SUPERSONIC NOZZLE VORTEX TUBE REFRIGERATION AND NANO-FLUID MINIMAL QUANTITY LUBRICATION COUPLING SUPPLY SYSTEM

Field of the Invention

The present invention relates to the technical fields of refrigeration and machining, and particularly relates to a supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system.

Background Art

Nano-particle jet minimal quantity lubrication grinding is a green, clean and energy-saving grinding technology. Based on the heat transfer enhancement theory that the heat transfer capacity of solid is greater than that of liquid and the heat transfer capacity of liquid is greater than that of gas, a certain amount of nano-scale solid particles are added into degradable minimal quantity lubrication oil to generate nano-fluid, and the nano-fluid is atomized via high-pressure air and delivered to a grinding zone in a jet manner. The high-pressure air mainly plays a role of cooling, chip removal and fluid delivery; the minimal quantity lubrication oil mainly plays a lubricating role; and the nano-particles increase the heat transfer capacity of the grinding zone and play a cooling role. Meanwhile, the nano-particles have good anti-wear and anti-friction properties and high carrying capacity. However, although nano-fluid jet minimal quantity lubrication can reduce the grinding temperature to a certain extent, it is still inferior to cast grinding, and still causes the phenomenon of grinding burn for materials difficult to process.

Thus, the technical problem to be solved urgently by those skilled in the art is how the temperature of the grinding zone can be lowered to avoid the grinding burn phenomenon, ensure the surface integrity of a workpiece and then improve the machining quality of the workpiece.

Through retrieval, Changhe Li invented a low-temperature cooling and nano-particle jet minimal quantity lubrication grinding coupling grinding medium supply system (patent No.: 201310180218.5); Songmei Yuan designed a low-temperature minimal quantity lubrication system (patent No.: 201010128275.5); and Bao Zhang invented a low-temperature quasi-dry, minimal quantity lubrication cooling device (patent No.: 201620263903.3).

However, in the prior art, the minimal quantity lubrication system, the minimal quantity lubrication

device and the low-temperature gas generating device are all assembled on a certain basis, and are not deeply improved from the refrigeration principle and structure. Moreover, in the prior art, the minimal quantity lubrication pump is mostly a pneumatic pump controlled by a gas frequency generator, and thus provides limited frequency and low output pressure. After nano-particles are added into the lubricant, the viscosity of the lubricant is increased, the flowability becomes poor, and the gas supply power is insufficient, so that the pneumatic pump cannot work. The low-temperature gas generating device consumes huge compressed air. In production practice, an air compressor not only drives large-sized machine tools such as a grinding machine and the like to work, but also drives a plurality of low-temperature gas generating devices and a plurality of pneumatic pumps, so that the operating burden of the air compressor is further increased.

Summary of the Invention

The embodiments of the invention provide a supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system for solving the problems of high temperature of a grinding zone, poor surface integrity of a workpiece and low machining quality of the workpiece in the prior art.

In order to solve the above technical problems, the embodiments of the present invention adopt the following technical solution:

The embodiments of the invention provide a supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system, including a low-temperature gas generating device, a nano-fluid minimal quantity lubrication supply system, a gas distribution control valve and at least one low-temperature oil gas external mixing atomizing nozzle, wherein the low-temperature gas generating device includes a vortex tube nozzle, a volute diverter and a vortex tube heat pipe sequentially arranged in an intake sleeve; a sealing end cover is arranged at one end of the intake sleeve, and a nozzle gas outlet pipe of the vortex tube nozzle penetrates out of the sealing end cover; a nozzle flow channel slot communicated with the gas path of the nozzle gas outlet pipe is formed in the intake end of the vortex tube nozzle, so that compressed air is sprayed out from the nozzle gas outlet pipe via the nozzle flow channel slot; one end of the volute diverter is communicated with a compressed air inlet of the intake sleeve, and the other end is communicated with the nozzle flow channel slot; the vortex tube heat pipe penetrates out of the end face of the other end of the intake sleeve, and is communicated with the nozzle flow channel slot; a gas outlet

tee joint communicated with the gas path is arranged at the end of the vortex tube heat pipe penetrating out of the intake sleeve, and a cool gas proportion adjusting valve is arranged in one port of the gas outlet tee joint; a gas inlet quick plug of the gas distribution control valve is communicated with the nozzle gas outlet pipe of the vortex tube nozzle via a thermal insulation pipe; the quantity of gas outlet quick plugs of the gas distribution control valve is matched with that of the low-temperature oil gas external mixing atomizing nozzles, and the gas outlet quick plugs are respectively communicated with the corresponding low-temperature oil gas external mixing atomizing nozzles via thermal insulation pipes; the nano-fluid minimal quantity lubrication supply system includes a camshaft and a pump which are arranged in a box, and the camshaft is connected with an electromagnetic speed adjustment motor via a camshaft key; a shell piston cavity, an oil inlet cavity and a one-way valve cavity communicated with each other are sequentially formed in the pump; one end of a piston presses against a cam on the camshaft and is connected with the bottom surface of the pump via a cam spring, and the other end stretches into the shell piston cavity of the pump and can move relative to the pump; the oil inlet cavity is communicated with an oil cup pipeline via an oil inlet; the one-way valve cavity is communicated with oil outlets; the quantity of the oil outlets is matched with that of the low-temperature oil gas external mixing atomizing nozzles, and the oil outlets are communicated with corresponding low-temperature oil gas external mixing atomizing nozzle pipelines respectively.

Optionally, the low-temperature gas generating device further includes a water tank; the water tank is sleeved on the outer wall of the vortex heat pipe; the water tank is arranged between the intake sleeve and the gas outlet tee joint, the end face of one end of the water tank is in tight contact with the end face of one end of the intake sleeve via a sealing gasket, the end face of the other end of the water tank is in tight contact with the end face of one end of the gas outlet tee joint, and the inner wall of the water tank is in tight contact with the outer wall of the vortex heat pipe via a Y-shaped sealing ring.

Optionally, the outer diameter of the volute diverter is equal to the inner diameter of the intake sleeve, and the cross section of the inner wall of the volute diverter is of Archimedes spirals.

Optionally, the supersonic nozzle includes a nozzle boss, a nozzle disc and a nozzle gas outlet pipe; a cool gas passage is formed inside the nozzle disc; the nozzle boss is formed on the end face of one end of the nozzle disc, a through hole is formed in the center of the nozzle boss, nozzle flow channel slots are formed in the inner wall of the through hole, the nozzle flow channel slots divide

the inner cavity of the through hole into a plurality of vortex chambers, and the volute diverter is arranged on the outer wall of the nozzle boss; the nozzle gas outlet pipe is arranged on the end face of the other end of the nozzle disc, and the inner diameter of the nozzle gas outlet pipe is gradually increased along the gas delivery direction; and the nozzle flow channel slots, the cool gas passage and the gas path of the nozzle gas pipe are communicated with each other.

Optionally, the center lines of the nozzle flow channel slots include one of equiangular spirals, Archimedes spirals and rectangular lines.

Optionally, threads are formed on the outer wall of the vortex heat pipe; or a plurality of ribs are uniformly arranged on the outer wall of the vortex heat pipe.

Optionally, the cool gas proportion adjusting valve includes a stud and a nut matched with the stud; the stud is a flat end face conical stud, and the tapered angle of the stud is between 35 and 55 degrees; an elastic collar is arranged close to the tapered angle of the stud on the stud, and an O-shaped sealing ring is arranged away from the tapered angle of the stud.

Optionally, the gas distribution control valve includes a shell; a plurality of shell gas channels independent from each other are formed inside the shell, and each shell gas channel is communicated with the gas inlet quick plug and the gas outlet quick plug; a gas control valve is arranged on the pipeline of each shell gas channel, and the gas control valve can move vertical to the gas channel.

Optionally, the low-temperature oil gas external mixing atomizing nozzle includes a coiled pipe, a nozzle gas inlet pipe, a thermal insulation pipe, a nozzle tapered pipe, a nozzle sleeve and a nozzle needle; one end of the coiled pipe is in threaded connection with one end of the nozzle gas inlet pipe, and the other end of the nozzle gas inlet pipe is in threaded connection with one end of the nozzle sleeve; the nozzle tapered pipe and the nozzle needle are sequentially arranged in the nozzle sleeve along the gas spray direction, and one end of the nozzle needle is communicated with the tapered end of the nozzle tapered pipe; a tapered pipe rib plate is further arranged on the outer wall of the plane end of the nozzle tapered pipe, and the tapered pipe rib plate is provided with at least one tapered pipe rib plate vent; the thermal insulation pipe is arranged in the nozzle gas inlet pipe, one end of the thermal insulation pipe is communicated with the plane end of the nozzle tapered pipe, and the other end of the thermal insulation pipe is pressed on a second step of the nozzle gas inlet pipe; one end of an oil delivery pipe penetrates through the pipeline of the thermal insulation pipe and is communicated with the nozzle needle, and the other end penetrates through the pipeline

of the coiled pipe and is communicated with the oil outlet of the nano-fluid minimal quantity lubrication supply system.

Optionally, the angle of the tapered end of the nozzle sleeve is the same as that of the tapered end of the nozzle tapered pipe, and the inner diameter of the straight part of the nozzle sleeve is greater than that of the straight part of the nozzle tapered pipe.

