Research on Crushing Liquid by Ultra-high Pressure Micro-impinging Stream Method

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ABSTRACT: This paper introduces the ultra-high pressure technology into the micro-impact technology, relying on ultra-high pressure device to provide a powerful source of power, in order to ensure a high-speed collision of two micro-streams and enhance refinement crushing effect of the liquid substance. Micro-tube retains the non-proliferation pressure energy, better playing the role of impinging streams. The mechanism of refining and crushing is analyzed from three aspects: ultra-high pressure mechanism, analysis of the outstanding advantages of the micro-size to crush, and the transverse shear wave mechanism. On this basis, designing an ultra-high pressure micro-impact device of contraposition type applicable to liquid refinement enables experiment with good results. Technical methods in this paper are purely physical, any other additives are not added, the product has high purity, and especially suitable for food and pharmaceutical industries.

KEYWORDS: Ultra-high pressure, Micro-tube, Simulation analysis, Liquid refinement

1 INTRODUCTION

Research into impinging streams has stretched to over 20 countries and regions in the last several years, resulting in a lot of progress in the field. The concept of Impinging Streams was first proposed by former Soviet Professor Elperin [1] in the early 60s. Since the mid-1970s, Professor Tamir of Ben-Gurion University [2] in Israel and the research group led by Tamir conducted a thorough research on a variety of chemical unit operation processes such as the drying process flow impact, impact flow combustion process, impact flow extraction, and preparation of ultrafine powders are mainly applied. Wuhan Institute of Chemical Technology, Professor Wu Yuan [3-5] studied impinging stream drying, preparation of ultra-fine solid products using self-developed submerged circulation impinging stream reactor. East China University of Science and Technology [6-7] have also carried out researches on impinging stream reaction for preparing nano-materials.

In the preparation of ultra-fine powder, researches at home and abroad [8-9] are still focused on refinement of solid particles. With the development of industry, the liquid material thinning study has attained more and more attention. Due to huge differences in properties of liquid and solid material, theory, methods, and devices of solid particles refined are difficult to apply to liquid.

As the research object of this article is liquid substance, and not blocked pipe, so the important components of device can be designed into micro-tubule. This paper merge the ultra-high pressure technology and micro-jet technology into impinging stream technology, rely on a powerful source of power provided by ultra-high pressure and packing advantage of micro-jet to ensure high-speed collision of two shares of the fluid. The basic principle of the impinging stream is that two strands of opposite fluid flowing collide at the middle point. During the impact, collision between droplets and shear force, and the pressing force results in refined liquid. Based on the theoretical and simulation analysis, the design of ultra-high pressure micro jet impinging stream device is suitable for liquid substances refinement, and as a validation experiment.

2 STRUCTURE AND SIMULATION ANALYSIS

2.1 Structure

Figure 1 is contraposition type of two nozzles in micro impinging stream reactor. Its structure is symmetrical, that guarantee the reactor receiving uniform force. Micro nozzle is the main component of the reactor, consisting of two micro-tubes with a diameter of 0.1 mm. After the liquid under the ultra-high pressure is imported into the bypass pipe, it is then sprayed from the nozzle, in a formation of impinging stream to crush droplets. Two micro-tubes can be placed in parallel, and can also be opposed.
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2.2 Mathematical model

Because the micro-pipe is unbent, so standard

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho ku)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_e}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k + G_p - \rho \varepsilon \frac{\partial Y_i}{\partial x_i} + S_k
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_e}{\sigma_{\varepsilon}} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1\varepsilon} \left( \frac{k}{\varepsilon} \right) \left( G_k + C_3 \varepsilon \right) - C_{1\varepsilon} \rho \frac{\varepsilon^2}{k} + S_{\varepsilon}
\]

Among them, \( C_{1\varepsilon} = 1.44, C_{1\sigma} = 0.09, \sigma_k = 1.0, \sigma_{\varepsilon} = 1.3. \)

2.3 Meshing and boundary condition

Hexahedral unstructured grid division is adopted as the pipe diameter is very small, and so the nozzle grid encryption processing is required, as shown in Figure 2. Liquid water as flow medium, setting inlet pressure 100MPa, inlet boundary type is defined as pressure inlet, outlet boundary types is defined as pressure outlet, and other side is smooth non-slip surface by default.

