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Detection and diagnosis of blockage in parallelized microreactors

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ABSTRACT

Microreactors engage the attention of researchers and engineers in the pharmaceutical and chemical industries as well as universities. When the production capacity of micro chemical plants is increased by numbering-up approach, it is important to realize the uniform flow distribution among the parallelized microreactors. In addition, a blocked microreactor needs to be identified as early as possible to achieve the stable long-term operation of micro chemical plants. However, it is not practical to install the sensors in all the microreactors from the viewpoint of cost or space. In this research, a system that can detect and diagnose a blocked microreactor by using just two flow sensors is developed. The effectiveness of the developed system is demonstrated by numerical and experimental investigations, and it is clarified that the developed method has high robustness to changes in the fluid properties and the microreactor characteristics such as pressure drop. The developed system will be applicable to various types of micro chemical plants with parallelized microreactors.

1. Introduction

Recently, micro chemical process technology (MCPT) has attracted considerable attention from both the academic and industrial sectors [1]. Advantages of MCPT include fast mass and heat transfer due to large surface to volume ratio, continuous operation, as well as improved safety. MCPT is particularly suited to producing high value-added functional materials such as pharmaceuticals and fine chemicals. An effective approach for increasing the production capacity of micro chemical plants (MCPs) is numbering-up, which means the parallelization of microreactors. Although the numbering-up approach has the ability to transfer research results more quickly into production, scientific and practical research has shown that it is necessary to achieve a uniform flow distribution among the parallelized microreactors. The characteristics of both manifold-type and bifurcation-type flow distributors have been analyzed by using an electrical resistance network model [2]. The influence of differences between parallelized microchannels on the reactor performance has been examined numerically and experimentally [3,4]. In addition, the chamber geometry of the miniaturized flow distributors has been optimally designed to realize the uniform flow distribution by using computational fluid dynamics (CFD) model or its simplified flow model [5–7].

Blockage or clogging is the most recognized trouble with MCPs. For example, Bayer et al. [8], who developed a continuous radical polymerization process having micro pre-mixers, mentioned that poor mixing conditions cause blockage in a reactor. Ju et al. [9] applied a stainless steel microchannel reactor for the continuous synthesis of zeolite NaA, and they found that aging the synthesis solution was a key procedure for avoiding blockage of the microchannel. In these literatures and others, one of the critical operation problems was blockage in microreactors, which negatively affects the flow distribution in the whole MCPs with numbering-up structure. The flowrate in each microreactor can be kept at a desired value by installing flow controllers, but it is not practical to install flow controllers in all the microreactors. To accelerate industrial application of MCPT, it is necessary to develop a process monitoring and control system for MCPs. So far, there are only a few papers about operation and control methods for MCPs. Kano et al. [10] developed the method of identifying a blockage in stacked microreactors from the output signals of temperature changes. Tonomura et al. [11] developed the effective operation and control method for parallelized microreactors to keep their flowrates at a desired value even when blockage occurs.

In this research, the split-and-recombine-type flow distributors (SRFDs) proposed by Tonomura et al. [12] are rigorously analyzed by using CFD simulation, and the SRFDs are re-designed to increase robustness to changes in operating conditions such as inlet flow velocity. In addition, a blockage detection and diagnosis system is developed. In the developed system, a small number of flow sensors are embedded in the SRFDs to isolate a blocked microreactor as

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early as possible from the parallelized microreactors. The effect of sensor location on blockage diagnosis is also investigated. Finally, the performance of blockage diagnosis by using the developed SRFD having two flow sensors is assessed through experiments.

2. Flow distribution in parallelized microreactors

This section shows the basic structures and characteristics of MCPs with parallelized microreactors. In addition, the characteristics of a specific flow distributor developed by Tonomura et al. [12] are rigorously analyzed through CFD simulations.

2.1. Split-and-recombine-type flow distributors (SRFDs)

The well-known strategy for increasing the production capacity of MCPs is the parallelization of the optimally designed identical microreactors. A schematic diagram of a MCP with externally parallelized microreactors is shown in Fig. 1. The parallelized section where microreactors are running in parallel is connected to a distribution section and a confluence section. The distribution section carries out a function of distributing a reactant flow among the parallelized microreactors. The distributed flows pass through microreactors and are collected into one flow at the confluence section. A lack of uniformity in the flow distribution lowers the MCP's performance.

Flow distributors, which are used at the distribution section in Fig. 1, are typically classified into two types: manifold-type and bifurcation-type. Unlike such flow distributors, Tonomura et al. [12] have developed SRFDs that have three or more bifurcation points and one or more junction points. Fig. 2 shows an example of SRFDs, in which one flow is divided into four flows. The SRFD consists of channels having a length of L [mm] and a width of d [mm]. It is assumed that $L_1 = L_4 = L$ and $L_2 = L_3 = \alpha\, L$. α is introduced to achieve the uniform flow distribution among the parallelized microreactors under a normal operating condition and determined by CFD simulation. u_{in} [m/s] is the averaged flow velocity at the inlet, and u_k [m/s] (k is channel number) is the averaged flow velocity at the outlet of each channel. The outlet of SRFD is opened to atmosphere. In this research, the commercial CFD software "COMSOL Multiphysics® 3.4" is used to estimate the flow distribution of water (293 K) in the SRFD. The normalized flow velocity u_k^*, which is given by u_k/u_{in}, is used to evaluate the flow distribution.