The technical solution provided by the embodiments of the present invention has the following advantages:

(1) The system exerts all the advantages of nano-fluid minimal quantity lubrication grinding, overcomes the defect of grinding burn caused by too high grinding temperature of the nano-fluid minimal quantity lubrication grinding, improves the surface integrity and machining precision of a machined workpiece, and realizes low-carbon and green cleaner production in an efficient, low-consumption, environment-friendly and resource-saving manner.

(2) The low-temperature gas generating device is designed on the basis of vortex tube refrigeration principle. The vortex tube nozzle is a supersonic nozzle, so that the outlet velocity of the vortex tube nozzle is improved. Further, different flow line types are formed for the flow channels of the vortex tube nozzle to improve the energy separation degree of gas at the vortex tube nozzle. Furthermore, a different heat transfer enhancement measure is adopted for the vortex tube heat pipe to promote the dissipation of energy in the vortex tube heat pipe to the outside and reduce the heat transfer of high-temperature free vortex energy to the low-temperature forced vortex direction.

(3) Different from the traditional pneumatic lubrication device, the nano-fluid minimal quantity lubrication supply system is driven by a motor, so that the supplied nano-fluid flow can be controlled more conveniently and precisely, higher power can be provided, and the problem that the pneumatic minimal quantity lubrication device cannot work due to too high viscosity of the nano-fluid is solved. Moreover, the motor drive adopted in the system is more beneficial to realizing intelligent and automatic control of the minimal quantity lubrication device, and the oil outlet capacity is controlled exactly by conveniently adjusting the revolving speed of the motor. Further, the motor and the machining equipment are connected via a computer into a closed loop system, and when the computer detects that the machining equipment needs to change the oil supply flow via an online signal of the grinding force or grinding temperature or the like, the revolving speed of the motor is automatically adjusted to provide a more convenient way for realizing intelligent and automatic flow adjustment of minimal quantity lubrication later.

(4) The gas distribution control valve can accurately control the gas flow while reducing partial loss of energy as much as possible based on the principle of a gate valve, and can be prevented from loosening due to gas shock by using a mechanical structure self-locking preventing control valve.

(5) The low-temperature oil gas external mixing atomizing nozzle can prevent the flowability of nano-fluid from becoming poor due to the fact that the temperature of gas is too low and is lower than the pour point of the nano-fluid, and the phenomenon of frost condensation on the inner wall of the nozzle is avoided by adopting an external mixing manner.

Brief Description of the Drawings

The accompanying drawings herein are incorporated into the specification, constitute one part of the specification, illustrate the embodiments of the present invention, and are used for interpreting the principle of the present invention together with the specification.

Fig. 1 is a structural schematic diagram of a supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system;

Fig. 2 is an exploded view of embodiment 1 of a vortex tube system;

Fig. 2(a) is an assembly view of embodiment 1 of the vortex tube system;

Fig. 3 is an exploded view of embodiment 2 of the vortex tube system;

Fig. 3(a) is an assembly view of embodiment 2 of the vortex tube system;

Fig. 4 is a front view of a vortex tube intake sleeve;

Fig. 4(a) is an A-A section view of Fig. 4;

Fig. 5 is a front view of a vortex tube volute diverter;

Fig. 6 is a front view of a vortex tube supersonic nozzle;

Fig. 6(a) is a schematic diagram of embodiment 1 of the supersonic nozzle;

Fig. 6(aa) is a schematic diagram of a flow channel of embodiment 1 of the supersonic nozzle;

Fig. 6(b) is a schematic diagram of embodiment 2 of the supersonic nozzle;

Fig. 6(ba) is a schematic diagram of a flow channel of embodiment 2 of the supersonic nozzle;

Fig. 6(c) is a schematic diagram of embodiment 3 of the supersonic nozzle;

Fig. 6(ca) is a schematic diagram of a flow channel of embodiment 3 of the supersonic nozzle;

Fig. 7 is an assembly view of the intake sleeve, the volute diverter and the volute supersonic nozzle;

Fig. 8(a) is a schematic diagram of embodiment 1 of a vortex tube heat pipe;

Fig. 8(b) is a schematic diagram of embodiment 2 of the vortex tube heat pipe;

Fig. 8(c) is a schematic diagram of embodiment 3 of the vortex tube heat pipe;

Fig. 9 is an assembly view of a vortex tube cool flow proportion adjusting valve, an O-shaped sealing ring and an elastic collar;

Fig. 10 is an exploded view of an MQLSS;

Fig. 11(a) is a front view of a total assembly view of the MQLSS;

Fig. 11(b) is a right view of the total assembly view of the MQLSS;

Fig. 12(a) is a full-section front view of a partial assembly view of the MQLSS;

Fig. 12(b) is a full-section right view of the partial assembly view of the MQLSS;

Fig. 13(a) is a top view of an MQLSS pump;

Fig. 13(b) is a front view of the MQLSS pump;

Fig. 13(c) is an A-A section view of Fig. 13(a);

Fig. 13(d) is a B-B section view of Fig. 13(b);

Fig. 14 is a front view of an MQLSS piston;

Fig. 15 is a front view, a top view and a C-C section view of an MQLSS oil outlet;

Fig. 16 is a top view and a front view of an MQLSS pump and box connecting fixing plate;

Fig. 17 is a front view of an MQLSS upper box;

Fig. 17(a) is a D-D section view of Fig. 17;

Fig. 18 is a front view of an MQLSS camshaft;

Fig. 19 is a schematic diagram of a coupling for connecting an MQLSS camshaft with a motor;

Fig. 20 is a schematic diagram of an MQLSS electromagnetic speed adjustment motor;

Fig. 21 is an exploded view of embodiment 1 of a GDCV;

Fig. 22 is an assembly view of a GDCV gas control valve;

Fig. 23(a) is an assembly top view of the GDCV;

Fig. 23(b) is an assembly left view of the GDCV;

Fig. 23(c) is an A-A section view of Fig. 23(a);

Fig. 24 is a top view of embodiment 1 of a GDCV shell;

Fig. 24(a) is a B-B section view of Fig. 24;

Fig. 24(b) is a C-C section view of Fig. 24;

Fig. 25 is a front view of a GDCV gas control valve joint;

Fig. 26 is an exploded view of embodiment 2 of the GDCV;

Fig. 27 is a front view of an assembly view of embodiment 2 of the GDCV;

Fig. 27(a) is a D-D section view of Fig. 27;

Fig. 28 is an assembly view of embodiment 2 of the GDCV;

Fig. 28(a) is an E-E section view of Fig. 28;

Fig. 29 is an exploded view of a nozzle;

Fig. 30 is a partial assembly view of the nozzle;

Fig. 30(a) is a partial enlarged view of Fig. 30;

Fig. 31 is a front view of a nozzle needle;

Fig. 32(a) is an isometric view of a nozzle tapered pipe;

Fig. 32(b) is a front view of the nozzle tapered pipe;

Fig. 32(c) is an A-A section view and an isometric view of Fig. 32(b);

Fig. 33 is a front view of a nozzle sleeve;

Fig. 34 is a front view of a nozzle gas inlet pipe;

Fig. 35(a) is a front view of a nozzle fixing block 1;

Fig. 35(b) is a front view of a nozzle fixing block 2;

In which: 101-intake sleeve, 102-volute diverter, 103-vortex tube nozzle, 104-first sealing gasket, 105-sealing end cover, 106-second sealing gasket, 107-third sealing gasket, 108-vortex tube heat pipe, 109-water tank, 110-hot gas outlet tee joint, 111-cool gas proportion adjusting valve, 112-O-shaped sealing ring, 113-elastic collar, 114-Y-shaped sealing ring, 201-box nut, 202-box gasket, 203-box nut gasket, 204-box bolt, 205-box upper cover, 206-fixed plate, 207-fixed plate inner hexagon positioning screw, 208-fixed plate gasket, 209-pump, 210-oil outlet, 211-oil cup, 212-first quick plug, 213-second oil conduit with valve, 214-first oil conduit with valve, 215-one-way valve spring, 216-one-way valve plug, 217-oil outlet positioning screw, 218-second quick plug, 219-pump positioning screw, 220-cam spring, 221-first star-like sealing ring, 222-second star-like sealing ring, 223-first Y-shaped sealing ring, 224-second Y-shaped sealing ring, 225-piston, 226-camshaft key, 227-camshaft, 228-bearing seat bolt, 229-bearing seat, 230-lower box, 231-electromagnetic speed adjustment motor, 232-coupling, 301-GDCV gas inlet quick plug, 302-first sealing gasket, 303-first GDCV shell, 304-second sealing gasket, 305-gas control valve joint, 306-gas control valve, 307-O-shaped sealing ring, 308-third sealing gasket, 309-gas outlet quick plug, 310-second GDCV shell, 311-second inlet gasket, 312-second intake end cover, 313-second bolt gasket, 314-second bolt, 401-nozzle needle, 402-nozze sleeve, 403-nozzle tapered pipe, 404-nozzle sealing gasket, 405-thermal insulation pipe, 406-nozzle gas inlet pipe, 407-first

