Effect of Nanoparticles on Cavitation in a Round Liquid Jet

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Abstract. Nanofluid has drawn great attention as a new efficient energy carrier for improving heat-transfer and combustion performance. However, universal consensus has not been reached on the mechanism of nanoparticles influencing atomization and combustion. In this paper, the focus was the cavitation of Al₂O₃-H₂O nanofluids inside and outside a nozzle with circular cross section. Comprehensive analyses of flow morphology were carried out based on a high-speed-macro shadow imaging system. The effects of nanoparticles on the initial development of round jet, incipient cavitation and supercavitation inside sharp-edge nozzle, and jet cavitation outside round-edge nozzle were discussed. Results showed that: nanoparticles accelerated the formation of cavitation inside the nozzle, and reduced the critical supercavitation pressure. Meanwhile, they promoted the formation and persistence of bubbles in liquid jet. These bubbles generated near the KH-instability wave peaks below the nozzle. Compared with that of basic fluid, the wave location of nanofluid jet was closer to the nozzle exit. In conclusion, the addition of nanoparticles promoted the cavitation inside and outside the nozzle. It can be attributed to the following changes: nanoparticles increased the original adsorption of air, reduced the tensile strength of liquid, speeded up the disturbances of jet, and played the role of heterogeneous nucleation points.

1. Introduction

As the simplest mode of pressure atomization, round liquid jet has been widely used in internal combustion engines, aviation gas turbines, liquid rocket engines, industrial spraying and spray drying et al. [1]. Jet cavitation has attracted intensive attention due to its critical and complex effects on flow, atomization and combustion performance. When the local pressure in the flow field is lower than the saturated vapor pressure, the liquid is quickly torn and cavitation bubbles will be generated; these bubbles are generally considered to originate from liquid vapor or gas dissolved in liquid [2]. At present, research methods of cavitation inside the flow channel mainly include visual imaging [3, 4], laser Doppler velocimetry [5], acoustic effect analysis [6], and numerical simulation [7]. Sou et al. [5] found that inception cavitation in a two-dimensional nozzle formed on the edge of the liquid separation boundary layer by LDV tests. Osta et al. [4] observed bubbles in jets outside the nozzle using X-rays, suggesting that these bubbles may originate from gas dissolved in the liquid. The bubbles in local cavitation constantly generated and collapsed, causing large-scale turbulent pulsations, which in turn enhanced the atomization [8]. Wu et al. [9] analyzed the effects of bubbles on the fracture of round liquid jets by high-speed imaging and linear stability theory. It was found that...
bubbles could significantly improve the atomization performance, and the jet fracture length decreased almost linearly with the increase of bubble diameter.

In recent years, scholars have made nanofluids by adding nano-scale metals or their oxide particles to the fluid in jets and found that they have outstanding effects on enhancing heat transfer and improving combustion [10-12]. Sonawane et al. [11] found that the addition of Al2O3 nanoparticles with a volume concentration of 1.0% increased the thermal conductivity, specific heat, and viscosity of aviation turbine fuel by 40%, 30%, and 38%, respectively. Basuet et al. [12] concluded that low-concentration nanoparticles could generally improve fuel economy by 15%–20%, while reducing pollution emissions by 40%–60%. However, due to the differences in nanoparticlesurface characteristics, particle size distribution, and nanofluid preparation process, scholars have not yet reached a consensus about the effects of nanoparticles on the fluid properties, flow stability, cavitation, and atomization [13]. The excellent properties of nanofluids are thought to be related to special microscale effects of particle groups, such as micromotion effects, local aggregation, solvation layer effects, and nanobubble surface adsorption [14-16].

