

# Experimental Research on Flash Boiling Spray of Dimethyl Ether

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**Abstract:** The high-speed digital imaging technique is applied to observe the developing process of flash boiling spray of dimethyl ether at low ambient pressure, and the effects of nozzle opening pressure and nozzle hole diameter on the spray shape, spray tip penetration and spray angle during the injection are investigated. The experimental results show that the time when the vortex ring structure of flash boiling spray forms and its developing process are determined by the combined action of the bubble growth and breakup in the spray and the air drag on the leading end of spray; with the enhancement of nozzle opening pressure, the spray tip penetration increases and the spray angle decreases. The influence of nozzle hole diameter on the spray tip penetration is relatively complicated, the spray tip penetration is longer with a smaller nozzle hole diameter at the early stage of injection, while the situation is just opposite at the later stage of injection. This paper establishes that the variation of spray angle is consistent with that of nozzle hole diameter.

**Keywords:** dimethyl ether; flash boiling spray; high-speed digital imaging; spray tip penetration; spray angle; vortex ring structure

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## 1 Introduction

The flash boiling spray has the potential to improve engine performance since it can be used to promote the atomization of fuels with a large spray cone angle and a smaller droplet Sauter mean diameter (SMD) (Zeng *et al.*, 2012; Duan *et al.*, 1999; Lienhard and Stephenson, 1996; Eran *et al.*, 2008; Yu *et al.*, 2007). In recent years, the research on flash boiling spray was mainly focused on superheated liquefied fuel and fuel containing dissolved gas (Kawano *et al.*, 2004; Zeng and Lee, 2002; Zuo *et al.*, 2000; Ra and Reitz, 2004; Hou *et al.*, 2005; Ma *et al.*, 2007). However, little has been reported about the characteristic research on flash boiling spray of fuels with low boiling point and high saturated vapor pressure, which has attracted widespread attention at present. As a clean fuel with potential long-lasting resources, dimethyl ether (DME) has been considered as a promising alternative fuel for compression-ignition engine (ICE) in recent years (Wang *et al.*, 2004; Lü *et al.*, 2003). The low boiling point and high

saturated vapor pressure nature make the DME spray undergo flash boiling at lower ambient pressure (Wakai *et al.*, 1999; Yu *et al.*, 2002), while the atomization of fuel plays a very important part in determining the temporal and spatial distribution of fuel in ICE which influences subsequently the quality of combustion and finally the performance and emissions of ICE (Wang and Zhou, 2001; Wen *et al.*, 2003; Zhou *et al.*, 2007). Therefore, the experimental research on DME spray under flash boiling condition is of great significance.

This paper consists of the experimental results of flash boiling spray characteristics, including the spray shape, the spray tip penetration and the spray angle, for liquid DME injected by a single-hole nozzle under different nozzle opening pressures and nozzle hole diameters. This study is the preliminary research for further understanding of air-fuel mixing and consequent combustion by adding the DME into ICE. Also, this study is helpful in offering a comprehensive database for the flash boiling spray characteristics of DME.

## 2 Experimental apparatus and conditions

Fig. 1 shows the schematic diagram of the experimental setup, it consists of a constant volume chamber, a single-hole injector, a fuel supplying system, a light source and optical system, an electronic controlling circuit and a high-speed digital imaging system. Two sides of the chamber are transparent to make the process of spray observable. In the light source and optical system, a common bulb rated for 2 kW is adopted to illuminate the constant volume chamber, and a frosted glass is placed between the bulb and chamber to reduce inhomogeneous impact of light intensity on imaging effect. In order to avoid evaporation of the DME in fuel supplying system, the DME tank is directly pressurized up to 1.8 MPa by nitrogen. In addition, some lubricating oil is added into the DME to prevent wear of fuel supplying system. The Fastcam\_SA1.1, which is produced by Photron Limited Corporation of Japan, is adopted in this experiment to capture the spray images using the software called Motion Plus. The frame rate is set at 30 000 fps, which is much higher than that in similar studies. Thus, many details about DME flash boiling spray are captured. About 5 processes of spray under the same

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experimental condition can be captured by the high-speed digital camera, the second process is chosen as the investigated subject because the fuel pressure is not established fully in the high-pressure fuel pipe during the first spray. The detailed experimental conditions are listed in Table 1.

