Design of microchannel annular flow generator using IASE method

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Abstract: In order to make up for the deficiency of liquid-liquid annular flow generator in microfluidic devices, IASE method is used to innovate the annular flow generator in microfluidic devices, and a feasible scheme is proposed, which meets the functional requirements of the annular flow generator in microfluidic devices and generates stable annular flow; Fluent software is used to analyze and compare the VOF model of the two schemes; Through their pressure, flow velocity and flow state screening, the device structure that meets the requirements is selected. This paper summarizes a flow channel structure of L-type flow channel and coaxial flow channel in series. This structure can generate stable annular flow pattern and is easy to manufacture, which is suitable for the requirements of microfluidic equipment manufacturing at present.

1. Introduction

The study of two-phase flow patterns in microchannels shows that the liquid-liquid two-phase flow in microchannels can form a series of flow patterns, such as slug flow, drop flow, parallel flow and annular flow. Compared with other flow patterns, annular flow can form two-phase flow with a larger flow ratio range, so it has a wider application range. Most of the researches on annular flow in microchannels are in theoretical and experimental state, and most of them focus on flow patterns. Dreyfus et al[2] studied the flow patterns of liquid-liquid two-phase flow, observed various flow patterns through experiments, monitored the surface velocity with the help of relevant equipment, and obtained the flow pattern diagram with dimensionless number. Different flow patterns have a great impact on the mass transfer in the microchannel. Akira Matsuoka et al[3] experimentally studied the liquid-liquid two-phase flow pattern and mass transfer rate in microchannels. It was mentioned that the annular flow in microchannels was related to the high flow rate of the fluid, and the two-phase flow would change from plug flow to annular flow at high flow rate.

Researchers have also made some attempts to develop some devices in micro channel annular flow liquid-liquid two-phase. Jin Yang of Sichuan University and others have studied and invented a series of microchannel annular flow forming devices[4-6], proposed microchannel devices for forming stable annular flow, simple microchannel devices for stabilizing annular flow, and three-way combined microchannel devices for stabilizing annular flow, and proposed a method for constructing stable annular flow in microchannels.
To sum up, at present, there are few researches on the microchannel liquid-liquid annular flow; The related devices have the problems of complex structure and difficult manufacturing. Based on the innovative method of IASE, a microchannel annular flow generator with simple structure and easy to form annular flow is designed.

2. Scheme design

2.1 design method
IASE method\(^{(7)}\) (identification, analysis, solve, evaluation) is an innovative method which combines the advantages of extenics and TRIZ theory.

2.2 Proposal

2.2.1 problem description
Due to the difficulty of fluid viscosity, interfacial tension and micro size design of microchannel, the overall design of microchannel annular flow generator becomes difficult. Solving the problem of annular flow generator in micro scale is the core of this paper.

2.2.2 path analysis
According to the innovation tool selection strategy of IASE innovation method. The above problems mainly focus on whether the structure and function of macro annular flow transmitter can achieve the same function on the same structure of micro channel annular flow generator. According to the IASE method and the actual situation, the following solution path is adopted.

Solution path: function analysis - Function Oriented Search - general solution and standard solution.

2.2.3 solution steps
1) Problem identification function analysis
   The function of microchannel annular flow generator is analyzed, and the functional components of the system are determined and the functional model is established.

   (1) Identify functional components
   The microchannel annular flow generator is analyzed and divided into system components, super system components and action objects, as shown in Table 1 below:

   | system            | major function | System components | Supersystem components | Object of action          |
   |------------------|----------------|-------------------|------------------------|--------------------------|
   | Microchannel     | Produce stable | Internal phase    | Fluid 1 (Internal fluid)|                         |
   | annular flow     | annular flow   | inlet channel     |                        |                          |
   | generator        |                | External phase    |                        |                          |
   |                  |                | inlet channel     |                        |                          |
   |                  |                | Outlet channel    |                        |                          |
   |                  |                | Microchannel      |                        |                          |
   |                  |                | annular flow      |                        |                          |
   |                  |                |                    |                        |                          |