The mechanism of nanoparticles acting on flow cavitation is still not clear, and there is some controversy even on the conclusions. Bidhendi et al. [17] studied the effect of nano-SiO2 on water cavitation, observed the delay of inception cavitation, and found that the nanoparticles significantly reduced the cavitation growth rate. The authors believe that a stable hydrogen bond formed between the nanoparticles and water, thereby stabilizing the flow. However, some other scholars have observed nanoparticles promote cavitation in their tests [18,19]. Gu et al. [6] recently studied the effect of nano-SiO2 on ultrasonic cavitation of degassed water. They found that both the cavitation pressure and critical bubble free energy were reduced by the addition of nano-SiO2. The increase in particle concentration further reduced the cavitation pressure, while increasing the particle size had almost no effect. Kabeel and Abdelgaied [20] studied the effect of nano-alumina concentration on the flow characteristics in sharp-edged orifice tubes by numerical simulation. The results showed that when the particle concentration increased from 0 to 2%, the turbulence intensity in the flow separation region increased by an average of 74%. The authors predicted large-scale cavitation in the flow field by the total stress criterion. Results showed that high concentration of nanofluids would accelerate the cavitation, and it should be attributed to the total pressure loss caused by the increase in viscosity. Gu YW [21] found that the addition of nano-SiO2 made the tensile strength of water smaller. From the test results of high-frequency pulsed ultrasound, cavitation was more likely to occur when the particle concentration increased; while the particle size in the range of 20~100 nm had little effect on the cavitation of water.

In this study, we try to capture more cavitation details of nanofluids inside and outside a nozzle by highspeed-macroflow visualization technology. Combined with data analysis of pressure and flux, we hope to reveal the regularity and reason of nanoparticles acting onflow cavitation. Then some fundamental research data can be provided to improve the atomization, heat transfer and combustion performance of nanofluids.

2. Experimental Details

2.1 Nanofluid Preparation and Properties

In this study, deionized water was used as the dispersion liquid, and γ-crystalline nano-alumina with high catalytic activity was selected as the additive (average particle diameter: 20 nm, density: 3.97 g/cm³, Shanghai Aladdin Biochemical Tech. Inc., China). Al2O3·H2O nanofluid was prepared by the classic two-step method. To improve the dispersion uniformity and suspension stability, SDBS anionic surfactant was added (Sodium dodecyl benzene sulfonate, Shanghai Aladdin Biochemical Technology Inc., China); a mechanical stirring and homothermal ultrasonic dispersion system was applied (Ningbo Xinzi 2400F ultrasonic disperser). For the prepared nanofluids in concentration of 0.5wt.%–2.0wt.%, neither delamination nor sedimentation was found within 4 hours.
The density of nanofluids was calculated by the mixing rule. Its viscosity and surface tension was tested respectively by a rotation viscometer (Shanghai Fangrui LVDV-1T, 0.6–2×10⁶ mPa∙s) and pendant-drop method (Germany Dataphysics OCA25, 1×10⁻²–2×10³ mN/m). Results show that the density, viscosity, and surface tension of Al₂O₃-H₂O nanofluids increase gradually as the concentration of nano-alumina increases. Compared to basic fluid without particles, these physical properties of nanofluid at 2.0wt.% increase by 1.5%, 21.0%, and 2.5% correspondingly.

2.2 Experimental Facility
In the experimental system, we used pressure air to drive the liquid injection, and applied shadow imaging with transparent pipeline to realize flow visualization. As shown in Figure 1, the liquid supply part integrated high-pressure cylinder, decompressor and pressure-resistant liquid tank to achieve continuous and stable adjustment of the injection pressure. A fine adjustment of the flowrate was achieved by a needle valve. An electromagnetic flowmeter (RONK DN4), temperature and pressure sensors, together with a data collector were used for real-time measurement and control of flow state. Some liquid pipelines were connected smoothly with transparent hoses, which can reduce pressure loss and suppress bubble generation. At the same time, it can also show the suspension state of the nanofluid to ensure that no obvious delamination occurred during the spraying process.

![Fig.1. Schematic diagram of the experimental system.](image)

In the flow visualization part, a transparent nozzle and spray chamber made of polymethyl methacrylate were designed. By using a high-definition-high-speed camera (Phantom V2640) and a 1000W LED light source, shadow images of flow inside the nozzle and near the exit were obtained. Two transparent nozzles, one with sharp edge and another round edge, were designed with outlet diameter of 2mm. The sharp-edge nozzle was used to study the cavitation inside the nozzle, while the round-edge one was used to study the flow outside the nozzle. Upstream of the nozzle inlet, a straight pipe section with a length of 300mm was used to obtain a fully developed uniform flow.