nozzle sealing ring gasket assembly, 408-second nozzle sealing gasket assembly, 409-coiled pipe, 410-fixing block inner hexagon screw, 411-first nozzle fixing block, 412-second nozzle fixing block, 413-oil delivery pipe, 10101-intake sleeve heat pipe outlet, 10102-compressed air inlet, 10301-nozzle boss, 10302-nozzle cool gas outlet, 10303-nozzle disc, 10304-nozzle gas outlet pipe, 10305-nozzle flow channel slot, 10306-nozzle vortex chamber, 10801-first vortex tube heat pipe, 10802-second vortex tube heat pipe, 10803-third vortex tube heat pipe, 11101-cool gas proportion adjusting valve stud, 11102-cool gas proportion adjusting valve nut, 20501-upper box flange hole, 20502-upper box threaded connecting hole, 20601-first fixed plate connecting hole, 20602-second fixed plate connecting hole, 20901-shell piston cavity, 20902-first shell gas relief hole, 20903-second shell gas relief hole, 20904-first oil inlet cavity, 20905-second oil inlet cavity, 20906-one-way valve cavity, 20907-positioning hole, 20908-second oil inlet, 20909-first oil inlet, 20910-MQL fixed plate threaded hole, 20911-first oil inlet cavity flow channel, 21001-oil outlet flow channel, 21002-one-way valve spring slot, 21003-threaded positioning hole, 22501-first piston star-like sealing ring slot, 22502-second piston star-like sealing ring slot, 22503-first piston Y-shaped sealing ring slot, 22504-second piston Y-shaped sealing ring slot, 22701-cam key groove, 22702-cam, 30301-GDCV shell gas inlet, 30302-GDCV shell gas control valve connector, 30303-GDCV shell gas outlet, 30601-gas control valve sealing groove, 30602-gas control valve stud, 30603-first gas control valve nut, 30604-second gas control valve nut, 40301-tapered pipe needle passage, 40302-tapered pipe rib plate, 40303-tapered pipe vent, 40601-first intake pipe step, 40602-second intake pipe step, 40603-intake pipe passage.

Detailed Description of the Embodiments

In order that those skilled in the art better understand the technical solution in the present invention, a clear and complete description of the technical solution in the embodiments of the present invention will be given below, in combination with the accompanying drawings in the embodiments of the present invention. Apparently, the embodiments described below are merely a part, but not all, of the embodiments of the present invention. All of the other embodiments, obtained by those of ordinary skill in the art based on the embodiments of the present invention without any inventive effort, fall into the protection scope of the present invention.

As shown in Fig. 1, a supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system is composed of a low-temperature gas generating device 1

(vortex tube for short), a nano-fluid minimal quantity lubrication supply system 2 (MQLSS for short), a gas distribution control valve 3 (GDCV for short) and low-temperature oil gas external mixing atomizing nozzles 4 (nozzles for short).

Fig. 2 is an exploded view of embodiment 1 of a vortex tube system, with each part being shown.

As shown in Fig. 2(a), the vortex tube system in embodiment 1 is composed of an intake sleeve 101, a volute diverter 102, a vortex tube nozzle 103, a first sealing gasket 104, a sealing end cover 105, a second sealing gasket 106, a third sealing gasket 107, a vortex tube heat pipe 108, a water tank 109, a hot gas outlet tee joint 110, a cool gas proportion adjusting valve 111, an O-shaped sealing ring 112, an elastic collar 113 and a Y-shaped sealing ring 114. Firstly, the second sealing gasket 106 is mounted on the vortex tube heat pipe 108 and then the whole is mounted inside the intake sleeve 101. Next, the volute diverter 102 is mounted at a nozzle boss 10301, the first sealing gasket 104 is mounted at a vortex tube nozzle cool gas outlet pipe 10304, and the whole is mounted inside the intake sleeve 101 and closely attached to the end of the vortex tube heat pipe 108. Finally, the intake sleeve 101 and the inner assembled parts are sealed by using the sealing end cover 105. Then, the third sealing gasket 107, the Y-shaped sealing ring 114 and the water tank 109 are mounted at the other end of the vortex tube heat pipe 108 in sequence. Next, the cool gas proportion adjusting valve 111 is mounted inside the hot gas outlet tee joint 110 to cooperate with the elastic collar 113 and the O-shaped sealing ring 112. Then, the whole cool gas proportion adjusting valve 111, the O-shaped sealing ring 112 and the elastic collar 113 and the whole hot gas outlet tee joint are mounted on the vortex tube heat pipe 108, and are tightened to fit with the water tank 109 and tightly press the water tank 109 on the intake sleeve 101 at the same time.

When embodiment 1 is adopted, the gas flow velocity inside the vortex tube heat pipe 106 is relatively high, fluid flows turbulently in the pipe and is subjected to forced convective heat transfer with the wall, and the heat transfer coefficient is α_{1i}. The outer wall of the vortex tube heat pipe 106 is immersed into cooling water to undergo natural convective heat transfer, and the heat transfer coefficient of the cooling water and the wall is α_{1w}. The heat transfer coefficient of the cooling water and the wall is further greater than that of the air and the wall, i.e., $\alpha_{1i}<\alpha_{1w}$.

Fig. 3 is an exploded view of embodiment 2 of a vortex tube system, with each part being shown.

As shown in Fig. 3(a), different from embodiment 1 of the vortex tube system, the water tank 109 as well as the third sealing gasket 107 and the Y-shaped sealing ring 114 for sealing the water tank 109 are not mounted in this embodiment. In this embodiment, although the refrigerating effect

declines a little, it is small, convenient to mount and reliable, so embodiment 1 is preferred if there is no special requirement. When embodiment 2 of the vortex tube system is adopted, air inside the vortex tube heat pipe 108 and the wall undergo forced convective heat transfer with the heat transfer coefficient α_{2i}, the exterior of the heat pipe 108 and air undergo natural convective heat transfer with the heat transfer coefficient α_{2w}, air is inside and outside the vortex tube heat pipe 108 at the moment, and the forced convective heat transfer is further stronger than the natural convective heat transfer, i.e., $\alpha_{2i}>\alpha_{2w}$.

As shown in Figs. 4 and 4(a), the intake sleeve 101 is provided with an air inlet, and compressed air enters the volute diverter 102 tangentially. The intake sleeve 101 is matched with the volute diverter 102 to divert the compressed air, so that the air uniformly enters each nozzle flow channel 10305. The intake sleeve is provided with an intake sleeve heat pipe outlet 10101 and a compressed air inlet 10102. Further, the length l_{11} of the compressed air inlet is equal to the depth of the nozzle flow channel.

As shown in Fig. 5, the outer diameter of the volute diverter 102 is d_{16} and is the same as the inner diameter of the intake sleeve 101, and the line type of the inner wall of the volute diverter 102 is Archimedes spiral.

$$d_{15} = d_{13}e^{\frac{\phi M}{2\pi\rho_0 K l_{11}}}$$

In the formula, d_{15} is the inner diameter of the volute diverter, *m*; d_{13} is the outer diameter of the supersonic nozzle flow channel, *m*; θ is the angle between each point on each inner diameter of the volute diverter and the maximum diameter, *rad*; *M* is the inlet flow of compressed air, *kg/s*; ρ_0 is the density of compressed inlet air, kg/m^3; l_{11} is the width of the volute diverter, *m*; and K is an Archimedes spiral constant.

Figs. 6, 6(a), 6(aa), 6(b), 6(ba), 6(c) and 6(ca) show three embodiments of the vortex tube of the supersonic nozzle in this solution. Fig. 6 is a full-section view of a front view of the three embodiments. The supersonic nozzle is divided into a nozzle boss 10301, a nozzle disc 10303 and a nozzle gas outlet pipe 10304, which are machined integrally. Four to six equally-spaced nozzle flow channel slots 10305 and a vortex chamber 10306 are machined on the nozzle boss 10301, the diameter of the nozzle vortex chamber is d_{12}, the depth of the flow channel slots 10305 is equal to the height of the nozzle boss 10301 and is l_{11}, the nozzle disc is provided with a cool gas hole 10302, and the diameter of the cool gas hole is d_{11}. The nozzle gas outlet pipe 10304 is gradually expanded

to realize pressure expansion and speed reduction on high-speed gas, and then stably outputs the gas. The flow channel slots 10305 should be polished to reduce excessive energy loss caused by friction with the high-speed and high-pressure gas. The nozzle should be made of a material having a small thermal conductivity (e.g., 304 steel) to reduce heat transfer between the low-temperature gas in the nozzle and the outside, and the gradually-expanded angle should satisfy $2°\leq\beta\leq4°$.

Figs. 6(a) and 6(aa) show a first embodiment of the vortex tube supersonic nozzle. The center lines of the nozzle flow channels, i.e., the flow lines of compressed air, are equiangular spirals, the flow channel slots 10305 are further machined on the basis of the center flow lines, the depths l_{11} of the flow channel slots are kept unchangeable, but the distance from each point on the flow channel wall to the center line is changed, i.e., the flow area of each flow channel is changed. When the compressed gas uniformly enters the vortex tube flow channels 10305, the process I section is a nozzle diversion section, in which the gas stably enters the flow channels. At the process II section, the area of each flow channel is gradually reduced, and the flow velocity of the compressed gas is further improved. When the process II is ended, i.e., at the cross section CC', the flow area of the flow channels is minimum, and the gas reaches a sonic state at CC' or before CC'. Then, at the process III section, the flow area of the flow channels is gradually enlarged, and under the condition that enough pressure ratio is at the upstream and the downstream of the minimum flow area, the compressed gas is continuously accelerated to a supersonic state. Next, at the process IV section, the gas is sprayed out from the vortex tube supersonic nozzle flow channels 10305.

