ATOMIZATION OF HIGH-VISCOUS LIQUID JET BY INTERNAL MIXING TWIN-FLUID ATOMIZER

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ABSTRACT

The purpose of this study is to develop a waste oil combustion burner, which is able to atomize a large number of high-viscous liquid fuel like that waste oil using little energy and is able to reduce air pollutants. The burner developed in this study consists of an internal mixing twin-fluid atomizer in which waste oil and atomizing air are mixed in the mixing chamber. In this paper, the effects of kinematic viscosity of the injection liquid, supplying method of atomizing air, geometric shapes and measurements of the atomizer on atomization of the spray and Sauter mean diameter were investigated. Kinematic viscosity was varied from ν_f=0.66x10^{-6} [m^2/s] deserved kerosene and gasoline to ν_f=400x10^{-6} [m^2/s] deserved waste oil for tanker ships. Mass flow rate of liquid was changed from 5.9 [g/s] (15 [*l*/h]) to 115 [g/s] (400 [*l*/h]). The results of this study indicated that the atomizer invented in this study is possible to obtain excellent spray characteristics, which Sauter mean diameter is small and the spray angle is large with a small amount of atomizing air. Almost the same Sauter mean diameter independent of liquid flow rate was obtained at relatively a small amount of atomizing air flow rate.

1. INTRODUCTION

The effective use of waste materials is regarded as very important from a resources saving view point. Waste oil, which is waste engine oil and the leftover oil from tanker ships, is little used for the fuel of industrial burner. Since waste oil is usually of high viscosity, low quality and includes water, the disposal method of waste oil is quite difficult [1]-[4]. It is necessary to develop a combustion burner, which can burn low quality fuels, such asbanker fuel oil and waste oil, with high combustion efficiencies and low pollutant emissions. The newly developed internal mixing twin-fluid atomizer can make small droplets with low atomizing air flow rate [5]. The twin-fluid atomizer used in this study is mixed waste oil and atomizing air in a swirling flow in the mixing chamber. In order to determine the optimum atomizing condition and the best structure of the atomizer, we made the atomizer with transparent acrylic resin and observed the flow patterns and atomizing phenomena in the mixing chamber and exit port [6], [7].

In this paper, the effects of kinematic viscosity of the injection liquid, hole number of the atomizer, supplying method of atomizing air and height of the mixing chamber on atomization of high-viscous liquid were studied. The results of this study indicated that high atomization efficiencies of high-viscous liquid are achieved with little expenditure of energy, i.e., a small amount of atomizing air. Sauter mean diameter of the single hole atomizer becomes smaller than that for the case of the multi hole one at over range of mass flow rate of atomizing air. Swirl angle of atomizing air is little influenced to atomization of high-viscous liquid. Sauter mean diameter could be reduced by changing height of the mixing chamber. By usage of shorter length of the mixing chamber, smaller Sauter mean diameter can be obtained, independent of kinematic viscosity of liquid. When mass flow rate of liquid is considerably increased at M_f=115 [g/s] (400 [*l*/h]), the same Sauter mean diameter as the case of which mass flow rate of liquid is little of M_f=5.9 [g/s] (15 [*l*/h]) was obtained by increasing atomizing air of two or three times. Sauter mean diameter of a large amount of liquid flow rate of M_f=115 [g/s] is equal to that for a small amount of liquid of M_f=5.9 [g/s] at relatively a small amount of atomizing air flow rate.

2. EXPERIMENTAL APPARATUS AND METHOD

Schematic diagram of experimental apparatus is shown in Fig. 1. Test liquid is glycerol solution, and kinematic viscosity were varied from ν_f=0.66x10^{-6} [m^2/s] deserved kerosene and gasoline to ν_f=400x10^{-6} [m^2/s] deserved waste oil for tanker ships at T_f=300 [K]. Test liquid was supplied from an accumulator tank compressed by N_2 bomb to the atomizer and atomizing air was supplied by a compressor to the atomizer. The internal flow in the mixing chamber and disintegration behaviour of the spray were photographed by back diffusion light illumination method, using a stroboscope. The droplet size and its distributions were measured by a narrow-angle forward scattering type LDSA particle analyzer at 150 [mm] downstream from the atomizer exit. Mass flow rate of liquid M_f were changed from 5.9

[g/s] (15 [l/h]) to 115 [g/s] (400 [l/h]), mass flow rate of atomizing air M_a were varied from 0.2 [g/s] to 3.5 [g/s].