(2) Establish functional model
The interaction between components is represented by standardized function description. As shown in the figure.
System function analysis conclusion

Through the analysis of component model, the composition of components in the system and the relationship between them are clear, and it is concluded that the functional factors leading to the failure of annular flow in microchannel are as follows: 1. Channel structure; 2. Due to the size of microchannel, the fluid is prone to instability; 3. Interfacial tension and inertial force between phases; 4. The initial state of each phase.

2) Problem analysis - function oriented search

- Problem identification: Stable annular flow generated by microchannel annular flow generator;
- Function generalization: Key function: the runner structure is designed to generate stable annular flow;
- Identify leading areas: The maturity of macroscopical annular flow generator design technology;
- Leading domain solutions: Referring to the design scheme of macro annular flow generator, the structure is studied and applied to the microchannel.

Aiming at the research field of macro annular flow generator, various cases of annular flow generation by optimizing the channel structure have been proposed in recent years. For example, Yao et al[8]. Studied the formation mode of annular flow in abrupt pipeline; Lu et al[9]. adjusted the angle structure and pipe material of the annular flow pipe to study the formation of annular flow. In addition, some patents of macro annular flow generator have also been invented through structural optimization design. For example, Jiang et al[10]. Invented an annular flow generator and a low viscosity annular heavy oil transportation and stabilization device.

The forming process of annular flow is simple and the forming time is short, which is also a design problem that annular flow must face.

3) Problem solving - final ideal solution

After the problem analysis stage, some existing methods to solve the structure of macro annular flow generator are searched. These methods are used for the design of micro channel annular flow generator, and then the final ideal solution is used for further concretization.
According to the tips of Chinese leading technology in function oriented search and combined with the existing structural design resources of macro annular flow generator, two schemes are obtained: The structure of L-shaped channel and coaxial channel in series is shown in the figure(a). The structure of the flow channel is shown in the figure(b).

3. Scheme analysis

3.1 watershed model and physical parameters

In order to determine the advantages and disadvantages of the two schemes, the two schemes are numerically simulated and analyzed by FLUENT software. Their specific structural dimensions are shown in the figure 3, and the unit is μm. The physical parameters of the selected fluid are shown in the table. The working state of the microchannel annular flow generator in the two schemes, including flow velocity, inlet and outlet flow and annular flow fluctuation, is preliminarily analyzed, and finally the final scheme is determined based on the fluctuation as the main evaluation standard.

| fluid                  | Density (kg/m³) | Viscosity (mPa•s) | Interfacial tension (mN/m) |
|-----------------------|-----------------|-------------------|----------------------------|
| Deionized water       | 991.4           | 1.05              | 5                          |
| (External phase)      |                 |                   |                            |
| 30% TBP               | 845.0           | 2.09              |                            |
| (Inner phase)         |                 |                   |                            |

3.2 governing equations

The annular flow forming process of microchannel studied in this paper is a two-phase Newtonian fluid system. The fluids selected in this paper can be regarded as immiscible and incompressible viscous fluids. These two fluids in microchannel are controlled by continuity equation and momentum equation:

\[ \nabla \vec{U} = 0 \]  

\( \frac{\partial}{\partial t} \left( \rho \vec{U} \right) + \nabla \cdot \left( \rho \vec{U} \vec{U} \right) = -\nabla P + \nabla \cdot \left( \mu \left( \nabla \vec{U} + \nabla \vec{U}^T \right) \right) + F \]
Where $\vec{U}$ is velocity vector, $\rho$ is density, $t$ is time, $P$ is pressure, $\mu$ is dynamic viscosity, source term $F$ includes interfacial tension $F_i$ and gravit $g$. The effect of gravity can be neglected in the flow, therefore $F = F_i$.

