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Numbering-up strategies of micro-chemical process: Uniformity of distribution of multiphase flow in parallel microchannels

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ABSTRACT

The key step in micro-chemical technology from basic research to industrial applications is the scaling-up of micro-chemical processes. In order to realize the high-throughput, easy-to-control and uniform production of the products in the industrialized operation, the "numbering-up" of the micro-chemical process is mainly achieved from two directions: fluid distribution among the multi-channels and splitting of products step-by-step. Based on the two major directions, in the present review, the key scientific issue of "uniformity of distribution of multiphase flow in parallel microchannels" is focused, the progress of the numbering-up of micro-chemical process is described, and the directions for the research in the future are prospected.

1. Introduction

Over the recent two decades, with the development of the miniaturization such as micro-total analysis system (μ-TAS) and micro-electro-mechanical systems (MEMS), micro-chemical technology has gradually become one of the frontiers in the chemical engineering field [1]. Studies have shown that, micro-chemical engineering and technology often show unique advantages compared with traditional chemical engineering and technology. For instance, the micron size of microchannels makes the micro-chemical equipment has larger specific surface area, so that it can enhance the mass and heat transfer efficiency of the corresponding process. The micro-chemical engineering is also easy to control the internal fluid flow and residence time, and can achieve safe production of the toxic, flammable, explosive and other chemicals. Therefore, micro-chemical technology has gradually being applied to chemical reactions [2–4], bio-medicine [5,6], energy environment [7,8] and other fields [9].

Microchannels are the basic components of micro-chemical technology. At present, the research on multiphase flow in a single microchannel and the production of bubbles or droplets are relatively mature. For example, several contributions have been devoted to the liquid-liquid two-phase flow [10], droplets dynamics [11], gas-liquid two-phase flow [12], bubbles dynamics [13], compound droplets dynamics [14] and Janus droplets generation [15] in microfluidics. Although micro-chemical technology has many advantages in basic research, the small size limits large-scale industrial production at the same time. However, the development of micro-chemical technology must not be limited only for the study in the laboratory. So the scaling-up strategies of micro-chemical technology are of great significance for the industrial applications. In order to advance micro-chemical technology to industrial applications and to produce high-throughput and controllable required products, some scholars have carried out a series of exploration based on the "numbering-up" strategies of microchannels. The key issue that needs to be solved is the uniformity of the distribution of multiphase flow in the parallelized microchannels, including the distribution of the fluid among parallelized microchannels and of the products such as bubbles or droplets. These contents will be specifically introduced as shown in Fig. 1 in the following sections. In this paper, the core idea of the "uniformity of distribution of multiphase flow in parallelized microchannels" is focused, the scaling-up strategy of micro-chemical process and equipment is summarized and the research direction of this field for the future is prospected.

2. The numbering-up strategies of microchemical system

At present, the numbering-up of micro-chemical process is mainly achieved in two directions: (I) via the fluid distribution, that is, each of the single phase fluid is first distributed, and then the two fluids contact with each other to be amplified in parallel. This method includes two modes: single-phase fluid is distributed and two-phase fluids are

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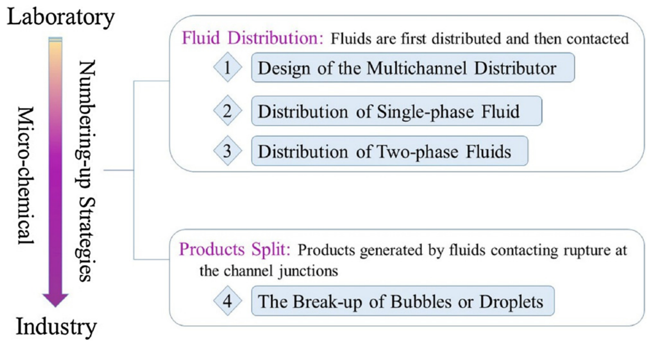

Fig. 1. The numbering-up strategies for micro-chemical process.