Structure of the internal mixing twin-fluid atomizer invented in this study is shown in Fig. 2. The internal mixing twin-fluid atomizer is mixed liquid with atomizing air given a swirling flow in the mixing chamber. The detaile structure of the internal mixing twin-fluid atomizer and the nozzle chip are shown in Figs. 3 and 4, respectively. In order to determine the optimumatomizing condition and the best structure of the atomizer, hole number of the atomizer, swirl angle of atomizing air and height of the mixing chamber were varied, the atomizer made of transparent acrylic resin was used, and flow patterns, disintegration behavior in the mixing chamber and the exit port were observed. The atomizers are single exit hole and multi exit holes with the same total sectional area of the atomizer holes. The nozzle chip has air port with swirl angle and liquid port. Liquid is supplied from 6 holes, which are installed at the center of the nozzle chip in the mixing chamber. Atomizing air is supplied to the mixing chamber at a certain circular angle for better mixing liquid with atomizing air.

3. EXPERIMENTAL RESULTS AND DISCUTIONS

3.1 EFFECTS OF KINEMATIC VISCOSITY

The effects of kinematic viscosity of liquid on Sauter mean diameter at mass flow rate of liquid of M_f=5.9 [g/s] is shown in Fig. 5. Sauter mean diameter becomes small with an increase in mass flow rate of atomizing air. When mass flow rate of atomizing air is relativelylittle of less than aboutM_a=1.8 [g/s], kinematic viscosity of liquid is affected of atomization of the spray, Sauter mean diameter of high-viscous liquid is larger than that for low-viscous liquid. However, when mass flow rate of atomizing air excesses about M_a=2 [g/s], Sauter mean diameter becomes constant and small for increasing mass flow rate of atomizing air independent of kinematic viscosity. As the results, this atomizer is able to atomize high-viscous liquid under relatively a small amount of atomizing air.

3.2 EFFECTS OF HOLE NUMBER OF ATOMIZER

It is guessed that when total sectional area of holes is the same, a multi hole atomizer is easy to atomize rather than a single hole one, because the hole diameters of the multi hole atomizer are smaller than the single hole one. The effects of hole number of the atomizer on the droplet size distributions and Sauter mean diameter is shown in Figs. 6 and 7, respectively. The hole number of the atomizer is affected to the droplet size distributions. In case of the multi hole atomizer (N=4), the droplet size distributions are biased to large droplet and accounts for relatively large droplets larger than 400 [μm]. The cumulativeness of small droplets less than 100 [μm] is about 20 [%], the droplet size distributions