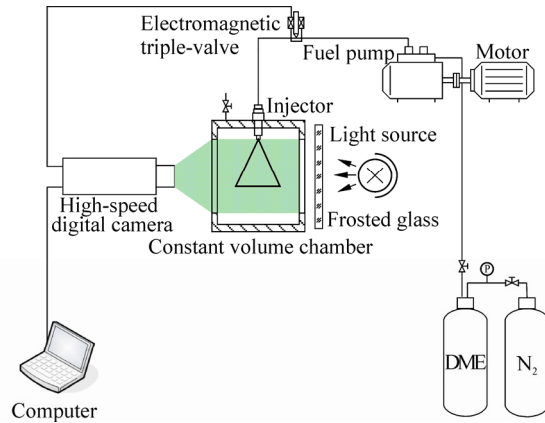


Fig. 1 Schematic diagram of experimental setup

Table 1 Experimental conditions of spray

Item	Description
Fuel	DME
Injector	Single-hole injector
Nozzle opening pressure/MPa	7.0, 12.0, 17.0
Nozzle hole diameter/mm	0.18, 0.32, 0.5
Ambient pressure/MPa	0.1
Ambient temperature/K	285

### 3 Results and discussion

#### 3.1 Structure of flash boiling spray

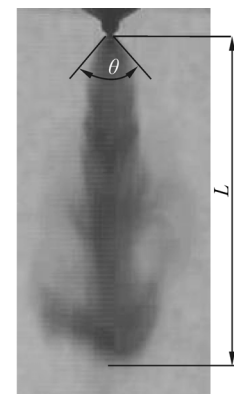
Spray shape, spray tip penetration and spray angle are usually used to characterize the macroscopic spray structure. In this study, the spray tip penetration and spray angle were directly measured from the spray image captured by the high-speed digital camera. Considering the spray shape near the nozzle tip takes on parabolic pattern, the spray angles were obtained by measuring the angles between two tangent lines of the edges of spray near the nozzle tip. In addition, the distance from the nozzle tip to the leading end of spray was defined as the spray tip penetration of the whole spray. Fig. 2 gives the definitions of spray tip penetration and spray angle.

#### 3.2 Influence of nozzle opening pressure

The spray images for liquid DME under three kinds of nozzle opening pressures are provided in Figs. 3, 4 and 5 respectively. Usually, a higher nozzle opening pressure will result in a higher maximum injection pressure, and thus the influence of nozzle opening pressure on injection process can represent that of maximum injection pressure to a large extent. For the limit of paper length, the time interval

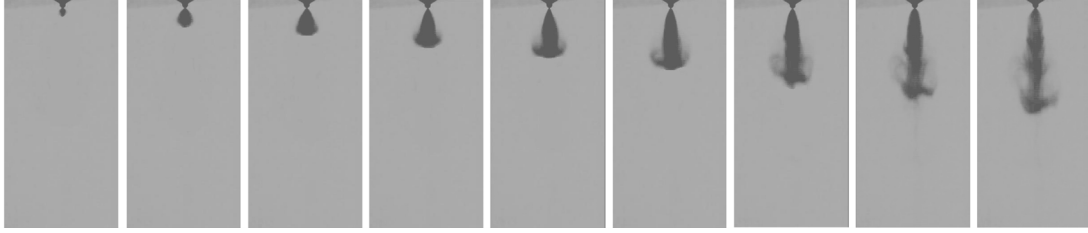
between two spray images is taken as 1/15 000 s. The formation and development of vortex ring structure are clearly observed in Fig. 4. When the liquid DME is injected into the constant volume chamber, the bubble begins to form, grow and break up in the spray because of the superheated state, which extends the spray in the radial direction. The greater air drag on the larger spray leading end resulting from the radial extended effect of bubble growth and breakup on the fuel jet (Zeng and Lee, 2001) largely contributes to the formation of vortex ring structure, and the appearance of vortex ring structure is a typical characteristic of the flash boiling spray (Oguma *et al.*, 2002; Lee *et al.*, 2001; Yu and Bae, 2003; Yu *et al.*, 2009). When the vortex ring structure begins to form on two sides of the spray leading end at about 0.210 9 ms after start of injection, the spray leading end takes on inverted mushroom-like shape at the same time. As the spray develops with time, the two sides of the spray leading end shrink radially and narrow gradually because of the effect of air entrainment produced by vortex ring structure. Meanwhile, the spray shape near the nozzle tip takes on parabolic pattern. As the time goes on, the vortex ring structure begins to become large and long under the action of air drag. In addition, the spray leading end begins to change from inverted mushroom-like shape to anchor-like one and disappears gradually because of the evaporation of droplets. Because the jet velocity of fuel is higher, the time when the vortex ring structure forms under the highest nozzle opening pressure in Fig. 3 is later compared with that in Fig. 4. For the same reason, the radial extended effect of bubble growth and breakup on the fuel jet is not obvious in Fig. 3, while the following development of vortex ring structure is relatively rapider, which can be attributed to the greater air drag on the spray leading end.