The polar coordinate equation of the equiangular spirals is:

$$\rho(\theta)=ae^{b\theta}$$

The polar coordinate equation is converted into a parameter equation:

$$x=\rho(\theta)\cos\theta=ae^{b\theta}\cos\theta;\quad y=\rho(\theta)\sin\theta=ae^{b\theta}\sin\theta$$

In the formula, θ is a polar angle, and $\rho(\theta)$ is the polar radius.

As shown in Fig. 6(aa), taking four flow channels as an example in this embodiment, the center flow line is from point O to point O', the polar radius is changed from ρ_1 to ρ_2, and the turning angle is θ_1, wherein the origin O'' of the equiangular spirals is the circle center of the nozzle boss 10301 and also the circle center of the nozzle vortex chamber 10306. The start point O of the center flow line is a quartering point of the external circle of the nozzle boss 10301, and the final point O' is a quartering point of the external circle of the vortex chamber 10306. The polar coordinate equation

of the equiangular spirals can be fitted according to the ρ_1, the ρ_2 and the turning angle variation θ_1, then the constant α can be obtained, and the parameter equation of the equiangular spirals is further obtained, thus facilitating machining on a numerical control machine tool. At the process II section, the flow channels are divided into n portions, and the width of each portion of flow channels is l_{oi}. At the process III section, the flow channels are also divided into n portions, and the width of each portion of flow channels is $l_{oi'}$. l_{oi} is maximum at AA' and minimum at CC', and the minimum value is l_c. $l_{oi'}$ is maximum at DD' and also minimum at CC', and the minimum value is l_c. The inner flow channel inlet section BA' should be internally tangent with the outer circumference of the nozzle boss 10301, and the outer flow channel inlet section DE' should be externally tangent with the outer circumference of the wall of the vortex chamber.

$$A_1 = \frac{m}{\sqrt{k(\frac{2}{k+1})^{\frac{k+1}{k-1}}}} \frac{P_0}{\sqrt{RT_0}}; \quad A_1 = l_c \square_{11} = \frac{m}{\rho V};$$

In the formulas, A_1 is the flow area of the minimum cross section CC' of the throat, m^2; m is the mass flow rate of gas flowing through the flow channels, kg/s; k is a gas adiabatic exponent; P_0 is an inlet stagnation pressure, MPa; T_0 is an inlet stagnation temperature, K; R is a gas constant, $J/Kg \cdot K$; V is the velocity of gas at the throat, m/s.

The shrinkage section of process II is designed based on a quintic shrinkage curve:

$$l_{oi} = 2l_a(\eta(1-(\frac{l_c}{l_a})^{\varepsilon})+1)^{\frac{1}{\varepsilon}}; \quad \eta = -10\varepsilon^3 + 15\varepsilon^4 - 6\varepsilon^5; \quad \varepsilon = \frac{l_{ai}}{l_{ac}}$$

In the formulas, l_{oi} is the flow channel width at any point in process II, m; l_{ai} is the arc length from any point of the center flow line of process II to the start cross section AA' of process II, m; l_c is the flow channel width of the minimum cross section CC' of the throat, m; and l_{ac} is the total arc length of the center flow line of process II, m.

The expanded section of process III is designed based on an area ratio formula:

$$\frac{l_{oi'}}{l_c} = \frac{1}{M_{oi'}}[(1+\frac{k-1}{2}M_{oi'}{}^2)\square(\frac{2}{k+1})]^{\frac{k+1}{2(k-1)}}; \quad M_{oi'}{}^2 = 1+(M_d-1)(l_{ci'}-\frac{1}{2\pi}\sin 2\pi l_{ci'})$$

In the formulas, $l_{oi'}$ is the flow channel width at any point in process III, m; $l_{ai'}$ is the arc length from any point of the center flow line of process III to the throat CC', m; l_c is the flow channel width of the minimum cross section of the throat; m; $M_{oi'}$ is a mach number of any point in process III; and M_d is a mach number at the end section DD' of process III.

Figs. 6(b) and 6(ba) show a second embodiment of the vortex tube supersonic nozzle. The working process and principle of this embodiment are the same as those of embodiment 1 of the supersonic nozzle, and the difference lies in that the center lines of the flow channels in this embodiment are Archimedes spirals.

The Archimedes spiral equation is:

$$\rho = a + b\theta$$

The polar coordinate equation is converted into a parameter equation:

$$x = \rho(\theta)\cos\theta = (a + b\theta)\cos\theta\,;\; y = \rho(\theta)\sin\theta = (a + b\theta)\sin\theta$$

As shown in Fig. 6(ba), taking four flow channels as an example in this embodiment, the center flow line is from point M to point M', the radius is changed from ρ_3 to ρ_4, and the turning angle is θ_2. The origin M'' of the Archimedes spirals is the circle center of the nozzle boss 10301 and also the circle center of the nozzle vortex chamber 10306. The start point M of the center flow line is a quartering point of the external circle of the nozzle boss 10301. The polar coordinate equation of the Archimedes spirals can be fitted according to the ρ_3, the ρ_4 and the turning angle variation θ_2, then the constants α and b can be obtained, and the parameter equation of the Archimedes spirals is further obtained, thus facilitating machining on a numerical control machine tool. The final point M' is a quartering point of the external circle of the vortex chamber 10306. At the process II section, the flow channels are divided into n portions, and the width of each portion of flow channels is l_{mi}. At the process III section, the flow channels are also divided into n portions, and the width of each portion of flow channels is $l_{mi'}$. l_{mi} is maximum at FF' and minimum l_h at HH'. $l_{mi'}$ is maximum at JJ' and also minimum l_c at HH'. The inner flow channel inlet section GF should be internally tangent with the external circular arc of the nozzle boss 10301, and the outer flow channel inlet section $J'K$ should be externally tangent with the outer circumference of the wall of the vortex chamber 10306. The shrinkage, expansion curve and width of the flow channels are designed as the same methods in embodiment 1 of the vortex tube supersonic nozzle, and thus are not repeated.

Figs. 6(c) and 6(ca) show a third embodiment of the vortex tube supersonic nozzle. The working process and principle of embodiment 3 are the same as those of embodiment 1 and embodiment 2 of the supersonic nozzle, and the difference lies in that the center lines of the flow channels in this embodiment are rectangular spirals.

As shown in Fig. 6(ca), taking six flow channels as an example in this embodiment, the center flow

line is from point N to point N', and at the outlet point N', the angle between the rectangular flow line and the arc normal of the point is θ_3. The origin N of the rectangular center flow line is a six-equal point of the external circle of the nozzle boss 10301, and the final point N' is a six-equal point of the external circle of the nozzle vortex chamber 10306. The process I section is an arc transition diversion section; the compressed air enters the process II section, the flow channels are gradually shrunk, the lengths of the gradual shrinkage sections of the flow channels are l_{rq}, and the gradual shrinkage angles α should satisfy $5°\leq\alpha\leq15°$; and in the process III section, the flow channels are gradually expanded, the lengths of the gradual expansion sections of the flow channels are l_{rs}, and the gradual expansion angles β should satisfy $4°\leq\beta\leq6°$. The inner flow channel inlet section PQ should be internally tangent with the external circular arc of the nozzle, and the outer flow channel outlet section ST should be externally tangent with the outer circumference of the wall of the nozzle vortex chamber 10306. The width l_r at the flow channel RR' should satisfy:

The throat area:

$$A_3=\frac{m}{\sqrt{k(\frac{2}{k+1})^{\frac{k+1}{k-1}}}}\frac{P_0}{\sqrt{RT_0}},\quad A_3=l_r\square_{11}=\frac{m}{\rho V}$$

In the formulas, A_3 is the flow area of the minimum cross section RR' of the throat, m^2; m is the mass flow rate of gas flowing through the flow channels, kg/s; ρ is the density of compressed air, kg/m^3; k is a gas adiabatic exponent; P_0 is an inlet stagnation pressure, MPa; T_0 is an inlet stagnation temperature, K; R is a gas constant, $J/Kg\cdot K$; V is the velocity of gas at the throat, m/s.

Fig. 7 shows an assembly view of the intake sleeve 101, the volute diverter 102 and the volute supersonic nozzle 103.

Figs. 8(a), 8(b) and 8(c) show three embodiments of the vortex tube heat pipe 108. The internal machining precision of the vortex tube heat pipe 108 should be relatively high to reduce huge energy loss caused by friction of free vortexes and the inner wall of the pipe. According to $Q=KF\Delta t_m$, in order to dissipate as many free vortexes to the outer side of the vortex tube heat pipe 108 as possible, the heat transfer coefficient K of the vortex tube heat pipe 108, the heat transfer area F and the temperature difference Δt_m of the inner and outer sides of the vortex tube can be improved. The outer wall of the vortex tube heat pipe 108 can be in different shapes to improve the heat transfer area F and enhance energy dissipation of hot air flow in the heat pipe to the outside. The vortex tube heat pipe 108 should be preferably made of a material having high thermal

conductivity (e.g., pure copper) to improve the heat transfer coefficient thereof. The inner diameter of the vortex tube heat pipe 108 should satisfy $1.8d_{11}<d_{18}<2.2d_{11}$; and the length of the vortex tube heat pipe 108 should satisfy $20d_{18}<l_{12}<60d_{18}$.