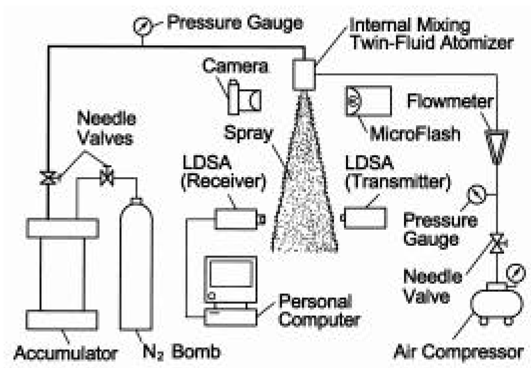


Fig.1 Schematic of experimental apparatus

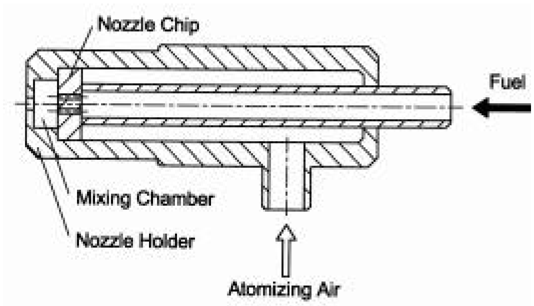
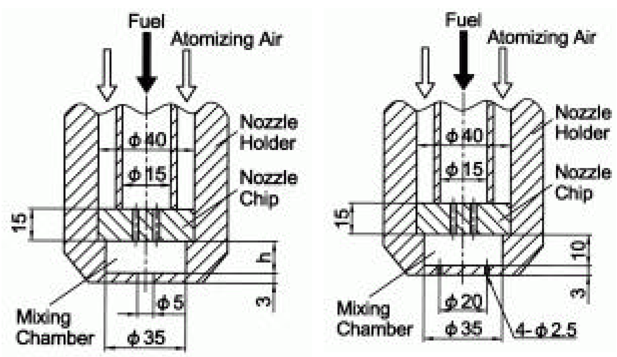
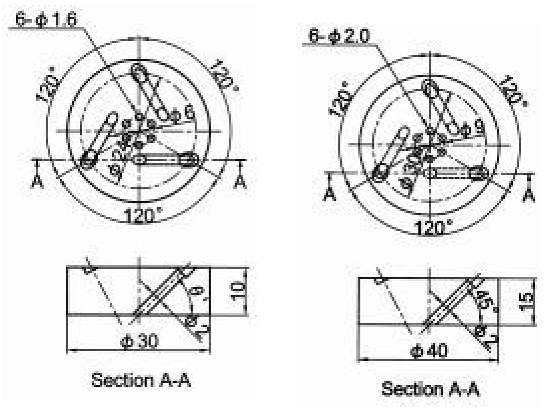


Fig.2 Internal mixing twin-fluid atomizer



(a) Hole number N=1 **(b) Hole number N=4**

Fig.3 Detailed structure of the internal mixing twin-fluid atomizer



(a) Type-D (For small amount of fuel) **(b) Type-D' (For large amount of fuel)**

Fig.4 Detaile structure of the nozzle chips

which large droplets accounts for about 50 [%] of the cumulativeness is obtained. To the contrary, in case of the single hole atomizer (N=1), relatively large droplet size distributions more than about 500 [μm] is little obtained and the cumulativeness of it is a few percents. The cumulativeness of small droplets less than 100 [μm] is high of about 50 [%], and it is high frequency comparing with the multi hole atomizer. As shown in Fig. 7, although Sauter mean diameter becomes small with an increase in mass flow rate of atomizing air, Sauter mean diameter of the single hole atomizer is smaller than that for the multi hole one at the same mass flow rate of atomizing air. Moreover, the single hole atomizer is obtained the excellent spray with small Sauter mean diameter, and it is able to atomize high-viscous liquid giving a small amount of atomizing air. It is considered that in case of the multi hole atomizer, the droplets disintegrated in the mixing chamb er are hardly to eject and the injection velocity decreases at the exit of the atomizer due to small hole diameters.

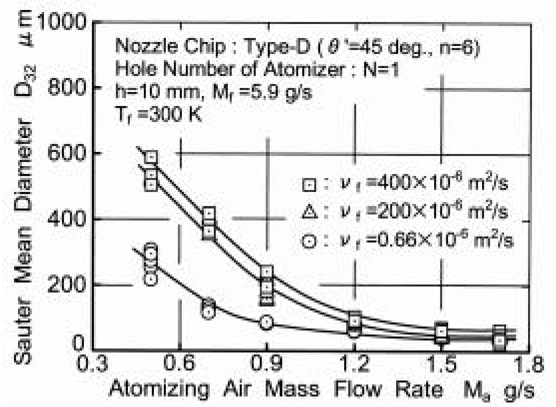
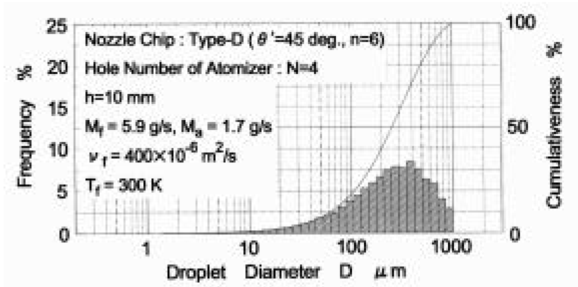


