Design of a new abrasive slurry jet generator

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Abstract. With the advantages of a low system working pressure, good jet convergence and high cutting quality, abrasive slurry jet (ASJ) has broad application prospects in material cutting and equipment cleaning. Considering that the generator plays a crucial role in ASJ system, the paper designed a new type ASJ generator using an electric oil pump, a separate plunger cylinder, and a spring energized seal. According to the determining of structure shape, size and seal type, a new ASJ generator has been manufactured and tested by a series of experiments. The new generator separates the abrasive slurry from the dynamic hydraulic oil, which can improve the service life of the ASJ system. And the new ASJ system can reach 40 MPa and has good performance in jet convergence, which deserves to popularization and application in materials machining.

1. Introduction
As a branch of abrasive water jet machining, abrasive slurry jet machining (ASJM) aims at improving the uniformity of abrasive particles and reducing the nozzle wear. In recent years, the scholars carried out a lot of research works and obtained numerous achievements in ASJ.

Liu [1] used the abrasive slurry jet to incise the carbon steel and aluminum plate under different pressure when the jet contained polyacrylamide. After the experiment, she discovered it has different depths with different concentrations of polyacrylamide jets. Kowsari [2] made an experiment using abrasive slurry jet machining to drill holes on the glass plate, 110 copper and 6061 Aluminum. The jets pressure was 4 MPa to 7 MPa containing 50 weight parts per Million polyethylene oxide. He revealed that elasticity and viscosity of the abrasive slurry jet had a strong effect on the shape, depth, and diameter of drill holes. Qi [3] investigated a machining process on quartz crystals, and the pressure of abrasive slurry jet was 8 MPa to 20 MPa. He found the material removal process, surface roughness and channel depth depend on the characteristics of abrasive slurry jets. Haghbin [4] carried out experiments to compare the abrasive water jet machining (BWJM) and abrasive slurry jet machining (ASJM) in glasses and aluminum cutting. When the pressure was 235 MPa, using 25 μm diameter Al2O3 particles, the ASJM was 50% lower centerline waviness and 16% lower centerline roughness than the AWJM. Nouraei [5] compared the characteristics of abrasive slurry jet micro-machining and abrasive air jet micro-machining. Seiji [6] used different types of particles: steel bead, alumina, glass bead and plastic shot to investigate abrasive slurry jets. He found that the larger particles jets are more breakable than small ones. Luo [7] made an experiment under the pressures of 4.5 MPa, nozzle diameter 400 μm to study the jet erosion morphology and material mechanism. With different incident angles having different polishing depths, the 30 deg incident angle ensured the largest depth. Wan [8] found that the pump shutdown resulted in the blocking of ASJ nozzle and pipe. In order to increase the nozzle service life, Katz [9] designed an innovative porous nozzle using
lubricant oil device with abrasive particles. Liu [10] and Cadavid [11] used electrochemical slurry and helium atmosphere to enhance abrasive slurry jet machining.

In recent years, most scholars focus on the structure of abrasive slurry jet and preparation of slurry. However, there are fewer studies on the abrasive slurry jet generator. The paper presented a novel ASJ generator using a plunger cylinder, which can isolate the abrasive slurry from the dynamic hydraulic oil. The performed experiments verified the feasibility of the new ASJ system.

2. ASJ machining system

As shown in figure 1, the paper presents an ASJ system, which contains the new generator. The electric oil pump was adopted as a power source, which can provide power oil within 63 MPa by adjusting the pressure (1 MPa is the minimum pressure). The system was used by the device of the hydraulic cylinder with the abrasive slurry. The double independent abrasive slurry loop and dynamic oil circulation avoided the impact of the hydraulic oil.

![Figure 1. Abrasive slurry jet system diagram:](image)

1. oil tank; 2. filters; 3. oil pump; 4. overflow valve; 5. pressure gauge; 6. energy accumulator; 7. magnetic exchange valve; 8. power cylinder; 9. ASJ generator; 10. globe stop valve; 11. globe stop valve; 12. water tank 13. abrasive slurry mix tank; 14. nozzle.