Fig. 5 shows the dynamic process of DME flash boiling spray under the lowest nozzle opening pressure. As can be seen in Fig. 5, the vortex ring structure forms earlier and develops slower compared with the phenomena observed in Fig. 4. The reasons can be analyzed similarly.

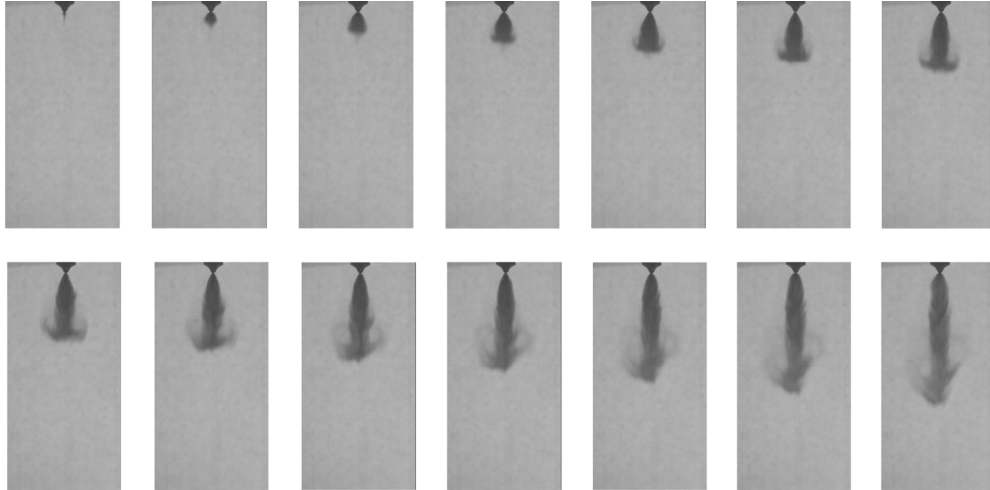


$\theta$ : Spray angle  
 $L$ : Spray tip penetration

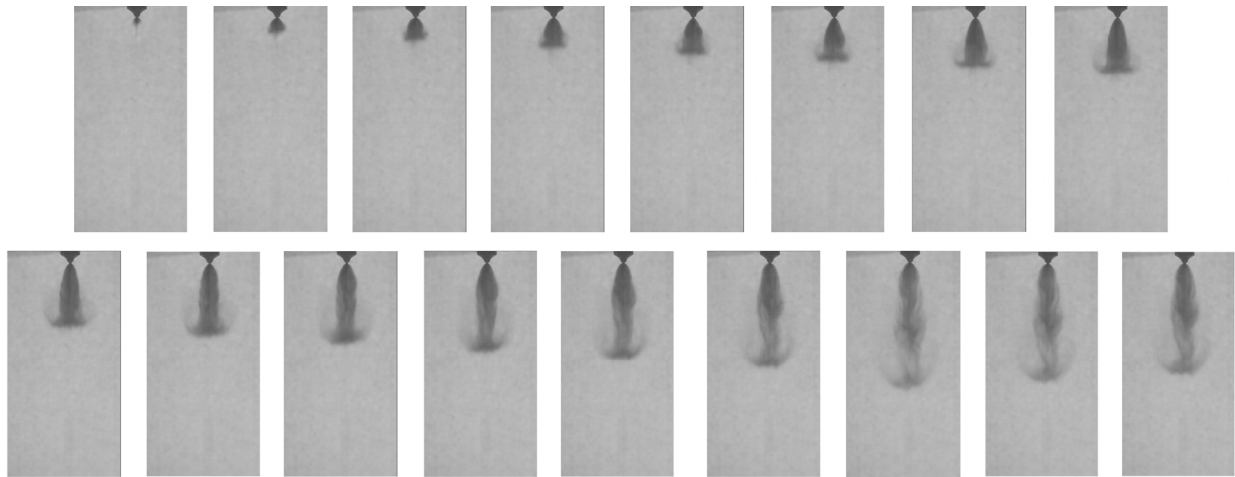
Fig. 2 Definitions of spray tip penetration and spray angle