Fig.5 Effects of kinematic viscosity of liquid on Sauter mean diameter

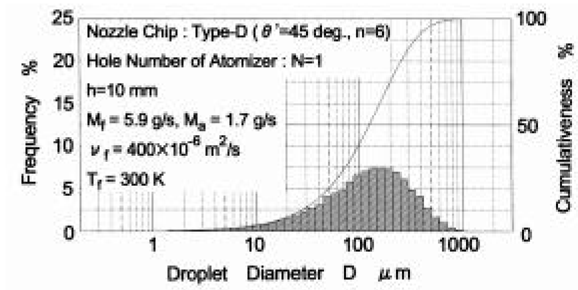
3.3 EFFECTS OF SWIRL ANGLE OF ATOMIZING AIR

It is necessary to mix liquid with atomizing air in the mixing chamber in order to enhance atomization of high-viscous liquid. The atomizer used in this study is given swirling flow. The droplet size distributions at swirl angle of atomizing air of θ'=45, 60 and 90 [degs.], and the effects of swirl angle of atomizing air on Sauter mean diameter are shown in Figs. 8 and 9, respectively. The droplet size distributions at any swirl angle of atomizing air are almost the same, and the droplet size distributions, which are accounted for droplets of about 150 [μm], are obtained independent of swirl angle of atomizing air. Moreover, as shown in Fig. 8, when mass flow rate of atomizing air is little of M_a=0.7 [g/s], Sauter mean diameter of the atomizer with large swirl angle of atomizing air (θ'=90 [deg.]) becomes large comparing with the atomizer of small swirl angle of atomizing air. This tendency is remarkably shown at high-viscous liquid. However, when mass flow rate of atomizing air is large of M_a=1.7 [g/s], swirl angle of atomizing air is little influenced to atomization of the spray, Sauter mean diameters are almost the same values independent of kinematic viscosity of liquid.

It is guessed that when mass flow rate of atomizing air is little, the atomizer with large swirl angle of atomizing air (θ'=90 [deg.]) is weak the swirling force of atomizing air in the mixing chamber rather than small swirl angle of atomizing air (θ'=45 [deg.]). Therefore, it is considered that in case of large swirl angle of atomizing air, the disintegration of liquid, mixing of liquid and atomizing air are not enhanced, as the results, the large droplets and the liquid column are issued from the atomizer.



(a) N=4



(b) N=1

Fig.6 Effects of hole number of the atomizer on the droplet size distributions

3.4 EFFECTS OF THE HEIGHT OF THE MIXING CHAMBER

The effects of the height of the mixing chamber on the spray angle and Sauter mean diameter are shown in Figs. 10 and 11, respectively. Figures 10, 11 (a) and (b) are shown the cases of mass flow rate of liquid of M_f=5.9 [g/s], M_f=115 [g/s]. As shown in Fig. 10, the spray angle of the atomizer of h=2 [mm] is large compared with ones of h=10 [mm] and h=30 [mm] independent of kinematic viscosity and mass flow rate of liquid. As shown in Fig. 11, when mass flow rate of liquid is little of M_f=5.9 [g/s], Sauter mean diameter

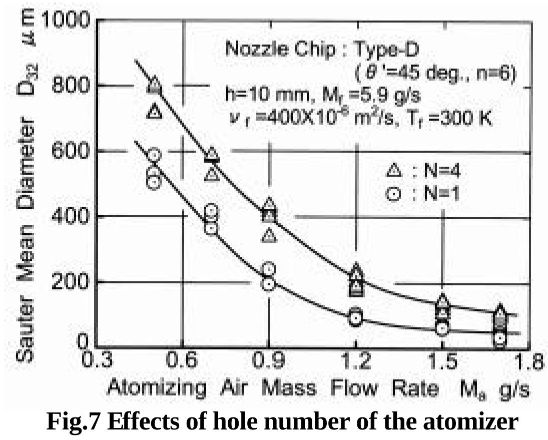


Fig.7 Effects of hole number of the atomizer on Sauter mean diameter

of h=30 [mm] are slightly large, the height of the mixing chamber is little influenced to atomization of the spray. However, when mass flow rate of liquid is considerably large of M_f=115 [g/s], Sauter mean diameter becomes large with an increase in the height of the mixing chamber, atomization of the spray becomes wrong.