Experiments were carried out at room temperature of 20°C and ambient pressure. Test conditions are shown in Table 1. The liquid injection pressure was changed from 0.1MPa to 0.65MPa, and the flow velocity at the nozzle exit corresponded to 8.8-23.9m/s. Before each test, a high injection pressure (above 0.6 MPa) was used to remove large air bubbles inside the pipeline. During the experiment, the camera was equipped with a macro lens (TOKINA, 100mm, F2.8D), and set as a resolution of 600×1500 with 15000fps at an exposure time of 5 μs. According to size calibration, a single pixel of the jet shadowgraph corresponds to a size of 50 μm.
Table 1. Liquid properties and test conditions (293K, 101kPa).

| Fluids          | Basic Fluid | Nanofluids |
|-----------------|-------------|------------|
| Nano-alumina Concentration [wt.%] | 0 | 0.5 | 1 | 1.5 | 2 |
| Density [kg/m³] | 998.2 | 1002.0 | 1005.7 | 1009.5 | 1013.4 |
| Dynamic Viscosity [mPa·s] | 1.00 | 1.10 | 1.14 | 1.18 | 1.21 |
| Surface Tension [mN/m] | 33.01 | 33.29 | 33.36 | 33.50 | 33.85 |
| Total Pressure [MPa] | 0.10 – 0.65 | 0.10 – 0.65 |
| Liquid Jet Exit Velocity [m/s] | 8.8 – 23.9 | 8.8 – 23.9 |
| Liquid Reynolds Number | 15347 – 46260 | 15347 – 46260 |

3. Results and Discussion

3.1 Morphology Analysis on the Initial Flow

For the sharp-edge nozzle, due to the sudden shrinkage of the flow channel, the boundary layer will separate at the nozzle wall near the entrance of the narrow section, thereby forming a recirculation zone. As the flow accelerates, the static pressure decreases. When the pressure in the recirculation zone is lower than the saturated vapor pressure, local cavitation begins to form. As we know, the gas bubble (air or water vapor) and liquid water have different refractive indices for visible light. When cavitation occurs inside the liquid core, the light transmittance on the optical path will decrease, and so darker areas appear on the shadowgraph.

As shown in Figure 2, at a high injection pressure of 0.65 MPa, the initial flow had gone through three stages: without cavitation, inception and partial cavitation, and supercavitation. For the basic fluid, within 3ms of the injection beginning, the flow shadowgraph remained uniform and transparent inside the nozzle. That is, no cavitation zone was observed. In the stage, the jet appeared as an umbrella structure due to RT instability. As the flow accelerates, the jet core developed from a smooth laminar flow to turbulence. At the time of 4ms, a black area appeared inside the nozzle, that is, a relatively stable cavitation had occurred and developed to about half the length of nozzle pinhole. At about 5ms, the cavitation began to develop to the nozzle exit, that is, the supercavitation had formed. At 6ms, due to the formation of a supercavitating gas layer on the inner wall of the nozzle, the structure of the
liquid boundary layer began to adjust, and the turbulence intensity at the nozzle exit decreased. Therefore, the jet showed as a smooth and transparent laminar flow in a short time.

For nanofluid at a concentration of 0.5 wt.%, Figure 2 shows that the initial flow had gone through the same development stage. In comparison to basic fluid, besides the decrease in light transmission, the development of cavitation inside the nozzle accelerated significantly for nanofluid. For further verification, the variation of cavitation onset time with nanoparticle concentration was obtained through repeated tests. As shown in Figure 3, the cavitation onset time of basic fluid was about 3.3 ms. After adding 0.5-2.0 wt% nanoparticles, the cavitation onset time was shortened to about 1.6 ms. It shows that the nanoparticles can promote the formation of cavitation, while the particle concentration has little effect on the onsets of cavitation.

