the impeller given by the manufacturer $\left(N_Q = Q/N D^3\right)$. Thus, in standard configuration ($T = 3\,D$, $H = T$), the circulation time is given by:

$$t_C = \frac{27\,\pi}{4\,N\,N_Q} \tag{4}$$

Moreover, two characteristic length and velocity scale can be introduced to rewrite the circulation time $t_C = L_0/U_0$ where, L_0 is the characteristic length scale of circulation loops related to the mean flow pattern generated by the impeller and U_0 is a circulation velocity associated to this large scale mean motion.

1.1.2. *Macromixing time t_M*

Experimentally, a classical method of measuring macromixing time is based on injection of a small volume of passive tracer and measure of concentration versus time; injection and measurement are performed in two distinct locations in the vessel. The plot of concentration C versus time t can exhibit different shapes; for sake of simplicity, we will consider a characteristic shape that is valid both in turbulent and laminar regimes, and usually more pronounced in presence of draft tube (Fig. 1).