If the pressure of the hydraulic is higher than the set pressure, the hydraulic oil will through overflow valve flow back into the oil tank. In order to observe the pressure of hydraulic oil and abrasive slurry we designed two pressure gauges (5(a) and 5(b)). The energy accumulator is used to absorb the pressure pulsation of the hydraulic pump to ensure that the system pressure is stable. When open the global stop valve 11 and close valve 10, we can pump water from the water tank to clearing the ASJ generator. Figure 2 shows the flow of abrasive slurry and hydraulic oil for the ASJM feeding and jetting processes.

It is simple, economical and easy to operate for the working principle of the system. It is set as 50 MPa for the design maximum pressure of the system power resource, which can realize abrasive slurry pressure within 1-40 MPa by regulating the infinite pressure and provide support for the abrasive slurry jet under different pressure conditions, polishing, and cutting performance.
3. **Abrasive slurry generator**

Figure 3 shows the design of the slurry generator. The plunger type cylinder of the overall structure is unidirectional, driven by dynamic plunger cylinder to run the suction and compression processes.

![Diagram of the abrasive slurry generator](image)

**Figure 3.** The abrasive slurry jet generator:

1. jet connection joint; 2. generator cylinder bottom; 3. generator plunger; 4. pressure gauge holes; 5. generator cylinder; 6. spring energized seal; 7. O-type ring; 8. oil filter point; 9. scraper seal; 10. flange hole; 11. generator extended period; 12. fixed bolt; 13. abrasive slurry drain hole.

### 3.1. The operating principle of the generator

As shown in figure 1, the stop valve 10 is turned off and the stop valve 11 is opened, and the abrasive slurry generator is driven by power cylinder. The abrasive slurry is suctioned into the generator when the power cylinder goes back. The power cylinder takes forward movement after the electromagnetic directional valve reverses direction. The abrasive slurry will be turned to the jet stream by the driven generator plunger from the nozzle jet after the increasing pressure. As shown in figure 2, generator extended period plays a guiding role in fixing the spring energized seal. The friction can be reduced by adding the lubrication through the oil injection hole 8, between the plunger and the extended. Jet pressure can be adjusted in a range of 1-40 MPa through regulating the electric pump oil pressure, which is used to study the cutting performance of the abrasive slurry jet in various pressure conditions.

### 3.2. The design of the main technical performance parameters of the generator

The Bernoulli equation has the following form:
where $p_1$ is jet pressure, $\rho$ is fluid density, $v_1$ is jet velocity, $p_2$ is internal fluid pressure, $v_2$ is internal fluid velocity, $h$ is the vertical height.

When the generator is placed in the horizontal position, we get $h_1 = h_2$.

\[ p_1 + \frac{\rho v_1^2}{2} + \rho g h_1 = p_2 + \frac{\rho v_2^2}{2} + \rho g h_2 \]  

(1)

The parameter $p_1$ is reduced to zero after the fluid leaves the nozzle. The level of the fluid speed ($v_2$) is a few millimeters per second in the generator, while the internal fluid velocity can be neglected, as compared to the jet velocity.

\[ \frac{\rho v_1^2}{2} = p_2 \]  

(3)

The maximum fixed pressure is 40 MPa when designing the inner part of the abrasive slurry generator. Assuming $\rho=1.0*10^3$ kg/m$^3$, $v_1$ can be proved to 282.8 m/s, if the fluid is considered as an ideal one. This amounts to about 5-6 minutes when designing the single continuous stream. There are two kinds of nozzle diameter specifications, namely 0.6 mm and 0.8 mm. The inner space capacity in the generator is about 30 liters. The standard seamless steel pipe will be chosen when considering the economy and process. The plunger stroke is designed to 500 mm, the external diameter of the generator plunger is designed to 273 mm, the abrasive slurry injection volume is 29.23 L.