3.2 Cavitation inside a Sharp-edge Nozzle

Cavitation is considered to be affected by many factors, such as flow structure, liquid surface tension, amount of dissolved gas, amount and shape of suspended solid particles [2]. For a fixed nozzle structure and fluid type, the cavitation number \( K \) is usually used to characterize the flow performance of the system. Here, the cavitation number is defined as:

\[
K = \frac{p_{\text{in}} - p_v(T)}{p_{\text{in}} - p_{\text{out}}}
\]

Among them, \( p_{\text{in}} \) and \( p_{\text{out}} \) are the inlet and outlet pressure of the nozzle when cavitation occurs. Here, \( p_{\text{out}} \) is the ambient air pressure equal to 100.6 kPa, and \( p_v(T) \) is the saturated vapor pressure of water at 20 °C equal to 2.3388 kPa.

As shown in Figure 4, when cavitation inception occurred in the nozzle at steady flow state, the bubbles were small and unstable. They formed and collapsed within a very short time (less than 1/15 ms), and the cavitation location changed quickly near the entrance of the nozzle. No significant change was found by comparing the jet shape before and after cavitation. That indicates the weak inception cavitation has little effect on current flow system. The nozzle inlet pressure was measured corresponding to inception cavitation under different concentrations of nanoparticles, and then inception cavitation number was calculated.

Figure 5 shows that the inception cavitation pressure was kept around 226.1 kPa, and the addition of nanoparticles had no obvious effect on the inception cavitation number. We can see that for a certain type of liquid and temperature, the key to inception cavitation is the static pressure of flow in recirculation zone. Cavitation will only form when the injection pressure is high enough, and the nanoparticles have no significant effect on the static pressure and saturation vapor pressure.
When the injection pressure increased to around 296.9 kPa, the flow began to develop from local cavitation near the nozzle inlet to supercavitation (as shown in Figure 6). Transient images show that supercavitation was a dynamic change process: high-frequency changes in the area and intensity of cavitation were observed, and the bubbles were constantly generated and collapsed. When more cavitation bubbles formed on one side, the gather and collapse of bubbles cause asymmetric local atomization, which is called deflecting jetflow (the red rectangular area in Figure 6). Due to the reduction in nozzle flow area, the shadowgraph after supercavitation shows stronger sense of flow, reflecting a significant increase in the jet velocity. Except that the unilateral deflecting jetflow had reached atomization state, the main bodies of jets before and after supercavitation were both in secondary wind-induced breakup mode.

The nozzle inlet pressure was measured corresponding to critical supercavitation for nanofluids at different concentrations, and then the critical supercavitation number was calculated (as shown in Figure 7). As the nanoparticle concentration increased from 0 to 2.0 wt.%, the critical pressure of supercavitation in the sharp-edge nozzle gradually decreased from 302.9 kPa to 293.2 kPa, with a max reduction of 3.2%. Accordingly, the critical supercavitation number increased. And the change was more obvious below the concentration of 1.0 wt.%, while little change between the concentration of 1.0~2.0 wt.%. We can see that after the pressure in the recirculation zone reaches cavitation conditions, the nanoparticles act as heterogeneous nucleation points. They promote the accumulation of cavitation bubbles, and extend their existence time. When the number of nanoparticles is sufficient, the effect on cavitation will become saturated.

Besides the deflecting jetflow, another feature of supercavitation is sudden flux changes due to the flow congestion. Current monitoring data show that the flow rate dropped from 170.5 L/h to 151.6 L/h when the nozzle inlet pressure increased from 292.4 kPa to 295.0 kPa for nanofluids at 1.0 wt.%. And the corresponding flow coefficient dropped from 0.74 to 0.63, which is equivalent to reducing the flow area by $0.11A_0$ ($A_0$ is the nozzle cross-sectional area). The average thickness of the supercavitation bubble layer near the nozzle wall was about 0.056 mm based on a rough estimation.