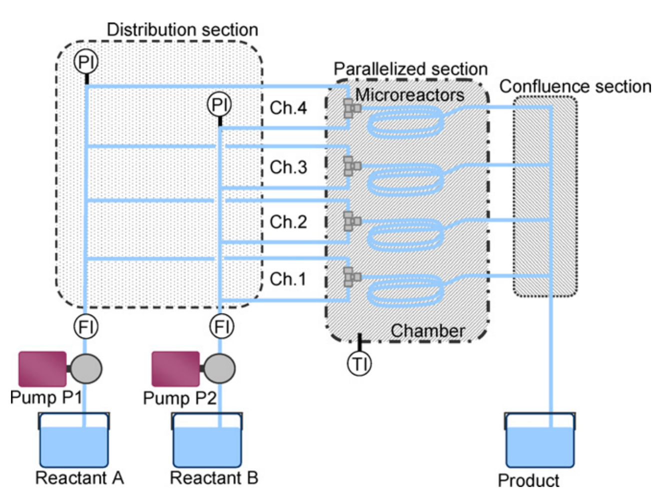

Fig. 1. Schematic diagram of micro chemical plants with parallelized microreactors.

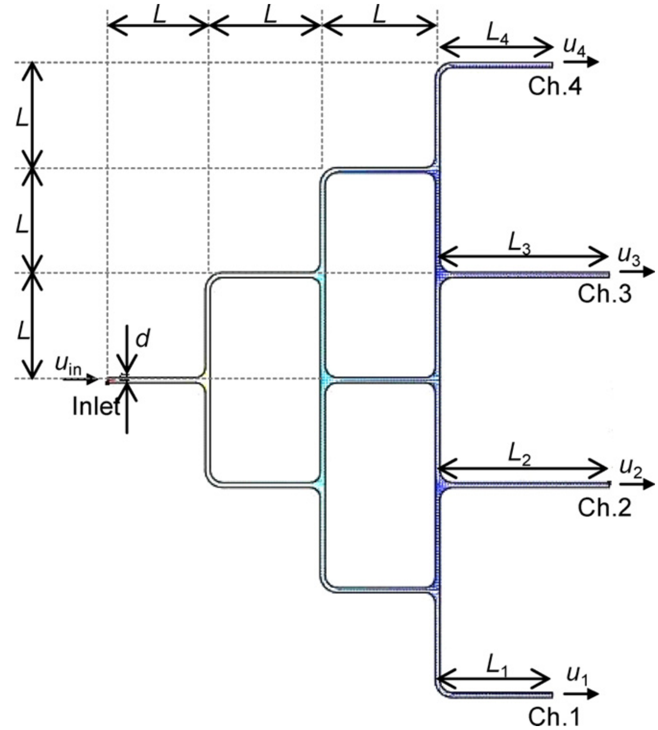

Fig. 2. Split-and-recombine-type flow distributors (SRFDs).

2.2. Effects of design parameters and Reynolds number on flow distribution

It is preferable that the uniform flow distribution in the SRFD is maintained even when the inlet flow velocity or the material properties of the fluid change. In this section, L and d are selected as design parameters. Table 1 shows the representative simulation conditions for SRFDs. When a circular channel having $L = 10$ mm and $d = 1.0$ mm is adopted, $u_{\mathrm{in}} = 0.2$ m/s corresponds to inlet volumetric flowrate $V_{\mathrm{in}} = 10$ mL/min. In this section, the effects of design parameters on the flow distribution are investigated by using two-dimensional CFD simulation. Fig. 3 shows the results of CFD simulation. L/d and Reynolds number, Re, are used as parameters to systematically investigate the flow distribution of the SRFD. Re is a dimensionless number that gives a measure of the ratio of inertial force to viscous force. Re is calculated from given information on channel diameter, flow velocity, density, and viscosity. In Fig. 3, the vertical axis denotes the differences between two normalized flow velocities, u_2^* and u_1^*, and the flow distribution is highly uniform when each plotted point in Fig. 3 is located near zero. The uniform flow distribution is achieved independently of L/d, when Re is less than 100. At higher Re, the difference in flow velocity between Ch. 2 and Ch. 1 becomes large. In such a case, the SRFD needs to be re-designed so as to realize the uniform flow distribution. The alternative approach is to use flow controllers. However, the installation of flow controllers in all the channels requires high cost and extra space.

Table 1
Representative simulation conditions for SRFDs.

L/d	L [mm]	d [mm]	α	u_{in} [m/s]	Re
5	10	2.0	1.80	0.05	100
10	10	1.0	1.75	0.2	200
20	10	0.5	1.78	0.8	400
40	40	1.0	1.67	0.2	200