The equation of the hydraulic oil cylinder thickness is as follows:

\[ \delta = \delta_0 + C_1 + C_2 \]  

(4)

\[ \delta_0 \geq \frac{P_{max} D}{2.3 \sigma_p - 3P_{max}} \]  

(5)

where $C_1$ is cylinder outer diameter tolerance allowance, $C_2$ is corrosion allowance, $P_{max}$ is the maximum operating pressure in the cylinder, $D$ is cylinder inner diameter, $\sigma_p$ is allowable stress.

The rated pressure in the design system is 40 MPa. In other words, $P_{max} = 40$ MPa, the inner diameter of the generator cylinder is 274.5 mm, but it does not meet the requirements of the material mechanics using the ordinary pipe steel. Alternatively, the 27SiMn seamless steel tube can be selected as cylinder material. Considering the convenience and economy, the generator keeps a steady speed when reaches the rated working pressure that is regarded as working under the static load, so take 4 as the safety coefficient, $\sigma_p = 250$ MPa, and $\delta_0 \geq 24.13$mm. According to the national standard, the model $\Phi325*30$ seamless tube is chosen. It is flat at the bottom of the cylinder of the generator, the thickness $\delta_1$ can be calculated, according to the formula of the intensity of the embedded disk,

\[ \delta_1 \geq 0.433 * D \frac{P}{\sigma_p} \]  

(6)

where $D$ is the inner diameter of the generator, $\delta_0 \geq 60.1$mm. The design thickness is 63 mm, which can be achieved by using the 63 mm-thick 45 carbon steel tube.

Long-term operation will lead to wear and rust accumulation inside the generator, considering the working medium is an abrasive slurry. To improve the hardness and rusting resistance, the inside surfaces of the whole generator are covered with chromium plating. Chromium plating layer has good chemical stability, which can be applied to the different abrasive slurry additives, in order to prevent the corrosion due to acidic and alkaline slurry in the generator and reduce its internal surface wear.
3.3. The design of the generator seal
The rated internal pressure is 40 MPa inside the generator, which falls into the high-pressure range, the working medium contains garnet abrasive particles, and seal needs to be applied to the high pressure and wear resistant properties, the spring energized seal (figure 4) is selected to use with O-rings, which consists of two parts: sealing and spring. Sealing is filled with PTFE, and spring is stainless steel that is used in heavy-duty conditions, has low friction coefficient, good wear resistance, high-pressure resistance, stable composition, etc. The spring perforce will compress seal lip to ensure the sealing of the plunger when the generator internal pressure is low. The radial force between the liquid and seal lip, which is mainly invoked by the liquid, increases with the liquid pressure in the system. The spring perforce can also be used to prolong the service life by compensating backlash of the seal lip and plunger. The spring-invoked seal designed in this system is used for reciprocating motion whose pressure is below 60 MPa.

![Figure 4. (a) Spring energized seal (b) Installation instruction.](image)

4. Experimental
Figure 5 shows the proposed ASJ machine design, which mainly consists of power system, ASJ generator system, and control system. The water jet, slurry water jet, and abrasive slurry jet tests were conducted, respectively, when the abrasive slurry generator pressure was set as 5 MPa and 40 MPa. The methyl cellulose was used as the thickener, at weight concentration of 2.0 percent. The diameter of garnet sand used was 74 μm, and the volume concentration was 10%. Figure 6 shows the comparison of the experimental jets structure when the pressure is 5 MPa. It can be observed that the aggregation of the slurry jet and abrasive slurry jet outperforms the water jet by its cutting performance.

![Figure 5. The proposed ASJ machine design.](image)

5. Conclusions
- A simple and efficient design of the abrasive slurry generator is proposed and validated. The double independent system can avoid leakage influence of the system of hydraulic oil and the abrasive slurry. An abrasive slurry jet can be achieved in the pressure range of 10-40 MPa.
- Spring energized seal, which is filled with PTFE, is applicable of the abrasive slurry jet generator at pressures below 40 MPa.
The particular generator service life can be assessed by additional tests of the ASJ system.

Figure 6. The appearance of water, slurry, and abrasive suspension at pressure of 5 MPa.

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