The reason why the differences of atomization of the spray are shown by the height of the mixing chamber is considered as follows. The photographs of the liquid flow in the mixing chamber are shown in Fig. 12, and the schematics of the expected stream line in the mixing chamber is shown in Fig. 13. Figures 12 (a) and (b) are shown the cases of kinematic viscosity of ν_f=0.66x10^{-6} [m^2/s], ν_f=400x10^{-6} [m^2/s], respectively. As shown in Figs. 12 and 13, in case of h=30 [mm], the liquid flow in the mixing chamber dominates the circling flow from the inner plate toward the bottom plate, from the bottom plate toward the inner plate and the top plate. It can be seen that the vicinity of center of the mixing chamber is cavity due to inadequacy of mixing liquid and atomizing air. To the contrary, in cases of h=2 [mm] and h=10 [mm], although the behavior of the liquid flow at vicinity of center of the mixing chamber is hardly grasped from the photographs, it seems that liquid and atomizing air are mixed sufficiently. From these results, it is considered that in case of h=30 [mm], when mass flow rate of liquid is considerably large, the disintegration and mixing liquid and atomizing air in the mixing chamber are not enhanced, the large droplets and the liquid column are issued from the atomizer.

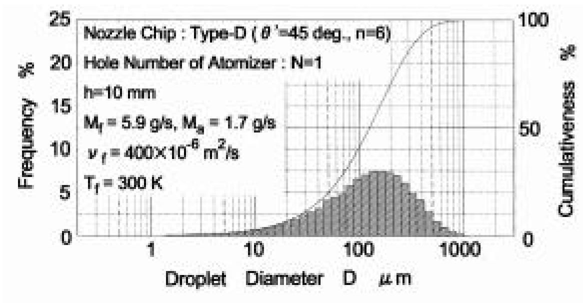
From these results, when the atomizer in which the single hole atomizer (N=1), swirl angle of atomizing air is inclined of θ'=45 [deg.] toward the liquid flow and height of the mixing chamber is low of h=2 [mm] was used, the spray with the small Sauter mean diameter is obtained independent of kinematic viscosity, and it is possible to atomize high-viscous liquid like that waste oil.

3.5 EFFECTS OF MASS FLOW RATE OF LIQUID

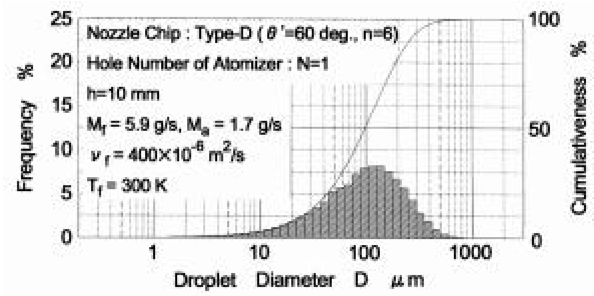
It is necessary to consume the waste oil largely, since it has been accumulating every days. When mass flow rate of liquid is considerably increased, it has investigated about the effect of mass flow rate of liquid on atomization of the spray and about the amount of atomizing air to achieve atomization of a great deal of waste oil. The variations of Sauter mean diameter at the case of which mass flow rate of liquid was changed from M_f=5.9 [g/s] to M_f=115 [g/s] was shown in Fig. 14. Figures 14 (a) and (b) are shown the cases of kinematic viscosity of ν_f=0.66x10^{-6} [m^2/s], ν_f=400x10^{-6} [m^2/s], respectively. As shown in Fig. 14 (a), the smallest Sauter mean diameter of about 40 [μm] is obtained increasing mass flow rate of atomizing air, independent of mass flow rate of liquid. When mass flow rate of atomizing air is M_a=1.7 [g/s] for mass flow rate of liquid of M_f=5.9 [g/s], and it is M_a=3.5 [g/s] for M_f=115 [g/s], Sauter mean diameter of a large amount of liquid flow rate of M_f=115 [g/s] is equal to that for a small amount of liquid of M_f=5.9 [g/s] at relatively small amount of atomizing air flow rate.

Thus, even though mass flow rate of liquid is considerably increased, the spray with the same and the small Sauter mean diameter is obtained by increasing two times as large as mass flow rate of atomizing air of which is obtained the smallest Sauter mean diameter under small amount of liquid of M_f=5.9 [g/s].

