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Mass and heat transfer at an array of vertical tubes in a square stirred tank reactor

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ABSTRACT

Rates of mass transfer at a square array of vertical cylinders contained in a square agitated vessel were measured by the diffusion controlled dissolution of copper in acidified $K_2Cr_2O_7$ in an attempt to throw some light on the heat transfer behavior of the tube array (by analogy with mass transfer), the vertical tube array can act as a cooler or simultaneously as a cooler and a catalyst support for conducting exothermic diffusion controlled reactions. Variables studied were impeller rotation speed, cylinder diameter, cylinder spacing within the array, distance between the array and tank wall, impeller geometry (radial flow turbine and axial flow turbine) and superimposed axial solution flow. The mass transfer data for a batch reactor using a radial flow turbine were correlated by the equation:

$$\mathrm{Sh} = 0.85 \times \mathrm{Sc}^{0.33} \times \mathrm{Re}^{0.57} \times \left(\frac{s}{T}\right)^{0.5}$$

where s is cylinder separation within the array and T is the tank diameter. Radial flow turbine was found to produce higher rates of mass transfer than axial flow turbine. Superimposed axial flow within the range of $400 < \mathrm{Re_s} < 4000$ was found to decrease the rate of mass transfer especially at high impeller rotation speeds. The importance of the present results in the design and operation of catalytic stirred tank reactor with a builtin heat transfer facility suitable for diffusion controlled exothermic reactions which need rapid cooling to protect heat sensitive catalysts and heat sensitive products was noted. Also the possibility of using the mass transfer equation in predicting the rate of diffusion controlled corrosion of the metallic tube array cooler was highlighted.

Keywords: Mass transfer; Heat transfer; Stirred tank reactor; Diffusion controlled reactions

1. Introduction

Heat and mass transfer study in agitated vessels is important for the rational design and operation of stirred tank reactors used to conduct diffusion controlled exothermic reactions. Different heat transfer facilities have been developed to remove excess heat from agitated vessels the simplest of which is cooling jackets, which have the advantage of easy maintenance. However as the volume of the reactor increases, cooling jackets become insufficient to cool the reactor. In this case internal helical cooling coils concentric with the rotating shaft are used; they have the advantage that a large amount of heat transfer surface area can be obtained for a given volume of process fluid. They are in general however more costly to fabricate and more difficult to maintain (Oldshue, 1983).

A third class of coolers use vertical tubes which act also as baffles to eliminate swirl flow, the vertical tubes act also as turbulence promoters and improve the rate of heat transfer. The heat transfer behavior of such vertical tubes has been studied (Dunlap and Rushton, 1953; Havas et al., 1982; Petree and Small, 1978; Kato et al., 2007) by either measuring the rate of heat transfer or the rate of mass transfer by virtue of the analogy between heat and mass transfer (Mizushina et al., 1969; Ko et al., 2006). The majority of previous studies on heat and mass transfer in agitated vessels were conducted using cylindrical agitated vessels, rectangular agitated vessels have received little attention despite their practical importance (Kresta et al., 2006; Clark et al., 1994; El-Shazly et al., 1997; Sedahmed et al., 2004). Rectangular agitated vessels have the advantage that they do not need baffles to eliminate the undesirable swirl

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List of symbols

A	cylinder array area
a	constant
C_o	initial dichromate concentration
C	dichromate concentration at any time
d_i	impeller diameter
d	cylinder diameter
D	diffusivity
H	solution height in the agitated vessel
K	mass transfer coefficient
Q	solution volume
s	cylinder separation within the array
t	time
T	equivalent tank diameter
V	superimposed solution velocity during continuous operation
Z	distance between impeller and tank bottom
Re	Reynolds number of agitated vessel ($\rho_w d_i{}^2/\mu$)
Re_s	axial flow Reynolds number ($\rho VT/\mu$)
Sc	Schmidt number (μ/i)
Sh	Sherwood number (Kd/D)
ρ	solution density
ε	specific energy consumption
μ	bulk solution viscosity
w	impeller rotation speed (rps)
υ	kinematic viscosity

flow in favor of axial and radial flow which have a high mixing efficiency (Oldshue, 1983).

The aim of the present work is to study the rate of heat and mass transfer behavior of an array of vertical tubes in a square agitated vessel using a mass transfer technique based on measuring the rate of diffusion controlled dissolution of copper in acidified dichromate the technique has been used widely to study rates of liquid–solid mass transfer under different conditions in view of its simplicity and accuracy (Gregory and Riddiford, 1960; Madden and Nelson, 1964; Abdel-Aziz et al., 2010; Gruber and Melin, 2003a,b).

