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Mixing studies in unbaffled stirred tank reactor using electrical resistance tomography

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ABSTRACT

Unbaffled stirred tanks are extensively used in chemical process industries for variety of applications including semi-batch reactions. In un-baffled stirred tanks, impeller rotation generates a vortex and reactants are added into this vortex. There is a growing interest towards understanding the mixing performance of such unbaffled stirred vessels. The present work is aimed at providing experimental results on mixing time and solid particle distribution inside an unbaffled vessel using electrical resistance tomography (ERT). A methodology for using ERT for characterizing vortex and mixing in unbaffled stirred vessel was established. The ERT was used to measure the mixing time with and without solid particles (glass beads, 250 μm) in a stirred reactor. In this study, ERT technique was effectively applied for imaging solid–liquid flow and developed suitable data processing methodologies. It observed that estimated liquid phase mixing time for Un-baffled vessel was more as compared to baffled vessel. Radial solid concentration profiles showed Gaussian distribution inside the vessel. The presented methodology of using ERT and experimental results will be useful for designing and estimating mixing and solid distribution in unbaffled stirred tanks.

1. Introduction

Un-baffled stirred tanks are being extensively used in chemical process industries for variety of applications such as crystallization and precipitation processes, mixing and reactions in manufacturing of fine and specialty chemicals and pharmaceutical processes. In un-baffled stirred tanks impeller rotation generates a vortex around rotating shaft. The rotational motion of liquid in absence of any motion in vertical direction is expected to be less effective for mixing compared to that obtained in baffled tanks. ‘Mixing’ is defined as the reduction of in-homogeneity in order to achieve a desired process results in desired time. The in-homogeneity can be one of concentration, phase or temperature and secondarily mass and heat transfer, reaction or product properties etc. In this work we have used Electrical Resistance Tomography (ERT) for quantifying mixing and solid distribution in unbaffled tank.

Hydrodynamics, mixing and solid suspension in baffled tanks have been widely investigated [5,17,20,26,27]. There are relatively few investigations of unbaffled tanks. In the absence of baffles, weak axial flows are generated which cause poorer mixing. If a free surface is present, a pronounced vortex is formed depending upon the rotational speed of the stirrer. Yet, there are cases in which the use of un-baffled tanks may be desirable such as crystallizers, where the presence of baffles may promote the particle attrition phenomenon. Vortex causes the liquid surface to be pushed up at tank wall and sucked down near the impeller shaft. This resultant suction forms a ‘whirlpool’ like vortex that entrains or draws the floating or slowly sinking solid particles into the liquid medium. Un-baffled vessels are also used for mixing solids in liquids in variety of food and other specialty chemicals applications. Thus, un-baffled stirred tanks, despite their poorer mixing performance with respect to baffled vessels, are of industrial interest as they provide significant advantages in selected applications, including a number of fine and specialty chemical processes.

In the present work focus has given towards the combination of un-baffled vessel and new upcoming technique i.e. ERT for the investigation of liquid phase mixing time and solid distribution inside un-baffled vessel. ERT technique was adopted here to obtain the mixture distribution across the cross-section of mixing vessel. Literature review, overall methodology of work, results and discussions are presented in following section.

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Nomenclature

T	tank diameter, m
D	impeller diameter, m
H	liquid height, m
Θ_{mix}	mixing time, s
N	impeller speed, rpm
K	proportionality constant
C	impeller clearance, m
X	solid loading, % v/v
g	gravitational acceleration, m/s^2
σ	standard Deviation
δ	homogeneity criteria in %.
C_i	Concentration at ith pixel
$\bar{C}$	mean concentration
N	number of pixels
$N\theta$	Dimensionless mixing time
SBP	sensitivity back projection,
STM	sensitivity theorem method,