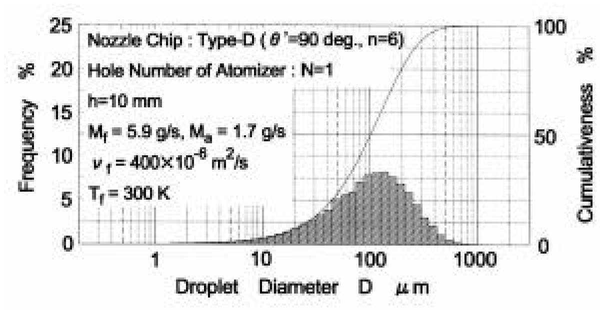
As shown in Fig. 14 (b), when mass flow rate of liquid is relatively small of less than equal to M_f=15 [g/s], the smallest Sauter mean diameter of about 40 [ìm] is obtained increasing mass flow rate of atomizing air like that low-viscous liquid of ν_f=0.66x10^{-6} [m^2/s]. On the other hands, when mass flow rate of liquid is large of M_f=115 [g/s], Sauter mean diameter is about 110 [μm], and it is about three times as large as Sauter mean diameter obtained at



(a) θ'=45 [deg.]



(b) θ'=60 [deg.]



(c) θ'=90 [deg.]

Fig.8 Effects of swirl angle of atomizing air on the droplet size distributions

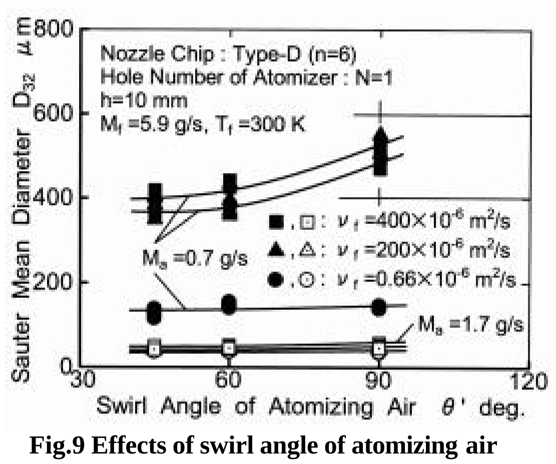
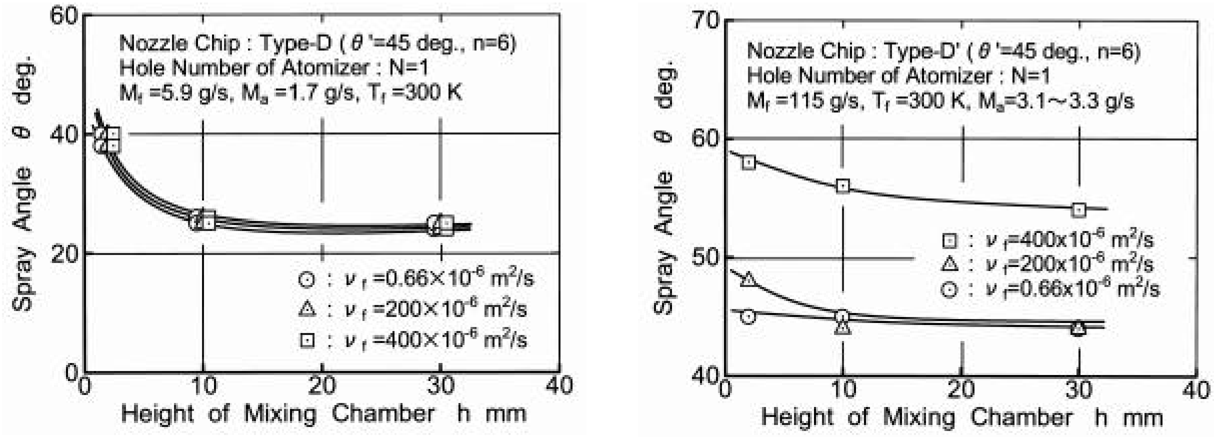


