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The study of influence of a rotating magnetic field on mixing efficiency

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ABSTRACT

The study presents the results of an experimental analysis of the mixing process under the influence of a rotating magnetic field (RMF). Dimensionless correlations are proposed to predict the power consumption and mixing time for the analyzed mixing system. The results showed that the mixing behavior of the RMF mixer may be described by means of the dimensionless mixing energy as the product of the power input and the mixing time. The effects of various liquids (aqueous solutions of NaCl brine; distilled water; Herstin-Schramm medium) on these mixing parameters are approximated mathematically. The obtained experimental results suggest that the application of the RMF enables the efficient mixing of liquids.

Contents

1. Introduction

Static or alternating magnetic fields may be used to augment the process intensity instead of the mechanical mixing [11,12,14]. The alternating magnetic field (AMF), e.g. the rotating magnetic field (RMF), may be used as a non-intrusive stirring device and it can be engineered to provide any desired pattern of stirring [32,34]. The application of this kind of magnetic field (MF) to augment the transport process intensity was discussed in the relevant literature [43,44,41].

The mixing time represents one of the most useful criteria for characterization of the mixing system design and optimization of the mixing process [20,19]. The parameter contains information about hydrodynamics and mixing within the mixer and can be useful for the scaling up [3]. The mixing time is often used as an indicator of the effectiveness of the mixing system or a parameter describing the hydrodynamics in the mixing vessel [24].

The cost of the mixing process is depended on the power consumption [2]. The parameter may be applied to characterize the energy-consumption of technological processes [41]. As a consequence power consumption cannot be solely the best

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Nomenclature

Symbols
B Magnetic field vector, $kg\,A^{-1}\,s^{-2}$
D Diameter of container, m
f Frequency of electrical current, s^{-1}
H^* Dimensionless height of container, –
l Characteristic measurement, m
U Voltage, V
I Current intensity, a
P_{RMF} Active power, $J\,s^{-1}$
R^* Dimensionless radius of container, –
t_{95} Mixing time, s
S Skin effect, –
T Temperature, °C
U Voltage, V
$w_\varphi|_{max}$ Maximum peripheral velocity of the mixed liquid under the RMF action, $rad\,s^{-1}$

Greek letters
η Dynamic density, $Pa\,s^{-1}$
ν Kinematic viscosity, $m^2\,s^{-1}$
$\boldsymbol{\nu}_m$ Magnetic viscosity, $m^2\,s^{-1}$
ρ Density, $kg\,m^{-3}$
μ_m Magnetic permeability of the vacuum, $kg\,m\,A^{-2}\,s^{-2}$
σ_e Electrical conductivity, $A^2\,s^3\,kg^{-1}\,m^{-3}$
τ Time, s
ω_{RMF} Angular velocity of RMF, $rad\,s^{-1}$
Ω_{RMF} Angular velocity of liquid under the action of the RMF, $rad\,s^{-1}$

Dimensionless numbers
$(e_{RMF})^*$ Dimensionless mixing energy
$Po_{RMF} = \frac{P_{RMF}}{(\Omega_{RMF} D)^3 D^2 \rho}$ Newton number for the RMF mixing system
$Re_{RMF} = \frac{\Omega_{RMF} D^2}{\nu}$ Reynolds number for the RMF mixing system
$\Theta = \frac{t_{95}\nu}{D^2}$ Mixing time number

Subscripts
avg Averaged
max Maximum

Abbreviations
BC Bacterial cellulose
HS Herstin-Schramm medium
MF Magnetic field
RMF Rotating magnetic field
SMF Static magnetic field

criterion to evaluate the mixing efficiency [17]. In order to acquire a more complete description of the mixing efficiency, the mixing energy (or homogenization mixing) may be calculated [30]. It is defined as a product of the mixing time and the corresponding power dissipated Ochieng and Onyang, 2008.

The main aim of the present work was to investigate the possibility of mixing a system using an RMF generator, a device used for mixing of various types of liquids, including water and NaCl solutions. The paper reports on a study which is connected with the application of the tested MF to mix Hestrin-Schramm medium [13]. The medium is commonly used for cultivation of bacterial cellulose (BC). Exopolysaccharide produced by various species of bacteria has been found to have a chemical formula of plant cellulose but with unique physical properties, e.g. high crystallinity, high degree of polymerization, high purity, high mechanical and tensile strength, high water capacity, moldability, porosity, and high Young's modulus [5]. Bacterial cellulose (BC) is biocompatible and is thus becoming a promising material for several applications such as a scaffold for tissue engineering of cartilages [46], blood vessels [22], as well as for artificial skin [8]. Bacterial cellulose (BC) is also used in technological applications [47] and food industry [18]. However, its high cost and low-yield production have limited its commercial application and industry potential. The increase of productivity may be achieved in several ways through using new or modified microorganisms' strains or developing new bioreactors and optimizing operation strategies [42]. Recently, increasing attention has been directed towards bio-magnetic stimulation of microorganism using various types of MFs [15]. It should be noticed that the HS medium contains various charged particles, e.g. Na^+, K^+, Mg^{2+}, NH^{4+} and the associated anions, e.g. sulphate, phosphate and chlorate, along with the microbial cells that contain various components including ionic solutions, proteins and lipids. The RMF interacting with an electric charge can cause microscopic mixing which influences the transfer process between the cell surface and the liquid phase [1,9,16].

Therefore, the main aim of the study was to analyse the interaction of the applied MF with liquids characterized by different values of electrical conductivity (from 0.05 to 14 $A^2\,s^3\,kg^{-1}\,m^{-3}$). One of the advantages of rotating magnetic field (RMF) is that it can be used to mix liquids applied in biotechnology (i.e. HS medium). The application of a non-instructive stirring device with the RMF generator can be engineered to provide a desired patter of stirring. Another aim was to describe the influence of RMF on the mixing process by means of the relation between the dimensionless mixing time and Reynolds numbers. The effect of the magnetically assisted mixing system on the mixing process was defined by power consumption. Obtained parameter values were used to define the efficiency of the magnetically assisted mixing process using the mixing energy.

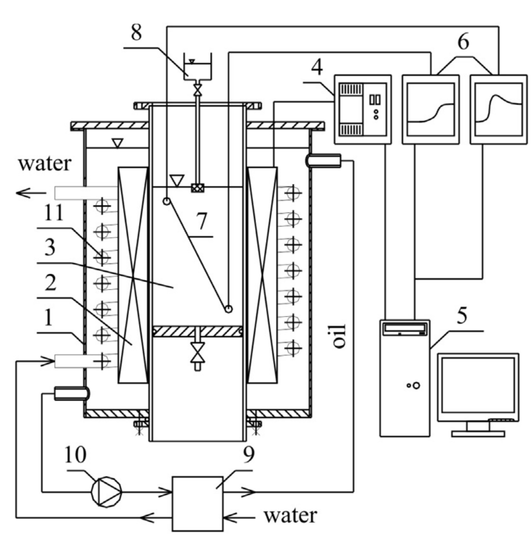

Fig. 1. Scheme of experimental apparatus: 1 – cooling jacket, 2 – RMF generator, 3 – vessel, 4 – a.c. transistorized inverter, 5 – personal computer, 6 – recorders (CX-701), 7 – electrodes, 8 – batcher, 9 – heat exchanger, 10 – pump, 11 – internal coil.