**Fig. 3** Images of DME flash boiling spray development (first image 0.056 4 ms, nozzle opening pressure 17.0 MPa, nozzle hole diameter 0.5 mm)



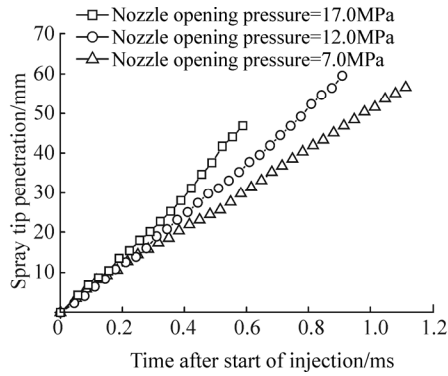
**Fig. 4** Images of DME flash boiling spray development (first image 0.044 4 ms, nozzle opening pressure 12.0 MPa, nozzle hole diameter 0.5 mm)



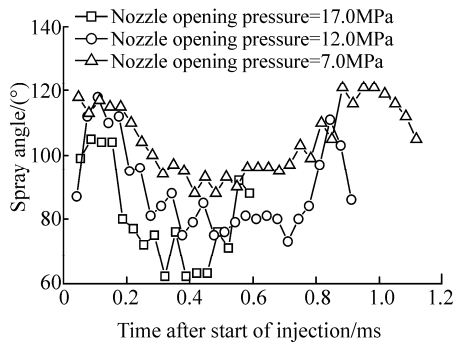
**Fig. 5** Images of DME flash boiling spray development (first image 0.05 ms, nozzle opening pressure 7.0 MPa, nozzle hole diameter 0.5 mm)

Figs. 6 and 7 show the variations of spray tip penetration and spray angle versus time under three kinds of nozzle opening pressures, respectively. It can be seen that under the influence of pressure fluctuation in the fuel injection system, the spray tip penetration has acceleration during the injection. This phenomenon is similar to the results observed by Suh *et al.* (2006). Obviously, the spray tip penetration increases with the enhancement of nozzle opening pressure. In addition, the variation curves of spray

angle versus time approximately take on the letter U shape. This means the spray angles in the middle stage of injection are smaller than those at the early and late stages of injection. The reason these phenomena occur is that the fuel jet velocity is lower at the early and late stages of injection, and the bubble growth and breakup have a greater radial extended effect on the DME jet. Meanwhile, Fig. 7 illustrates that with the enhancement of nozzle opening pressure, the spray angle decreases.