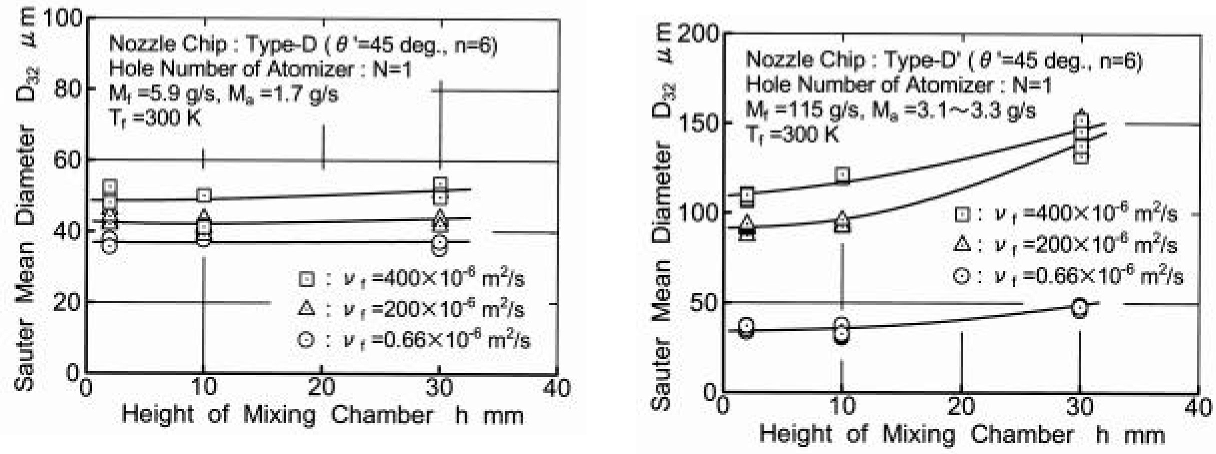
Fig.9 Effects of swirl angle of atomizing air on Sauter mean diameter

small amount of liquid of M_f=5.9 [g/s]. However, it is guessed from variations of Sauter mean diameter toward increasing of mass flow rate of atomizing air that when mass flow rate of atomizing air is slightly increased, the same Sauter mean diameter as one of which is obtained at small amount of liquid of M_f=5.9 [g/s] is obtained. From these results, even though mass flow rate of liquid is considerably increased, this atomizer is able to obtain the spray with small



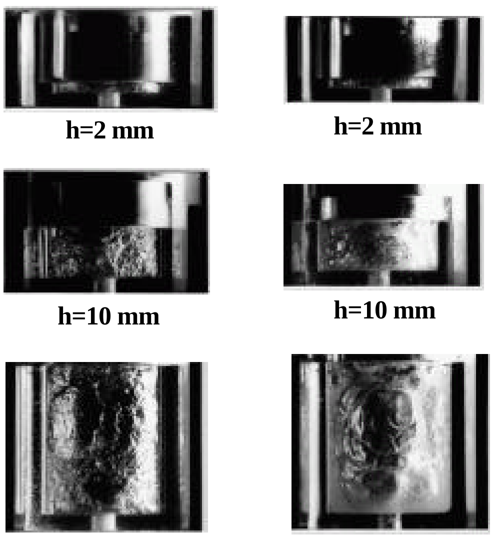
(a) M_f=5.9 [g/s] (b) M_f=115 [g/s]

Fig.10 Effects of the height of the mixing chamber on the spray angle



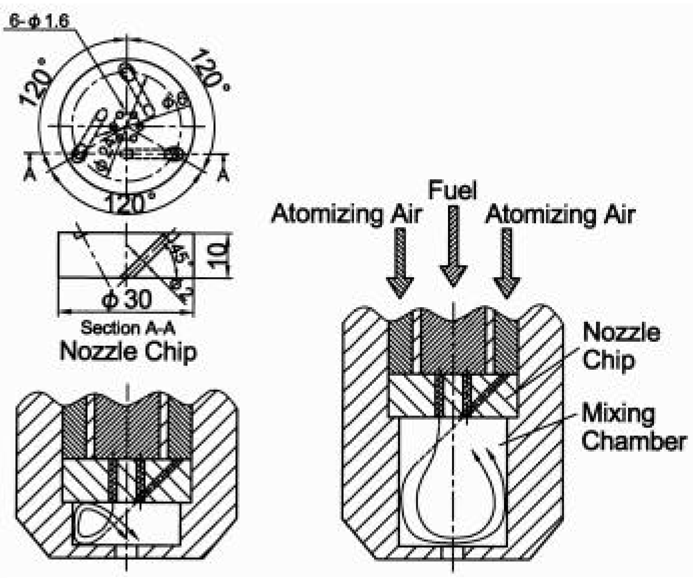
(a) M_f=5.9 [g/s] (b) M_f=115 [g/s]