As shown in Fig. 8(a), the exterior of the vortex tube heat pipe 108 is a light pipe that does not need special machining, and the heat transfer area of the outer side of the vortex tube heat pipe 108 is small, so the machining process is simple.

As shown in Fig. 8(b), threads are machined on the exterior of the vortex tube heat pipe 108 to improve the heat transfer area of the outer side of the heat pipe 108, so the machining process is relatively simple.

Fig. 8(c) shows embodiment 3 of the vortex tube heat pipe 108. Similar to the principle in embodiment 2 of the vortex tube heat pipe 108, ribs are added outside the vortex tube heat pipe 108 to enlarge the heat transfer area between the heat pipe and the outside. The ribs may be straight ribs, oblique ribs, etc., preferably high ribs. However, the ribs enlarge the heat transfer area to a certain extent, but the cost is high and the process is relatively complex.

When the supersonic nozzle vortex tube system with the water tank 109 is adopted, i.e., the supersonic nozzle vortex tube system in embodiment 1 is adopted (combining Fig. 2), $\alpha_{1i}\leq\alpha_{1w}$, and a first vortex tube heat pipe 10801 and a second vortex tube heat pipe 10802 are preferred. Because the outer heat transfer coefficient of the vortex tube heat pipe 108 is further greater than the inner heat transfer coefficient, it has little influence on the overall heat transfer of the vortex tube heat pipe 108 to enlarge the outer heat transfer area of the pipe. When the first vortex tube heat pipe 10801 and the second vortex tube heat pipe 10802 are adopted, the machining process is relatively simple, and the heat dissipation performance of the heat pipe is optimal.

The overall heat transfer coefficient of the vortex tube heat pipe 108 is calculated based on the inner surface area of the heat pipe:

$$\frac{1}{K_1}=\frac{1}{\alpha_1}+r_{s,1}+\frac{\delta_w}{\lambda_w}(\frac{d_1}{d_m})+r_{s,2}(\frac{d_1}{d_2})+\frac{1}{\alpha_2}(\frac{d_1}{d_2})$$

When the supersonic nozzle vortex tube system without the water tank 109 is adopted, i.e., the supersonic nozzle vortex tube system in embodiment 2 is adopted (combining Fig. 3), $\alpha_{2i}\geq\alpha_{2w}$. At the moment, the heat transfer effect of the vortex tube heat pipe 108 can be remarkably enhanced by enlarging the heat transfer area of one side having a small heat transfer coefficient. Thus, the second vortex tube heat pipe 10802 and a third vortex tube heat pipe 10803 are preferred. The second

vortex tube heat pipe 10802 is smaller in heat transfer area and poorer in heat transfer effect but simpler in machining process than the third vortex tube heat pipe 10803.

The overall heat transfer coefficient of the vortex tube heat pipe is calculated based on the outer surface:

$$\frac{1}{K_2}=\frac{1}{\alpha_1}(\frac{d_2}{d_1})+r_{s,1}(\frac{d_2}{d_1})+\frac{\delta_w}{\lambda_w}(\frac{d_2}{d_m})+r_{s,2}+\frac{1}{\alpha_2}$$

In the formula, K is the overall heat transfer coefficient of the heat pipe, α_1 is the inner heat transfer coefficient of the pipe, $W/m^2\cdot℃$; α_2 is the outer heat transfer coefficient of the pipe, $W/m^2\cdot℃$; $r_{s,1}$ is the fouling resistance of the inner wall of the pipe, $W/m^2\cdot℃$; $r_{s,2}$ is the fouling resistance of the outer wall of the pipe, $m^2\cdot℃/W$; δ_w is the wall thickness of the pipe, m; λ_w is the heat transfer coefficient of the pipe, $W/m^2\cdot℃$; d_m is the average diameter of the pipe, $d_m=\frac{d_2-d_1}{\ln(d_2/d_1)}$.

Fig. 9 is an assembly view of the cool fluid proportion adjusting valve 111, the O-shaped sealing ring 112 and the elastic collar 113. The cool fluid proportion adjusting valve 111 can be controlled to control the flow area of hot fluid and the outflow quantity of the hot fluid, so as to control the return quantity of cool fluid and the proportion of the cool fluid and the total gas. The cool fluid proportion adjusting valve 111 includes a stud 11101 and a nut 11102. The stud is provided with two grooves for mounting the elastic collar 113 and the O-shaped sealing ring 112 respectively. The elastic collar 113 is used for preventing the cool fluid proportion adjusting valve 111 from being excessively adjusted to screw out the hot gas outlet tee joint 110. The O-shaped sealing ring 112 has two effects: firstly, the O-shaped sealing ring can effectively prevent gas from leaking; and secondly, the O-shaped sealing ring is compressed to produce certain damping between the stud and the hot gas outlet tee joint to effectively reduce loosening of the gas control valve due to vibration under gas shock, thus playing a positioning role. The cool gas proportion adjusting valve nut 11102 is matched with the cool gas proportion adjusting valve stud 11101 to achieve a positioning and anti-loosening effect. The cool fluid proportion adjusting valve 111 is of a flat end face type, which is beneficial to reflow of forced vortexes. The tapered angle of the cool fluid proportion adjusting valve should satisfy $35°\leq\varphi\leq55°$.

Fig. 10 is an exploded view of parts of the nano-fluid minimal quantity lubrication supply system (MQLSS). The aim of the MQLSS is to change nano-fluid into pulse droplets having fixed pressure, variable pulse and unchanged diameters, and the pulse droplets are sprayed out from the external

mixing nozzle via the oil delivery pipe, atomized by high-speed and low-temperature gas and jet to a grinding zone.

As shown in Figs. 11(a) and 11(b), a camshaft 227 is connected with a coupling 232 via a cam key 226 and then connected with an electromagnetic speed adjustment motor 231, the camshaft 227 is mounted on a bearing support 229, a piston 225 implements force closure with the camshaft via a piston spring 220, a fixed plate 206 is fixed with an upper box 205 via fixed plate inner hexagon positioning screws 207 and simultaneously fixed with a pump 209 via pump positioning screws 219, a second quick plug 218 is in threaded connection with the pump 209, a first quick plug 212 is in threaded connection with an oil cup 211, and two ends of oil conduits 213 and 214 with valves are respectively inserted into the first quick plug 212 and the second quick plug 218 to guide oil. Further, a fixed plate gasket 208 for damping is arranged between the fixed plate 206 and the pump 209, and a box gasket 202 for fastening seal is arranged between the upper box 205 and a lower box 230. The internal mounting part of the pump 209 will be described in detail below.

As shown in Figs. 12(a) and 12(b), a first star-like sealing ring 221, a second star-like sealing ring 222, a first Y-shaped sealing ring 223, a second Y-shaped sealing ring 224 and a piston spring 220 are mounted on the piston 225. The whole pump is mounted in the pump 209. A one-way valve plug 216 and a one-way valve spring 215 are mounted on one side of the pump 209. An oil outlet 210 is connected and positioned with the pump 209 via an oil outlet positioning screw 217. One end of the one-way valve spring 215 is sleeved on the one-way valve plug 216, and the other end is embedded into a spring slot of the oil outlet 210 to prevent the one-way valve plug 216 from moving radially. The first star-like sealing ring 221 and the second star-like sealing ring 222 seal oil in the oil cavity to prevent oil leakage. The lip, facing the oil cavity, of the first Y-shaped sealing ring 223 further seals the oil, and the lip, facing the outside, of the second Y-shaped sealing ring 224 prevents external foreign matters from entering the pump 209. The piston spring 220 enables the piston 225 to be attached to the camshaft 227 all the time to stably supply oil. When the piston 225 travels once, air in a piston moving cavity 20901 is discharged to the outside via a first shell gas relief hole 20902 and a second shell gas relief hole 20903, a first oil supply cavity 20904 and a second oil supply cavity 20905 are filled with oil of certain pressure to prevent the resistance of the one-way valve spring 215 from being extruded into a one-way valve cavity 20906, next, the oil is atomized outside the low-temperature oil gas external mixing atomizing nozzle 4 by low-temperature gas via the oil outlet 210 and an oil delivery pipe 413 and jet to a machining zone. When the piston 225

returns once, the one-way valve plug 216 plugs up the first oil supply cavity 20904 and the second oil supply cavity 20905 due to the elasticity of the one-way valve spring 215 to prevent backflow of the oil. At the moment, the pressure in the first oil supply cavity 20904 and the second oil supply cavity 20905 is lower than the outside pressure, the oil is sucked into each oil supply cavity, and an oil supply is completed.

As shown in Figs. 13(a), 13(b), 13(c) and 13(d), the pump 209 is provided with a piston moving cavity 20901, a first gas relief hole 20902, a second gas relief hole 20903, a first oil supply cavity 20904, a second oil supply cavity 20905, a one-way valve cavity 20906, an oil outlet positioning hole 20907, a second oil inlet 20908, a first oil inlet 20909, a pump fixing threaded hole 20910 and a first oil supply cavity flow channel 20911. The first gas relief hole 20902 and the second gas relief hole 20903 play a gas relief role on the pump 209, otherwise, the gas cannot be discharged, and the gas pressure in the piston moving cavity 20901 is sharply increased, so that the whole pump 209 may be separated from the fixed plate 206. The first oil supply cavity flow channel 20911 communicates the first oil supply cavity 20904 with the one-way valve cavity 20906. The second oil inlet 20908 of the pump is formed on the second oil supply cavity 20905. After the return of the piston 225 is finished, the piston section having the diameter d_{22} should be below the second oil inlet 20908, and the second oil inlet 20908 is reserved to facilitate oil suction. Moreover, the sealing ring should not be moved out of each cavity to prevent the sealing performance from declining when the sealing ring frequently enters and exits each cavity; and after the travel of the piston 225 is finished, the top of the piston should cross the second oil inlet 20908, i.e., be located above the second oil inlet 20908, to prevent pressing oil into the second oil inlet 20908, each step should not collide with the pump 209, and a sufficient clearance should be reserved. The working process of the piston section having the diameter d_{21} is the same as that of the first oil inlet 20909.