**Fig. 6 Variation of spray tip penetration vs. time under different nozzle opening pressures**



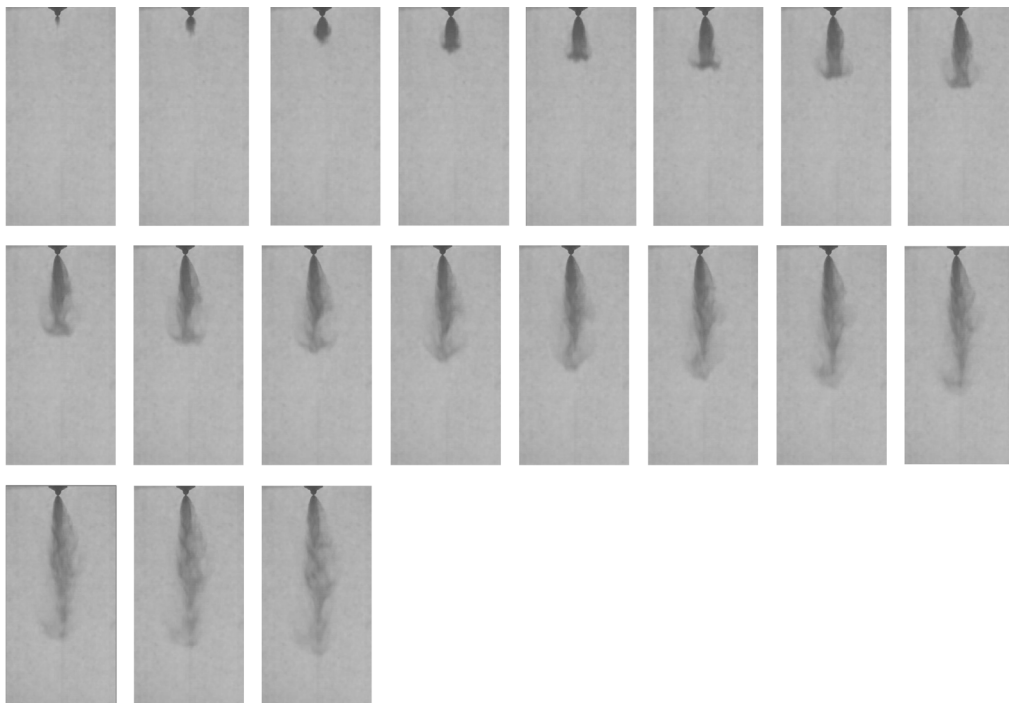
**Fig. 7 Variation of spray angle vs. time under different nozzle opening pressures**

### 3.3 Influence of nozzle hole diameter

Figs. 8 and 9 provide the DME spray images under two nozzle hole diameters, respectively. For the limit of paper length, the time interval between two spray images is also

taken as 1/15 000 s. It can be seen from Fig. 8 that the vortex ring structure forms later and its size is smaller compared with that in Fig. 4, because the smaller nozzle hole diameter decreases the front face area of spray as well as the air drag on the spray leading end. Besides, the decrease of bubble number in the fuel jet for smaller nozzle hole diameter weakens the radial extended effect of bubble growth and breakup on the fuel jet. In the following developing process of spray, the evolution of vortex ring structure is not distinct since the air drag on the spray leading end is smaller for smaller front face area of spray. As shown in Fig. 9, because the nozzle hole diameter is too small, the main spray body is very slim and the formation and development of vortex ring structure is hardly observed.

The spray tip penetrations and spray angles for different nozzle hole diameters are shown in Figs. 10 and 11. Clearly, the effect of nozzle hole diameter on the spray tip penetration is relatively complicated, i.e., the spray tip penetration is longer under smaller nozzle hole diameter at the early stage of injection, the situation is opposite at the late stage of injection. On the one hand, the decrease of nozzle hole diameter brings smaller front face area of spray and air drag acting on the spray leading end, which is favorable to increase the spray tip penetration. On the other hand, the smaller droplets injected by nozzle with smaller hole diameter decelerate quickly in the ambient air, which decreases the spray tip penetration. Thus, the complication of variation of spray tip penetrations versus time can be attributed to the competition between the positive factor and passive one mentioned above. Similarly, the variation curves of spray angle versus time also take on the letter U shape, and the smaller the nozzle hole diameter, the smaller the spray angle.