Beside its simple construction the outer surface of the suggested vertical tube array cooler can also act as a catalyst support to conduct liquid–solid catalytic reactions such as photocatalytic reactions, immobilized enzyme reactions, removal of organic pollutants by wet oxidation and catalytic organic synthesis. Since these reactions are often diffusion controlled, a study of the rate of mass transfer at the vertical tube array would assist in predicting the rate of the diffusion controlled reaction taking place at the outer surface of the tubes including the diffusion controlled corrosion of the tube array. The present reactor offers the advantage of rapid heat removal with a consequent protection of heat sensitive catalysts from deactivation and loss of yield and selectivity at high temperatures (Anxionnaz et al., 2008). It also protects heat sensitive products from decomposition. Development of heat exchanging reactors (multifunction reactors) has recently received a great attention in view of their compactness and low capital and operating costs (Anxionnaz et al., 2008; Zewail et al., 2010).

2. Experimental technique

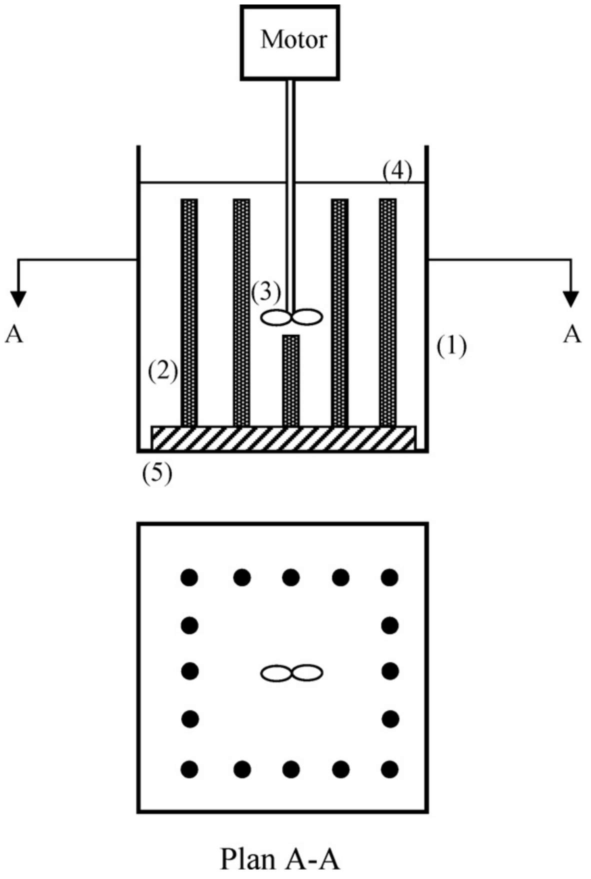

Fig. 1 – Apparatus (simple batch reactor). (1) Plexiglass container; (2) tube array; (3) impeller; (4) electrolyte level; and (5) plastic base (array holder).

The apparatus used in the present work (Fig. 1) consisted of 5.5 l plexiglass square vessel of 15 cm × 15 cm cross sectional area and 25 cm height. The vessel was fitted at its center with a turbine impeller (either 4 flat blade turbine or 45° four blade pitched turbine) mounted on a stainless steel shaft. The impeller which was made of copper and the stainless steel shaft were isolated with epoxy resin. The shaft was driven by 0.3 hp variable speed motor fitted with a variac and digital tachometer. The motor was fixed firmly against a brick wall to avoid vibrations. A square array of vertical separated cylinders made of copper was mounted around the rotating impeller, array cylinders were fixed in position by fitting the lower part of each cylinder in a hole drilled in a square plastic sheet of the dimensions 14.8 cm × 14.8 cm and a thickness 1 cm by epoxy resin, the plastic sheet holding the array was rested on the bottom of the agitated vessel. In constructing the cylinder array, 3 different cylinder diameters (0.6, 1 and 1.6 cm) were used. Cylinder spacing within the array ranged from 0.5 cm to 1.5 cm while the distance between the array and the container wall was 1.75, 2.5 and 3 cm. Table 1 shows the geometric parameters of the arrays used in the present study. In designing the present agitated vessel the following standard dimensions were used (El-Shazly et al., 1997): $d_i/T = 0.33$, $H/T = 1$, and $Z/T = 0.33$.

In order to examine the effect of superimposed axial flow on the array mass transfer coefficient a batch recycle reactor was used (Fig. 2). The reactor consisted of 20 l glass storage tank, 0.5 hp plastic centrifugal pump was used to circulate the solution between the glass storage tank and the stirred tank reactor. Solution was admitted to the agitated vessel at the center of its bottom. Solution velocity was controlled by means of a bypass and was measured by a graduated cylinder