Subscripts

s	solid
liq	liquid

2. Brief review of previous work

Conventional techniques for the mixing time measurement in stirred tank such as visual observations, de-colorization, PLIF, conductivity probe method, liquid crystal thermography mainly listed in available literature. Extensively used visual observation technique provides a crude approximation of the mixing time in most of the vessels with many limitations even though as it is a quick estimating mixing time method. Colorimetric method is an image analysis method to determine the macro mixing time in a transparent stirred tank. It consists of capturing a video of decolorization process by using a fast acid-base indicator reaction and employing image analysis to quantify the color evolution. The color change is quantified by means of individual thresholds on the RGB color model and provides a direct measurement of the macro mixing evolution as it can be seen by an operator in front of the vessel (Francois et al., 2007). In conductivity probe method a single-point sensor or a probe is used to measure the conductivity of the solution. The probe can only measure the local conductivity and the calculated mixing time depends on the probe position. This technique is neither applicable at higher temperatures nor for industrial reactors.

In planar laser induced fluorescence (PLIF) technique a laser sheet generator is directed towards the mixing tank and a fluorescent indicator (as a tracer) is used to measure the mixing time. After adding the tracer, it glows only at the plane of the laser sheet. In fact the technique is quantitative and totally non-intrusive. However PLIF is difficult to set up and is limited to small tanks because of the prohibitive laser power required in larger volumes. The liquid-crystal thermography (LCT) technique is based on the principle that thermo chromic liquid crystals (LCs) show a different color when subjected to different temperatures. The thermochromic LCs of very small size are suspended in the liquid. A thermal pulse is given, and the mixing of this thermal pulse imparts different colors to the LCs in different parts of the vessel. This can then be analyzed either visually or by a camera. It may be advantageous than visual techniques but it also requires transparent vessels and hence is not useful at an industrial scale. Salient features of these techniques are listed in Table 1.

Electric resistance tomography (ERT) is an upcoming technique available to study the mixing patterns. The mixing time measurement using ERT technique is based on the conductivity data. It is often used for the visualization of macro mixing of miscible fluids whose electric conductivity values are distinct in a stirred vessel. Tomography (greek word “tomos” meaning “to slice” and “graph” means “image”) is an imaging technique that defines the content of the vessel without physically looking inside the vessel. In this technique subsurface distribution of electrical resistivity from a large number of resistance measurements are made from electrodes. It involves reconstruction of spatial distribution of the resistance of the vessel on the basis of the difference of their electrical conductivities. The estimated conductivity distribution is expressed as pixel images that provide instantaneous information on a concentration distribution in a flow domain at a given location. It also provides detailed level of information about the mixing patterns in the vessel. Recent research on ERT technique for mixing time measurement is summarized in Table 2.

The literature review gives a clear picture of advantages and disadvantages of different methods that are being used in mixing studies. It is quite evident from this review that ERT may prove to

Table 1
Comparison between conventional techniques.

Method	Advantages	Drawbacks
Conductivity probe method [18,28]	Accurate, can be used in industrial tanks	Do not quantify segregated regions and dead zones, do not give the end point of the mixing
Decolorization methods [6,34,8]	Non-intrusive give the end point of the mixing, can identify unmixed zones	Inaccurate, crude, Transparent vessel needed
Radioactive tracer method [22]	Non-intrusive, accurate	Unavailability, health hazards
Hot wire anemometry [2,12]	Give the end point of the mixing	Intrusive, time lag
Liquid crystal thermography [19,22,29]	Advantageous than visual techniques	Transparent vessel needed and not useful for industrial scale
Planar laser induced fluorescence [8]	Technique is quantitative and totally non-intrusive	Limited to small tanks because of the prohibitive laser power required in larger volumes
pH Method [7]	Accurate	Intrusive, do not give the end point of the mixing
X-ray technique [11]	Non-intrusive	Depends on the X-ray opacity of the fluid and the vessel
Electric resistance tomography [1,15,31] etc.)	Non-intrusive, fast data acquisition, high accuracy, provides continuous measurements over a large range of scales, high temporal resolution of images	Works only for fluids with different electrical conductivities, End effects due to three dimensional nature of electricity.