**Fig. 8 Images of DME flash boiling spray development (first image 0.066 7 ms, nozzle opening pressure 12.0 MPa, nozzle hole diameter 0.32 mm)**

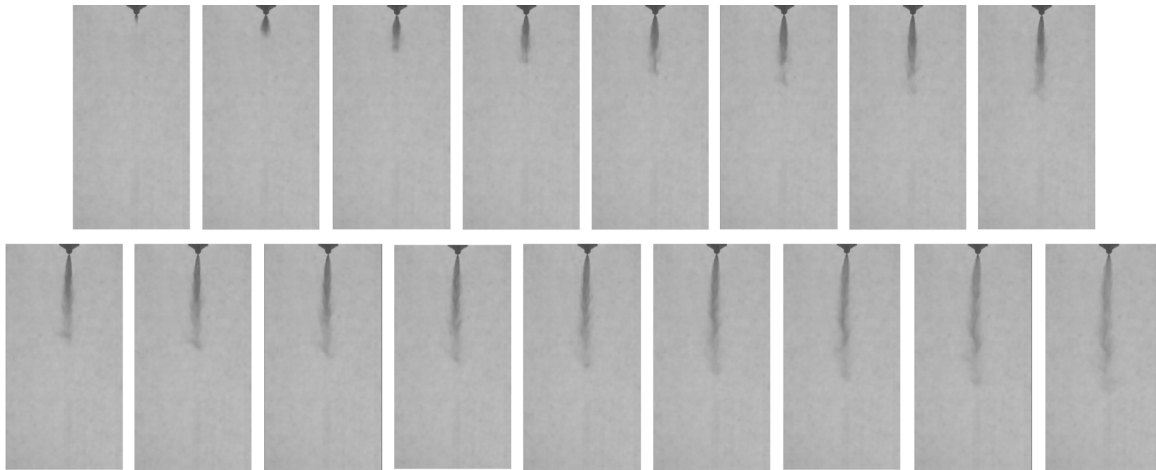


Fig. 9 Images of DME flash boiling spray development (first image 0.063 9 ms, nozzle opening pressure 12.0 MPa, nozzle hole diameter 0.18 mm)

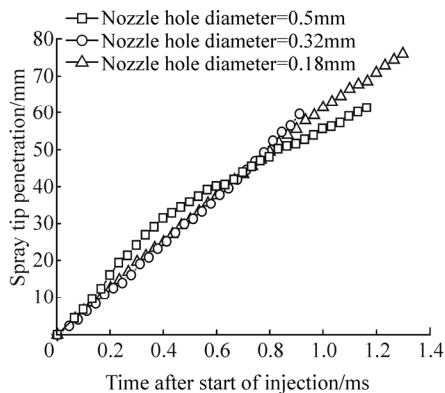


Fig. 10 Variation of spray tip penetration vs. time under different nozzle hole diameters

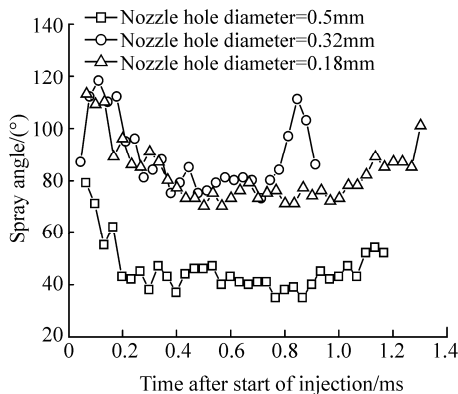


Fig. 11 Variation of spray angle vs. time under different nozzle hole diameters

## 4 Conclusions

The liquid DME spray undergoes flash boiling at lower ambient pressure for its low boiling point and high saturated vapor pressure nature. The formation and development of vortex ring structure during the injection is a typical characteristic of flash boiling spray. The experimental results

indicate that the combined action of the bubble growth and breakup in the spray and the air drag on the spray leading end determines the formation and development of vortex ring structure of flash boiling spray; with the enhancement of nozzle opening pressure, the spray tip penetration increases and the spray angle decreases; while the influence of nozzle hole diameter on the spray tip penetration is relatively complicated, the variation of spray angle is in accordance with that of nozzle hole diameter.

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### Author biography



**Peng Zhang** is an engineer at China Ship Development and Design Center. He has been the investigator of a large variety of funded research work regarding the design and optimization of marine power system. His research interests include simulation of marine power system, marine diesel technology, program evaluation of marine power system, design of marine power control system and so on. He has published over 14 papers about the research field mentioned above.