As shown in Fig. 14, the piston 225 is provided with four sealing ring slots 22501, 22502, 22503 and 22504 for mounting the first star-like sealing ring 221, the second star-like sealing ring 222, the first Y-shaped sealing ring 223 and the second Y-shaped sealing ring 224 respectively. The diameter of the piston rod of the first oil supply part is d_{22}, the diameter of the piston rod of the second oil supply part is d_{21}, and different oil supply quantities are provided according to different diameters of the piston rod. If the clearance between the piston 225 and the pump 209 is ignored, when the revolving speed n of a motor 231 is constant, the travel distance of the piston is l_{21} and only the oil conduit oil control valve 214 at the first oil inlet 20909 is opened, the oil consumption per hour is

Q_1. When only the second oil conduit oil control valve 213 at the second oil inlet 20908 is opened, the oil consumption per hour is Q_2. When both of the two oil control valves 213 and 214 are opened, the oil consumption per hour is Q_3.

As shown in Fig. 15, the oil outlet 210 includes oil outlet flow channels 21001, a one-way valve spring slot 21002 and a threaded positioning hole 21003. The oil outlet 210 may be provided with a plurality of oil outlet flow channels 21001, and the oil outlet 210 is changed by disassembling and assembling the oil outlet positioning screws 217 according to actual needs to select a proper quantity of the oil outlet flow channels 21001. Further, the oil outlet flow channels 21001 should be distributed in a circular equal interval manner, so that the nano-fluid uniformly enters each flow channel.

As shown in Fig. 16, the fixed plate 206 is provided with two step holes 20601 in the bottom and one step hole 20602 in the lateral surface, the fixed plate inner hexagon screws 207 are mounted in the step holes 20601 to fix the fixed plate 206 and the upper box 204, and the pump positioning screw 218 is mounted in the step hole 20602 to fix the fixed plate 206 and the MQLSS pump 209 (combining Fig. 11(a)). Further, a semicircular hole through which the piston 225 and the cam spring 220 penetrate is formed in the bottom of the fixed plate 206. Further, two fixed plates 206 are needed and mounted symmetrically. Further, after the fixed plates 206 are fixed with the upper box 205, a fixed plate gasket 208 is fixed on the two fixed plates 206 to damp the pump.

As shown in Figs. 17 and 17(a), the upper box is provided with flange holes 20501 and threaded holes 20502, and the flange holes 20501 are fixed with the lower box 230 via bolts 204, nut gaskets 203 and nuts 201. The upper box 205 is fixed with the fixed plate 206 via the threaded holes 20502 by means of the fixed plate inner hexagon positioning screws 207 (combining Fig. 11(a)).

As shown in Fig. 18, a cam 22702 is directly milled on the shaft, and the camshaft 227 is provided with a cam key groove 22701 and connected with the coupling 232 via a cam key 226. Further, a plurality of cams 22702 can be milled on the shaft according to actual situations to assemble a plurality of MQSSs, and the lift l_{21} of each cam is determined according to the actual working condition, so that multiple paths of nano-fluid are adjusted and provided at a constant revolving speed. Moreover, the flow rate of each path of nano-fluid may be different to meet the requirement of different working conditions.

As shown in Figs. 19 and 20, the whole MQLSS (combining Fig. 11) is driven by the electromagnetic speed adjustment motor 231, the oil supply frequency of the MQLSS is controlled

by controlling the revolving speed of the motor 231, and then the oil supply quantity of the MQLSS in unit time is controlled. The whole MQLSS is connected with the electromagnetic speed adjustment motor 231 via the coupling 232.

Fig. 21 is an exploded view of embodiment 1 of the GDCV, with each part being shown. Figs. 22, 23, 24 and 25 are all schematic diagrams of embodiment 1 of the GDCV. The gas distribution control valve (GDCV) controls the gas flow by using the principle of changing the flow area of flow channels, thus inevitably causing partial loss. This solution is designed based on the principle that partial energy loss of a gate valve is relatively low. The GDCV shell is provided with two to four air outlets corresponding to two or four gas control valves. This solution takes four gas control valves as an example.

As shown in Fig. 22, the gas control valve is composed of a stud 30602, a first gas control valve nut 30603 and a second gas control valve nut 30604, wherein fine threads are formed at one end of the gas control valve stud 30602, a hemisphere having the same diameter d_{31} as the stud is arranged at the other end of the stud 30602, and the stud 30602 is provided with a sealing ring slot 30601. The thread turning direction of the stud 30602 is the same as the turning directions of the second gas control valve nut 30604 and the first gas control valve nut 30603. The first gas control valve nut 30603 can play a positioning and anti-loosening role, and the second gas control valve nut 30604 is fixed with the stud 30602 in a certain manner (e.g., gluing) to prevent loosening of the second gas control valve nut 30604 and the stud 30602 when the gas control valve 306 is adjusted. The threads of the gas control valve are fine pitch threads, which can realize the effect of fine adjustment due to small pitches and can better achieve the air seal effect; and small lead angles of the fine pitch threads are more beneficial to controlling self-locking of the gas control valve 306.

As shown in Figs. 23(a), 23(b) and 23(c), firstly, the gas control valve stud 30602 is screwed in from the gas control valve joint 305, the first gas control valve nut 30603 and the second gas control valve nut 30604 are sequentially screwed in, then the O-shaped sealing ring 307 is mounted on the gas control valve stud 30602, and the gas control valve joint 305, the O-shaped sealing ring 307 and the whole gas control valve 306 are screwed into a first GDCV shell 303, wherein a sealing gasket 2304 is mounted between the gas control valve joint 305 and the GDCV shell 303. Finally, the gas inlet quick plug 301 and the gas outlet quick plug 309 are respectively screwed into the first GDCV shell 303. A first sealing gasket 302 is mounted between the gas inlet quick plug 301 and the first GDCV shell 303, and a third sealing gasket 308 is mounted between the gas outlet quick plug 309

and the first GDCV shell 303. The O-shaped sealing ring 307 has three effects: firstly, the O-shaped sealing ring 307 can effectively prevent leakage of gas; secondly, the O-shaped sealing ring 307 is compressed to produce certain damping between the gas control valve stud 30602 and the GDCV shell 303 to effectively reduce loosening of the gas control valve 306 due to vibration under gas shock, thus playing a positioning role; and thirdly, when the gas control valve 306 is screwed outward, the O-shaped sealing ring 307 moves to the gas control valve joint 305, but cannot continue to move outward because the outer diameter of the O-shaped sealing ring is greater than that of the gas control valve joint 305, thus preventing the GDCV gas control valve 306 from being excessively screwed out to separate from the gas control valve joint 305.

As shown in Figs. 24, 24(a) and 24(b), the first GDCV shell 303 is provided with a shell gas inlet main flow channel 30301, shell gas control valve connectors 30302, shell gas outlets 30303 and shell gas shunt channels 30304. The diameter of the shell gas shunt channel 30304 is d_{31}, and is equal to the diameter d_{31} of the hemisphere of the gas control valve stud 30602, so that when the gas control valve 306 is completely tightened, the gas control valve 306 is tightly combined with the shell gas shunt channel 30304 to prevent gas leakage.

Further, the shell gas inlet main flow channel 30301 is a circular channel, and the shell gas shunt channels 30304 are uniformly and circularly arranged along the center, so that the entering gas uniformly enters each flow channel 30304; and the gas control valves 306 are distributed on the left and right surfaces of the shell.

As shown in Fig. 25, the gas control valve joint 305 is provided with external threads 30501 and internal threads 30502, the external threads 30501 are connected with the GDCV shell 303, and the internal threads 30502 are connected with the gas control valve stud 30602.

Fig. 26 is an exploded view of embodiment 2 of the GDCV, with each part being shown. Figs. 22, 25, 27, 27(a), 28 and 28(a) are all schematic diagrams of embodiment 2 of the GDCV. The gas control valves 306 (Fig. 22) and the gas control valve joints 305 (Fig. 25) are the same as those in embodiment 1.

As shown in Figs. 27 and 27(a), a gas inlet end cover 312 and gas outlet quick plugs 309 are mounted onto a second GDCV shell 310. The gas outlet quick plugs 309 are in threaded connection with the second GDCV shell 310, and third sealing gaskets 311 are arranged between them. The gas inlet end cover 312 is connected with the second GDCV shell 310 by screws 314, and gas inlet end cover sealing gaskets 311 and screw gaskets 313 are arranged between them. Further, the shell gas

inlet main flow channel is a rectangular channel, and the gas shunt flow channels are distributed on the rectangular main channel at equal intervals; and the gas control valves 306 are all distributed on one surface of the shell.