### 3.3 Jet Cavitation outside a Round-edge Nozzle

The phenomenon of cavitation bubbles inside the jet is also worthy of attention. Due to the strong turbulence caused by the sharp-edge nozzle, the details of the flow inside the liquid core cannot be observed in the shadowgraph outside the nozzle. Therefore, around-edge nozzle was adopted here, and experiments were carried out at a low inject pressure (0.1 Mpa) to obtain smooth jet shadowgraph with weak turbulence. Relative to basic fluid, a special cavitation phenomenon for
nanofluid was found inside the jet below the nozzle exit. Figure 8 shows the formation of a bubble in the nanofluid jet core. The whole formation process was less than 0.5 ms. During the tests, it was confirmed that no bubble was observed inside the nozzle upstream, and no droplet peeled off the liquid core. Therefore, the droplet-shape dark zone inside the jet shadowgraph of Figure 8 can only be bubble generated around. The bubble formed in a squamous corrugated area below the nozzle exit, where a surface wave caused by KH instability. The high-frequency changes in the surface wave shape caused nearby liquid to oscillate. Near the wave peak where the oscillation was most intense, the internal liquid was torn by stretch effect, thereby forming cavitation bubbles. Then the bubble shape gradually became spherical under the influence of surface tension.

![Fig.8. Growth process of cavitation bubbles inside a jet (0.5 wt.% nanofluid, $p_{in} = 0.1$ MPa).](image)

For basic fluid (as shown in Figure 9), it appears that some embryo of bubble formed near the wave peak, but it quickly collapsed before dispersed. That is, no stable bubble formed inside the pure liquid jet. But for nanofluids, cavitation bubbles in size of 200–400 μm kept a stable shape without collapse in a distance of 20d from the KH wave zone. According to related literature, we hold the opinion that nanoparticles reduce the tensile strength of liquid [21], and at the same time play the role of heterogeneous nucleation points, thereby promoting the formation and stable existence of bubbles. For the source of these bubbles, it may be water vapor generated by local evaporation, or it may come from the air dissolved during the preparation of nanofluids. According to colloid and interface theory, the addition of nanoparticles will increase gas adsorption at the liquid-solid interface, including the...
formation of a certain amount of nano-bubbles [22]. For this reason, nanoparticles can simultaneously increase the number of cavitation bubbles. In addition, the KH wave region of nanofluid jet was closer to the nozzle exit compared with that of basic fluid. It means that nanoparticles also accelerated the development of jet disturbance, and this enhancement of instability further promoted the cavitation.

4. Summary and Conclusions
In this paper, Al$_2$O$_3$-H$_2$O nanofluids with five different concentrations were prepared by the classic two-step method. An experimental facility of jetflow visualization was self-designed, and high-speed shadow imaging method was used to obtain flow images inside and outside two nozzles with sharp edge and round edge. Through comprehensive analyses of flow morphology and state parameters, the effects of nanoparticle additives on the initial development of round jet, incipient cavitation and critical supercavitation inside sharp-edge nozzle, and jet cavitation outside round-edge nozzle were discussed. Results showed that: inside the nozzle, nanoparticles shorten the formation time of cavitation in unsteady flow mode, and reduced the critical supercavitation pressure in steady flow mode; while they have little effect on the inception cavitation pressure. The cavitation inside the nozzle showed a high-frequency change process: The bubbles continuously formed and quickly collapsed, and their positions and sizes were changing constantly. The weak inception cavitation had little effect on current flow system by checking the jet shape. Meanwhile, supercavitation caused asymmetric deflecting jetflow and flow congestion, which reduced the nozzle flow coefficient. Outside the nozzle, nanoparticles promoted the formation and persistence of bubbles in the jet core. These bubbles generated near the KH-instability wave peaks below the nozzle. Near the wave peak where the oscillation was most intense, the internal liquid was torn by stretch effect, thereby forming cavitation bubbles. Compared with that of basic fluid, the KH wave of the nanofluid jet was closer to the nozzle exit.

In conclusion, the addition of nanoparticles promoted the cavitation inside and outside the nozzle, and it can be attributed to the following changes: nanoparticles increased the original adsorption of air, reduced the tensile strength of liquid, speeded up the disturbances of jet, and played the role of heterogeneous nucleation points.

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