The interface tracking between two phases in the VOF model is completed by solving the continuous equation of the volume fraction of one or more phases. For the second phase $q$, there are the following equations:

$$
\frac{1}{\rho_q} \frac{\partial}{\partial t} (\rho_q \rho u_q) + \frac{1}{\rho_q} \nabla (\rho_q \rho u_q) = \frac{S_{eq}}{\rho_q} + \frac{1}{\rho} \sum_{j=1}^{q} \left( m_{eq} - m_{qr} \right) \tag{4}
$$

Where, $u_q$ is the velocity vector of the fluid, $S_{eq}$ is the source term, $m_{eq}$ and $m_{qr}$ are $r$ phase to $q$ phase mass transport and $q$ phase to $r$ phase mass transport respectively. In this study, there is no mass transport between the two phases, so the right term in the above formula has only the source term.

3.3 boundary conditions

Both the external phase inlet and the internal phase inlet are velocity inlet boundaries, in which the internal and external phase velocity is 0.25m/s; The outlet is the pressure outlet boundary, and the pressure is set to atmospheric pressure.

3.4 Results

3.4.1 pressure calculation results

As shown in the figure 3 is the cross-sectional pressure diagram of the corresponding two design schemes of microchannel annular flow generator. It can be seen that the pressure gradient in scheme (a) is clear, and the pressure decreases gradually from the inlet of the two phases(b) The pressure gradients in the two schemes permeate each other, have no obvious step shape, and are greatly affected by the
gap. The pressure gradient at the annular flow gap is approximately symmetrically distributed. As shown in the figure 4, the flow velocity vector diagram of two schemes of microchannel annular flow generator is shown in. It can be seen from figure (c) that when the two phases meet, due to the influence of interfacial tension, the two-phase velocity forms a good uniform direction velocity in the intersection area. In figure (d), the two-phase velocity forms the velocity vector region of turbulent flow in the intersection region, and there is a strong interference between the two-phase velocities.

3.4.2 Flow pattern waveform results

As shown in the figure 5, shown are the flow pattern fluctuation diagrams of two design schemes of microchannel annular flow generator. It can be seen from the two figures that both design schemes can form microchannel annular flow. In the observation figure (a), it can be seen that a stable interference layer is formed between the two-phase flow without strong fluctuation. It can be seen from the observation figure (b) that although a microchannel annular flow is formed between the two-phase flow, the interference layer between the two phases is wavy, and the fluctuation range is relatively large, and there are signs of instability near the outlet.

4. Scheme determination

Through numerical analysis, after comparing the pressure, velocity and flow pattern stability of the two schemes, it is found that the flow pattern fluctuation caused by the first L-shaped channel in series with the coaxial channel is small. The second type can be clearly seen in the pressure cloud diagram and velocity vector diagram \( \Psi \). There are local reflux and eddy current phenomena in the channel structure of series connection between type channel and coaxial channel. In conclusion, taking the microchannel annular flow pattern waveform and flow stability as the main evaluation criteria, the first channel structure with L-shaped channel in series with coaxial channel is determined as the final design scheme of microchannel annular flow generator.

5. Conclusion

Microfluidic equipment has a good development and application prospect in the fields of preparation, chemical reaction and micro chemical technology. The microchannel liquid-liquid annular flow generator device has the advantages of stable wrapping function and long-distance transportation in micron scale. It provides a device for multiphase flow transportation, droplet preparation, mass transfer between phases and chemical reaction between phases. Therefore, this paper uses IASE method to imitate and learn from the original macro annular flow generator, introduces it into the microchannel liquid-liquid annular flow generator, innovates the microchannel liquid-liquid annular flow generator, and gives two kinds of microchannel structures. Finally, the numerical simulation method based on VOF model of FLUENT software is used to verify the two schemes, and finally the
ideal scheme is obtained. The channel structure of L-shaped channel and coaxial channel in series can form a stable annular flow.

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