2.4 Optimization of structure and key size

Liquid water which was pressurized above 100MPa flowed into micro-channel that the diameter is 0.1 mm and the length is 10 mm.

The key size of ultra-high pressure micro impinging stream reactor that is needed to optimize are distance between two tiny tubes 2L and outlet diameter D, and size 2L is mainly determined to the flow characteristics of constraint jet. \(^{15,6}\) In the core area, the central part of jet will still keep the original export speed \(v_0\), the length of the core area is \(8 \sim 20\) times the diameter of the nozzle. In this article the diameter of micro-tube is 0.1 mm, the length of jet core \(L = 0.1 \times (8 \sim 20) \text{mm} = (0.8 \sim 2) \text{mm}\). To simulate the four dimensions, L were 0.5 mm, 1.0 mm, 1.5 mm and 2.0 mm. Fluid flow out from the outlet pipe as fluid has most of the energy consumption in the impact area, so the outlet pipe of fluid crushing effect is small. Its main function is to collect grain products, so only simulate two sizes 0.5 mm and 1.0 mm, that is shown in Table 1.

Figure 1 Micro-impinging stream reactor of contraposition type

Figure 2 Local grid amplification of micro-tube
Table 1 The optimization of the structure and size

<table>
<thead>
<tr>
<th>Structure</th>
<th>The distance of two impinging stream (L/mm)</th>
<th>Diameter of outlet (D/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel type</td>
<td>0.5, 1.0, 1.5, 2.0</td>
<td>0.5, 1.0</td>
</tr>
<tr>
<td>Contraposition type</td>
<td>0.5, 1.0, 1.5, 2.0</td>
<td>0.5, 1.0</td>
</tr>
</tbody>
</table>

3 ANALYSES AND DISCUSSION

3.1 The determination of optimum structure and size

(1) Axis speed of parallel type

Figure 3 Axis velocity of parallel type (the diameter of outlet is 0.5mm)

Figure 4 Axis velocity of parallel type (the diameter of outlet is 1mm)

(2) Axis speed of contraposition type

Figure 5 Axis velocity of contraposition type (the diameter of outlet is 0.5mm)
By analyzing the axis velocity above figures, the following conclusion can be drawn:

1. Axis velocity jetting from micro-tube has a short increasing process, tend to be stable, which illustrates that the micro pipe can maintain high pressure and energy storage.

2. In order to get the best structure and dimension, hit the distance $L$ as abscissa, axial velocity as the ordinate draw scatter plot, as shown in Figure 7.

In Figure 7, there is a same rule: when diameter of outlet is 0.5 mm, axis velocity is greater than the axial velocity of 1.0mm outlet pipe. Reason is that the micro pipes can maintain high pressure and energy storage. The smaller the diameter of outlet, the more energy is not easy to release. Most of the energy will be used for strong impacting, enhancing the refinement of crushing effect. So the diameter of outlet pipe is determined to be 0.5 mm.

It can also be seen from Figure 7, the diameter of export is 0.5 mm, the axis speed of the two structure at $L = 1$ mm maximum, the axis speed of contraposition type is bigger than parallel type, at $L = 1$ mm, the axis velocity of contraposition type attain 470 m/s, while only 415 m/s of parallel type is attained. The reason is that the liquid of parallel type first hit the wall and then turn 90° to the second impact. When the fluid hit the wall, the energy is consumed, so impinging between the fluid basically doesn't work. But fluid of opposed type directly collide, assuming the velocity of single strand of fluid is $v$, then impinging velocity of the two strands of fluid can reach $2v$. At $L = 1.0$ mm, the axis speed can attain 515 m/s, when $L$ is bigger or smaller, the axis speed reduce, so according to the simulation result, the best impact distance is $L = 1.0$ mm.