As shown in Figs. 28 and 28(a), the gas control valves 306 and the gas control valve joints 305 are mounted by the same methods as Fig. 23 of embodiment 1, and are thus not redundantly described herein.

Fig. 29 is an exploded view of a low-temperature oil gas external mixing atomizing nozzle (nozzle), with each part being shown.

As shown in Figs. 30 and 30(a), a nozzle gas intake pipe 406 is in threaded connection with a coiled pipe 409, a nozzle sleeve 402 is in threaded connection with the gas intake pipe 406, an oil delivery pipe 413 is in interference connection with a nozzle needle 401, a tapered pipe 403 is connected with a thermal insulation pipe 405 in clearance fit, and the nozzle needle 401 is connected with the tapered pipe 403 in clearance fit. The thermal insulation pipe 405 is arranged inside the gas intake pipe 406 and the nozzle sleeve 402, and the oil delivery pipe is arranged inside the thermal insulation pipe 405. A first nozzle sealing gasket assembly 407 and a second nozzle sealing gasket assembly 408 are arranged between the thermal insulation pipe 405 and the gas intake pipe 406, a nozzle sealing gasket 404 is arranged between the thermal insulation pipe 405 and the nozzle tapered pipe 403, and the coiled pipe 409 is fixedly mounted to the machining zone via nozzle fixing blocks 411 and 412.

As shown in Fig. 31, the nozzle needle 401 is provided with a step in the middle, for positioning the nozzle needle 401 and the nozzle tapered pipe 403.

As shown in Figs. 32(a), 32(b) and 32(c), the nozzle tapered pipe 403 is provided with a needle passage 40301, a tapered pipe rib plate vent 40302 and a tapered pipe rib plate 40303. The tapered pipe rib plate 40303 is connected with the nozzle sleeve 402 to play a certain supporting role on the thermal insulation pipe 405. Low-temperature gas flows through the tapered pipe rib plate vent 40302. At least three tapered pipe rib plates 40303 should be provided to realize stable supporting. The angle γ_1 of the tapered pipe should satisfy $3°\leq\gamma_1\leq15°$.

As shown in Fig. 33, the angle of the tapered part of the nozzle sleeve should be the same as that of the nozzle tapered pipe 403. The inner diameter d_{42} of the straight part of the nozzle sleeve is greater than d_{41}, in order to assemble the nozzle sleeve 402 better.

As shown in Fig. 34, the intake pipe is provided with a first intake pipe step 40601, a second intake

pipe step 40602 and an intake passage 40603. The first intake pipe step 40601 is used for positioning the first nozzle sealing gasket assembly 407, and the second intake pipe step 40602 is used for positioning the second nozzle sealing gasket assembly 408. Further, $20°<\gamma_2<40°$.

As shown in Figs. 35(a) and 35(b), a semi-hexagonal hole is formed in the middle of each of the first nozzle fixing block 412 and the second nozzle fixing block 413, and the second nozzle fixing block 413 is provided with a threaded hole. The two semi-hexagonal holes of the first nozzle fixing block 412 and the second nozzle fixing block 413 are combined to clamp a hexagonal coiled pipe nut, and the coiled pipe 409 is clamped and fixed by a fixing block inner hexagon screw 410, so that the whole nozzle 4 is fixed. The nozzle fixing blocks may be made of a magnetic material such as metal and the like, and can thus be attracted to a magnetic disc nearby the machining zone.

The specific working process of this solution is as follows:

The supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system is composed of a low-temperature gas generating device 1, a nano-fluid minimal quantity lubrication supply system 2, a gas distribution control valve 3 and low-temperature oil gas external mixing atomizing nozzles 4.

When the system is used for grinding a workpiece, the electromagnetic speed adjustment motor 231 is started first. Because the MQLSS oil outlet 210 is connected with the needle 401 of the low-temperature oil gas external mixing atomizing nozzle via the long oil delivery pipe 413, the MQLSS is started first to supply oil to the oil delivery pipe 413, while the oil conduits 213 and 214 with valves in the MQLSS are opened, thereby improving the revolving speed of the motor 231, accelerating oil supply to reduce oil supply preparation time, and improving the machining efficiency. The MQLSS is driven by the electromagnetic speed adjustment motor 231, the camshaft 227 is driven to rotate a circle once the motor 231 rotates a circle, the cam carries out a single travel-return motion, and a single oil supply is completed. The MQLSS controls the oil quantity by adjusting the revolving speed of the motor 231 and opening the oil conduits 213 and 214 with valves in the MQLSS. The oil conduits 213 and 214 with valves in the MQLSS are preferentially adjusted to realize three-stage adjustment on the oil supply quantity, and if the oil supply requirement cannot be met, the revolving speed of the motor 231 is adjusted to change the oil supply frequency. The motor preferentially works at a low frequency in the MQLSS, so that not only can the electrical energy of the motor be saved, but also the wear between the camshaft 227 and the MQLSS piston 225 and the wear between the sealing ring and the MQLSS pump 209 can

be effectively reduced.

After the nano-fluid provided by the MQLSS is sprayed out from the nozzle 4, the air compressor is started, pure gas after common cooling, filtration and drying enters the vortex tube, is quickly cooled after energy separation in the vortex tube 1, then sprayed out from the vortex tube 1, and delivered to the gas distribution valve 3 via the thermal insulation pipe. The flow area of the gas is changed by adjusting the control valve 306 of the gas distribution valve 3 to control the gas flow.

The low-temperature cool gas enters from the inlet pipe 406 of the nozzle 4, the nano-fluid supplied by the MQLSS is discharged from the nozzle needle 401 via the oil delivery pipe 413 to mix with the low-temperature gas outside the nozzle 4, the nozzle jets the gas in a tapered shape, the nano-fluid is atomized at the gas focusing position, and the low-temperature gas carrying the atomized small oil droplets penetrates through a wedge-shaped gas barrier layer of a grinding wheel and is jet to a grinding zone.

The refrigeration mechanism of the vortex tube is as follows:

The vortex tube is a separation device for converting pressure energy into velocity energy and then shunting intake flow into cool and hot gas flows having unequal total temperatures via vortex changes. High-pressure gas is refrigerated via gas temperature separation of the vortex tube, and the refrigeration is mainly divided into two parts: nozzle refrigeration and vortex chamber refrigeration. The high-pressure gas carries out three-dimensional compressible turbulent flowing in the vortex tube, the gas is expanded via thermal insulation of the nozzle, and the temperature declines to reach the minimum of the thermodynamic temperature. In this process, the nozzle refrigeration is regarded as a dynamic throttling process. The influence of gas velocity can be ignored in the throttling process. Because the gas velocity in the vortex tube is very high and cannot be ignored, so it is regarded as a dynamic throttling process.

After the nozzle refrigeration, the gas is divided into two parts: short-circuit flow and circulating flow. When the gas flow enters the vortex chamber tangentially, due to the inertia and the siphonage, part of the gas flow on the wall of a separation pore plate does not pass through an energy separation port but directly enters a cool end outlet to form the short-circuit flow. When the cyclonic flow in the center moves from the cool end outlet to a position nearby the vortex chamber, it cannot completely pass due to the influence of the aperture of an inlet separation plate, and part of the gas flow flows back to the outer layer to form the circulating flow. The circulating flow promotes the separation of vortex energy, and the short-circuit flow has a lower temperature to enhance the

refrigeration effect.

When the circulating flow flows to a hot end outlet, the separation chamber is divided into two zones: a free vortex flow zone and a forced vortex flow zone. Free vortex flow gas is on the outer side. Due to the centrifugal force and the pressure difference in the pipe, the free vortex flow gas does similar Archimedes spiral motion along the axial direction of the pipe wall, the revolving speed of the gas is particularly high, and the gas flows turbulently. The flow velocity on the surface of the pipe wall is 0, so the velocity gradient at the pipe wall is relatively large, the kinetic energy is quickly lost, the gas flow rubs with the pipe wall to generate heat, the axial velocity is increasingly low, but the temperature is increasingly high. Free vortexes are nearby the adjusting valve. Due to the friction obstruction of the pipe wall and the obstruction of the adjusting valve in the separation process, the gas at the hot end outlet nearly stops revolving, and only flows axially.

In inner-layer forced vortexes, since a pressure difference is produced between the cool hole end and the adjusting valve, part of the gas flow, which is blocked by the adjusting valve, flows back axially along the center, and produces forced vortexes under strong friction of outer-layer free vortexes (the energy flows from the exterior to the interior at the moment). The forced vortexes need to overcome centrifugal force, and gas molecules move from low-level energy to high-level energy, so that the mean kinetic energy of the gas molecules is converted into potential energy of the molecules. The mean kinetic energy of the gas is reduced, and the temperature decreases.

Under the action of a centrifugal force, the free vortexes are expanded axially and compressed radially, wherein the radial compression of the free vortexes leads to radial expansion of the forced vortexes to act on the free vortexes, so that the temperature decreases. Moreover, the forced vortexes play a braking role on the free vortexes owning to the opposite flowing direction in the axial direction and act on the free vortexes, so that the temperature decreases; and the forced vortexes are expanded axially, so that the temperature decreases.