distributed. The former case is that only one kind of fluid is distributed among multiple channels, and another fluid that reacts or contacts with it is delivered in the form of cavity or multiple devices. The cavity can be used to collect products, mostly in co-flow or step device systems [16–18]. The use of multiple devices to deliver fluids, on the one hand, can avoid the redistribution of fluids between channels, the three-dimensional design and crossing of the channels; on the other hand, different pumps can simultaneously control the delivery of multiple fluids to form products of different compositions [19]. The latter case is that only two sets of experimental operating systems (each phase has an entrance) were used to allow the two fluids to be distributed in a particular multi-channel structure, such as multi-layer or circular microchips. Thereby a series of fluid delivery devices and flow control devices are reduced, and the uneven distribution due to the instability of the pump is also reduced. This method can save costs and achieve a high level of the integration of the operating system for high-throughput production. However, one drawback of this method is that once a channel is blocked, the distribution of fluids in the remaining channels will be more inhomogeneous, and the whole process needs to be stopped to debug or clean up. (II) via the rupture of the products, that is, both fluids firstly contact with each other to generate bubbles or droplets, and then the products are split step by step through particular channel nodes such as T- or Y-junctions. The microchannel chip in this method is easy to design for the two-dimensional scaling-up. Since the two-phase fluids are not distributed before contacting, the differences in the distribution of the fluid among the channels are avoided. However it is necessary to fully understand the breakup dynamics and mechanism of bubbles or droplets at the nodes. Uniformity of fluid distribution is challenging in both directions. The main features of the two directions for the scaling-up are listed in Table 1, and the studies on these directions are summarized in Table 2.

2.1. Design of the multichannel distributor

The fluid among the channels is prone to mutual flow, and the slight manufacturing variations can result in the heterogeneity of the fluid distribution, which affects the flow stability and causes the nonuniformity of the products distribution. For the microreactor, the carbon deposition reaction, the coking reaction or the presence of the catalytic layers are easy to block the microchannels, resulting in uneven distribution of pressure drop, flow and temperature [20,21]. At the same time, the uneven distribution of flow will affect the distribution of residence time, mass transfer and heat transfer, this will further affect the conversion and selectivity of the reaction [21]. Some scholars have also shown that, for the first-order irreversible catalytic reaction, the non-uniformity of temperature has a greater impact on the conversion [22]. It is important to understand the fluid distribution in parallel channels for the enlargement of the industrial scale. Therefore, the study of the amplification of microchannels is focused on how to distribute fluids evenly among multiple microchannels.

Multichannel distributors are mainly available in two types: cavity type and configuration type. The configuration type of the distributor usually produces a high pressure drop at high flow rates, which is liable to cause damage to the pump and consume more energy, which is not desirable in industrial applications. However, the cavity structure has been proven to effectively reduce the pressure drop over the entire device and can decrease the footprint [23]. So the choice of fluid delivery equipment is particularly important. The precision of the syringe pump is high, and it is suitable for experiments under small flow conditions, but its discontinuity makes the operation cumbersome. Higher flow rates can select HPLC pump, however it is limited by the viscosity of the liquid. The peristaltic pump is suitable for experiments at high flow rates for continuous injection [23,24]. In addition to channel manufacturing tolerances and inherent instability of delivery equipment such as pumps, during the flowing of fluid, distributors have a significant effect on flow uniformity. Therefore, many scholars have conducted a series of studies on the flow distribution characteristics and the design of the distributor.

In order to reduce the diversity of the velocity distribution among the channels, Commenge et al. [25] analyzed the influence of the geometric dimensions of the microstructure of the reactor in laminar flow conditions. The reactor is a combination of multiple geometries. This structure can avoid the eddy current phenomenon, which may happen in simple cavity flow distributor. The reactor is simplified based on the resistance network model of pipe, and an approximate pressure drop model is proposed to estimate the mass and velocity differences of the fluid distribution in microchannels. The results of this study determine the influence of the microchannels' geometric structure on the flow distribution, and the design of the reactor for the realization of the uniformity of large fluid flow is optimized. Wei et al. [26] carried out numerical and experimental studies on flow distribution in a similar distributor. They designed perforated baffles at the entrance of the z-type parallel microchannels. The target flow distribution among parallel multi-channels was realized through the CFD simulation optimization and PIV velocity measurement technology. For heat exchangers with parallel microchannels, easy-coking fluids pose greater challenges to uniformity of distribution. Because the temperature and thermophysical properties of the fluid are in an unstable state, and coking is

Table 1
Main features of several numbering-up methods.

Research directions	Numbering-up methods	Convenience for the fabrication	Source of non-uniformity	Device integration	Economy
Single-phase fluid distribution	One fluid is distributed and another is delivered in the form of cavity or multiple devices	Yes	Pumps; distribution of fluid; vortex inside the cavity; manufacturing tolerance	Low	General
Two-phase fluid distribution	Only two sets of experimental operating systems are used to allow the two fluids to be distributed in a particular multi-channel structure	No	Distribution of two phases fluids; 3-D microchip; pump; manufacturing tolerance	High	Well
Products breakup	Products split at different configurations of channel junctions	Yes	Initial bubbles/droplets size; dynamics of breakup; pump; manufacturing tolerance	High	Excellent