3.2 The theoretical analysis of refining and crushing

3.2.1 Analysis of ultra-high pressure

Fluid under high pressure is possible to penetrate into the interior cavity of droplets and to reach an equilibrium state, if the outer fluid pressure is released slowly, the fluid inside the droplet has time to flow from the droplet so that the inner stress is about equal to the pressure of outer fluid, but if the outer pressure is quickly released, the internal fluid flow from droplets too late, the cavity has changed into the internal pressure container, so that explosion fragmentation of the droplet, to achieve the purpose of crushing.

The static pressure distribution of different radial positions is shown in Figure 8. At the position of the center of percussion the static pressure is up to 166MPa, the pressure is raised from the atmospheric pressure at the
outlet of the nozzle to 166MPa for a short time, and released to zero in a shorter time, and liquid particles in the role of alternating pressure will be effectively crushed.

![Figure 8 Static pressure distribution of different radial positions along the axial direction](image)

**Figure 8 Static pressure distribution of different radial positions along the axial direction**

### 3.2.2 Analysis of flow characteristics in micro-tube

In order to show the outstanding advantages of the micro-size to crush, while simulating of macro-dimension conduit, Figure 9 shows axial velocity distribution of micro-scale tube (d=0.1mm, d=1mm) and macro-scale tube (d=0mm). The horizontal axis indicates a dimensionless factor x/d (x represents the axial position of the pipe, d represents the diameter of the pipe).

![Figure 9 The axial velocity distribution of different diameter tube](image)

**Figure 9 The axial velocity distribution of different diameter tube**

Under the same inlet pressure (100MPa) condition, there is a period of acceleration during water flowing into the tube, in diameter of 0.1mm micro-sized tube, the maximum speed can reach 448m/s; tube of 1mm, the maximum speed can reach 407m/s; while it flows into the diameter of 10mm macro-tube, the maximum speed reached only 366m/s, then, since without the effect of external pressure, some energy is lost, all velocities declined, only a little decrease in the diameter 0.1mm of micro-size tube, in 0.1mm diameter of micro-tube, stable flow rate still attain 446m/s; in 1mm diameter of micro-tube, stable flow velocity reach 398m/s; while in diameter of 10mm macro-tube, stable flow rate can only reach 363m/s.

### 3.2.3 Impact stress wave

Impinging flow forming 2 times relative fluid velocity has great impact energy. During the impact of the impact energy into the instant impact force, its effect is not immediately propagated to all parts of the liquid particle, but from the power point by the stress wave spread to more distance. Shear stress waveform is divided into longitudinal wave and transverse wave. The longitudinal wave make the volume of the subject change, the transverse shear wave causes liquid shear-deformation, so the shear wave is the third refinement factor of liquid droplets.

### 3.3 Experiment

The result of experiment with structure of contraposition type, under 100MPa, is shown as Figure 10, which reveals that average diameter of apple juice is 0.118 micron, diameter of 75% of the particles was smaller than 0.158 micron, and the result is satisfactory.
4 CONCLUSION

(1) Combining ultra-high pressure technology and micro-tube with impinging stream, ultra-high pressure provide driving force, and micro-tube can keep the high pressure of non-proliferation, without loss, ensuring high-speed collision of two shares of the liquid.

(2) This paper simulated contraposition type and parallel type under 100 MPa, the axis speed of contraposition type is bigger than parallel type, so contraposition type has better refine effect.

(3) According to the simulation result, the best size is that impact distance is $L = 1.0 \text{ mm}$, diameter of outlet is 0.5mm.

(4) Analyzing the theories of refining and crushing from three aspects, ultra-high pressure is an important factor in crushing. Micro-pipe can keep the high pressure of non-proliferation, without loss, ensuring high-speed collision of two shares of the liquid. The transverse shear wave causes liquid shear-deformation. It is another refinement factor of liquid droplets.

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