To sum up, the refrigeration performance of the vortex tube can be improved by improving the velocity of the nozzle outlet of the vortex tube, the vortex strength and the energy separation degree of the vortex chamber. However, it is discovered in actual experiments that, after the mach number of the nozzle outlet reaches 0.9, the overall refrigeration effect of the vortex tube is no longer changed greatly, as gas is congested under a high mach number based on the analysis, wherein in a common reducing flow channel, gas is in a subsonic state all the time, a sonic velocity can be realized at the highest velocity, i.e., the mach number is 1, thus, the phenomenon of gas congestion

occurs, and the loss of energy is increased.

It is designed as a supersonic nozzle vortex tube in this solution, and the velocity of the nozzle outlet of the vortex tube reaches a supersonic velocity, so that the phenomenon of congestion of compressed gas is avoided. Moreover, the center flow line of the gas is designed into different basic line types, so that the vortex strength is further improved, and temperature separation of the gas at the nozzle is realized more efficiently. Beside, the vortex tube heat pipe is also improved in this solution, the heat transfer capacity of the vortex tube heat pipe is enhanced by multiple measures, the energy dissipation of free vortexes to the outside is promoted, and the heat transfer from free vortexes to forced vortexes is reduced, so that the energy separation capacity of the vortex chamber is strengthened.

The oil supply and flow adjustment mechanism of the nano-fluid minimal quantity lubrication supply system is as follows:

The nano-fluid minimal quantity lubrication supply system mainly depends on the fact that the motor drives the camshaft to rotate and then drives the cam piston to realize relative motion of the piston and the MQLSS pump, oil in each oil supply cavity of the MQLSS pump is discharged out when the MQLSS piston travels, vacuum is formed in each oil supply cavity of the MQLSS pump when the MQLSS piston returns to suck oil at the oil inlet into the oil supply cavity for next oil supply.

It is supposed that the clearance between the MQLSS piston and the MQLSS pump is ignored, when the revolving speed n of the motor is fixed, the travel distance of the piston is l_{21} and only the first oil conduit oil control valve 1 at the first oil inlet 1 is opened, the oil consumption per hour is Q_1. When only the second oil conduit oil control valve 2 at the second oil inlet 2 is opened, the oil consumption per hour is Q_2. When both of the two oil control valves are opened, the oil consumption per hour is Q_3. Wherein:

$$Q_1 = \frac{60\pi n(d_{21}^2 - d_{22}^2)l_{21}}{4}10^{-3}, \quad Q_2 = \frac{60\pi n d_{22}^2 l_{21}}{4}10^{-3}, \quad Q_3 = \frac{60\pi n d_{21}^2 l_{21}}{4}10^{-3}$$

In the formulas, Q is the oil supply quantity within the unit time, *ml/h*; n is the revolving speed of the motor, *r/min*; d is the diameter of the piston rod, *mm*; and l_{21} is the lift of the cam, *mm*.

1. A supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system, comprising a low-temperature gas generating device, a nano-fluid minimal quantity lubrication supply system, a gas distribution control valve and at least one low-temperature oil gas external mixing atomizing nozzle, wherein:

the low-temperature gas generating device comprises a vortex tube nozzle, a volute diverter and a vortex tube heat pipe sequentially arranged in an intake sleeve; a sealing end cover is arranged at one end of the intake sleeve, and a nozzle gas outlet pipe of the vortex tube nozzle penetrates out of the sealing end cover; a nozzle flow channel slot communicated with the gas path of the nozzle gas outlet pipe is formed in the intake end of the vortex tube nozzle, so that compressed air is sprayed out from the nozzle gas outlet pipe via the nozzle flow channel slot; one end of the volute diverter is communicated with a compressed air inlet of the intake sleeve, and the other end is communicated with the nozzle flow channel slot; the vortex tube heat pipe penetrates out of the end face of the other end of the intake sleeve, and is communicated with the nozzle flow channel slot; a gas outlet tee joint communicated with the gas path is arranged at the end of the vortex tube heat pipe penetrating out of the intake sleeve, and a cool gas proportion adjusting valve is arranged in one port of the gas outlet tee joint;

a gas inlet quick plug of the gas distribution control valve is communicated with the nozzle gas outlet pipe of the vortex tube nozzle via a thermal insulation pipe; the quantity of gas outlet quick plugs of the gas distribution control valve is matched with that of the low-temperature oil gas external mixing atomizing nozzles, and the gas outlet quick plugs are respectively communicated with the gas paths of the corresponding low-temperature oil gas external mixing atomizing nozzles via thermal insulation pipes;

the nano-fluid minimal quantity lubrication supply system comprises a camshaft and a pump which are arranged in a box, and the camshaft is connected with an electromagnetic speed adjustment motor via a camshaft key; a shell piston cavity, an oil inlet cavity and a one-way valve cavity communicated with each other are sequentially formed in the pump; one end of a piston presses against a cam on the camshaft and is connected with the bottom surface of the pump via a cam spring, and the other end stretches into the shell piston cavity of the pump and can move relative to the pump; the oil inlet cavity is communicated with an oil cup pipeline via an oil inlet; the one-way valve cavity is communicated with oil outlets; the quantity of the oil outlets is matched

with that of the low-temperature oil gas external mixing atomizing nozzles, and the oil outlets are communicated with corresponding low-temperature oil gas external mixing atomizing nozzle pipelines respectively.

2. The supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system according to claim 1, wherein the low-temperature gas generating device further comprises a water tank; the water tank is sleeved on the outer wall of the vortex heat pipe; the water tank is arranged between the intake sleeve and the gas outlet tee joint, the end face of one end of the water tank is in tight contact with the end face of one end of the intake sleeve via a sealing gasket, the end face of the other end of the water tank is in tight contact with the end face of one end of the gas outlet tee joint, and the inner wall of the water tank is in tight contact with the outer wall of the vortex heat pipe via a Y-shaped sealing ring.

3. The supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system according to claim 1, wherein the outer diameter of the volute diverter is equal to the inner diameter of the intake sleeve, and the cross section of the inner wall of the volute diverter is of Archimedes spirals.

4. The supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system according to claim 1, wherein the supersonic nozzle comprises a nozzle boss, a nozzle disc and a nozzle gas outlet pipe; a cool gas passage is formed inside the nozzle disc; the nozzle boss is formed on the end face of one end of the nozzle disc, a through hole is formed in the center of the nozzle boss, nozzle flow channel slots are formed in the inner wall of the through hole, the nozzle flow channel slots divide the inner cavity of the through hole into a plurality of vortex chambers, and the volute diverter is arranged on the outer wall of the nozzle boss; the nozzle gas outlet pipe is arranged on the end face of the other end of the nozzle disc, and the inner diameter of the nozzle gas outlet pipe is gradually increased along the gas delivery direction; and the nozzle flow channel slots, the cool gas passage and the gas path of the nozzle gas pipe are communicated with each other.

5. The supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system according to claim 1, wherein the center lines of the nozzle flow channel slots comprise one of equiangular spirals, Archimedes spirals and rectangular lines.

6. The supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system according to claim 1, wherein threads are formed on the outer wall of the

vortex heat pipe; or a plurality of ribs are uniformly arranged on the outer wall of the vortex heat pipe.

7. The supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system according to claim 1, wherein the cool gas proportion adjusting valve comprises a stud and a nut matched with the stud; the stud is a flat end face conical stud, and the tapered angle of the stud is between 35 and 55 degrees; an elastic collar is arranged close to the tapered angle of the stud on the stud, and an O-shaped sealing ring is arranged away from the tapered angle of the stud.

8. The supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system according to claim 1, wherein the gas distribution control valve comprises a shell; a plurality of shell gas channels independent from each other are formed inside the shell, and each shell gas channel is communicated with the gas inlet quick plug and the gas outlet quick plug; a gas control valve is arranged on the pipeline of each shell gas channel, and the gas control valve can move vertical to the gas channel.

9. The supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication coupling supply system according to claim 1, wherein the low-temperature oil gas external mixing atomizing nozzle comprises a coiled pipe, a nozzle gas inlet pipe, a thermal insulation pipe, a nozzle tapered pipe , a nozzle sleeve and a nozzle needle; one end of the coiled pipe is in threaded connection with one end of the nozzle gas inlet pipe, and the other end of the nozzle gas inlet pipe is in threaded connection with one end of the nozzle sleeve; the nozzle tapered pipe and the nozzle needle are sequentially arranged in the nozzle sleeve along the gas spray direction, and one end of the nozzle needle is communicated with the tapered end of the nozzle tapered pipe; a tapered pipe rib plate is further arranged on the outer wall of the plane end of the nozzle tapered pipe, and the tapered pipe rib plate is provided with at least one tapered pipe rib plate vent; the thermal insulation pipe is arranged in the nozzle gas inlet pipe, one end of the thermal insulation pipe is communicated with the plane end of the nozzle tapered pipe, and the other end of the thermal insulation pipe is pressed on a second step of the nozzle gas inlet pipe; one end of an oil delivery pipe penetrates through the pipeline of the thermal insulation pipe and is communicated with the nozzle needle, and the other end penetrates through the pipeline of the coiled pipe and is communicated with the oil outlet of the nano-fluid minimal quantity lubrication supply system.

10. The supersonic nozzle vortex tube refrigeration and nano-fluid minimal quantity lubrication

coupling supply system according to claim 9, wherein the angle of the tapered end of the nozzle sleeve is the same as that of the tapered end of the nozzle tapered pipe, and the inner diameter of the straight part of the nozzle sleeve is greater than that of the straight part of the nozzle tapered pipe.