INVESTIGATION OF FLUID FLOW PATTERNS IN A HOLLOW FIBER MODULE USING MAGNETIC RESONANCE VELOCITY IMAGING

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SUMMARY

Magnetic Resonance Imaging (MRI) was used to obtain new information about fluid flow patterns in hollow fiber reactors. Significant changes in inlet flow distribution were observed as a function of Reynolds number. Images taken at the tube bundle entrance and exit showed that maldistribution of flow persists throughout the module. Furthermore, the results suggest that individual fibers act in a mixed degree as feeders or collectors depending upon radial position. These effects must be considered when modelling or designing hollow fiber reactors.

INTRODUCTION

To design or model a hollow fiber membrane reactor, a knowledge of the flow field is required. Reactant and product distributions in the reactor are influenced by the overall and local fluid flux rates. The measurement of overall flux rates is generally easier when compared to local flux rates. This study focuses on the latter since an understanding of localized conditions will improve the design and modelling of hollow fiber membrane reactors.

In this study, local flux rates were measured using a novel noninvasive technique incorporating Magnetic Resonance Imaging. This technique produces a 2-dimensional image of a selected cross section based on spin echo proton Nuclear Magnetic Resonance (NMR). The MR image is composed of thousands of pixels (picture elements) where the brightness of each pixel is related to the fluid residence time in the corresponding voxel (volume element). Knowing the voxel size (for this study typically 0.56 mm x 0.56 mm and 5 mm in length) and the pixel intensity, it is theoretically possible to calculate the point fluid velocities.

This study demonstrates the usefulness of MRI for investigating fluid flow patterns and provides new evidence for the maldistribution of flow in hollow fiber modules.

BACKGROUND

Fluid Mechanics

Previous research has categorized the flow in the inlet distributor as possessing the characteristics of dividing manifold flow and an impinging jet. Park and Chang's (1986) numerical results, excluding the effect of gravity, showed that a toroidal eddy exists in the inlet distributor space for Reynolds numbers (Re) from 50 to 200. Consequently, there are two local axial velocity minima and maxima. One maximum is located at the center and one minimum is located at the
bundle radius, the position of these extrema is independent of Re. The other two extrema appear to move radially outward with increasing Reynolds number.

The experimental apparatus of Park and Chang (1986) consisted of 364, 810 μm I.D. impermeable hollow fibers enclosed in a Lucite cylinder. They verified numerical results experimentally by direct sampling from individual fibers, high-speed photography of a tracer dye and a residence time distribution (RTD) study. These experimental results are however not applicable to commercial systems since impermeable tubes were used, direct sampling was performed without an aft manifold, the exit tube wall obscured photography near the center of the manifold and RTD data were collected downstream of the module.

Commercially used hollow fiber modules have permeable tubes and the flow in the shell region is dependent on the pressure distribution and orientation with respect to gravity. For horizontal orientation, typical of animal cell culture reactors, gravity forces cause the flow about the axis to be asymmetric. Fluid flow in this mode of operation has not been adequately investigated.

**Magnetic Resonance Techniques**

MR, generally used for medical diagnostics, can be used for investigating fluid flow. For observation, the sample volume must contain a large number of protons. Each proton possesses an intrinsic spin and an associated magnetic moment. When the sample is subjected to a uniform external magnetic field, $B_0$ (e.g. along the z-axis), the individual moments sum resulting in a bulk nuclear magnetization vector. The direction of this bulk magnetization vector, initially aligned with $B_0$, may be manipulated by applying a transverse radio frequency (RF) field, $B_1$, at the system resonant frequency, $f_L$, also known as the Larmor frequency (Figure 1).

The added energy causes a change in the net transverse magnetization $M_{xy}$ and, therefore, changes the angle, $\Theta$, between $M$ and $B_0$. The system returns to equilibrium by dissipating the added energy over time by spin-lattice ($T_1$) and spin-spin ($T_2$) "relaxation". The time constants $T_1$ and $T_2$ are characteristic of the sample material properties.

In a typical spin-echo, time-of-flight (TOF) technique, a "slice selective" 90° RF pulse ($\Theta = 90°$) is applied, creating transverse magnetization within a single slice. The thickness of a slice is controlled by changing either the RF bandwidth or the magnitude of a magnetic field gradient applied simultaneously in for example, the z direction (perpendicular to the selected slice). Next, the spins are allowed to dephase ($T_2$) during a second magnetic gradient pulse (e.g. in the y direction), known as a "phase encode" gradient. Following this, a slice selective 180° RF pulse is delivered. After another delay, during which the transverse magnetization rephases, the RF receiver coil and read gradient (e.g. in the x direction) are switched on and the resulting "spin-echo" is obtained from the slice (at time TE). This procedure is repeated 128 times (for a 128 x 128 pixel image), each time changing the strength of the phase encode gradient.

The image of the selected slice is obtained by a 2-dimensional Fourier transform of this data set over the readout (x) and phase