Fig.11 Effects of the height of the mixing chamber on Sauter mean diameter



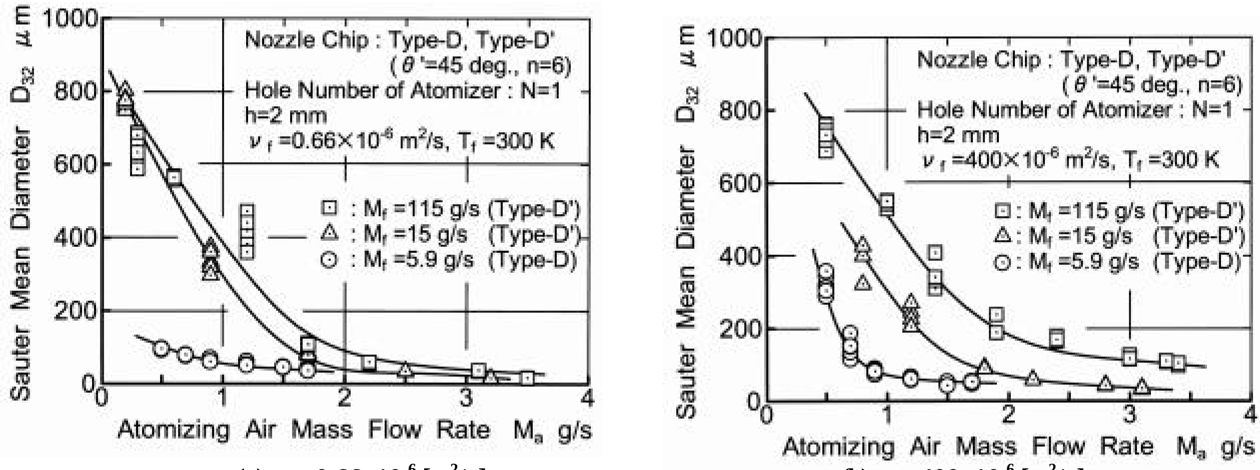
(a) ν_f=0.66x10^{-6} [m^2/s] (b) ν_f=400x10^{-6} [m^2/s]

Fig.12 Photographs of the liquid flow in the mixing chamber



(a) h=2, 10 mm (b) h=30 mm

Fig.13 Schematics of the expected stream line in the mixing chamber



(a) ν_f**=0.66x10^{-6} [m^2/s]** **(b)** ν_f**=400x10^{-6} [m^2/s]**

Fig.14 Effects of mass flow rate of liquid on Sauter mean diameter

Sauter mean diameter by increasing two times as large as atomizing air of which is obtained the smallest Sauter mean diameter at a small amount of liquid.

4. CONCLUSIONS

(1) The internal mixing twin-fluid atomizer invented in this study is able to atomize high-viscous liquid like that waste oil under a small amount of atomizing air, and it is able to obtain the excellent spray, which the spray angle is large and Sauter mean diameter is small.
(2) The swirl angle of atomizing air is little influenced to atomization of the spray, the hole number of the atomizer and height of the mixing chamber are affected to atomization of the spray. It is possible to obtain the spray with small Sauter mean diameter at small atomizing air by using the atomizer which the hole number of the atomizer is single (N=1), height of the mixing chamber is low of h=2 [mm].
(3) This atomizer is able to obtain the spray with small Sauter mean diameter independent of kinematic viscosity, even though mass flow rate of liquid is considerably increased.

NOMENCLATURE

Dimensional symbols			Greek symbols		
D	Droplet diameter	[μm]	θ	Spray angle	[deg.]
D_{32}	Sauter mean diameter	[μm]	θ'	Swirl angle of atomizing air	[deg.]
h	Height of mixing chamber	[mm]	ν_f	Kinematic viscosity of liquid	[m^2/s]
M_a	Mass flow rate of atomizing air	[g/s]	Subscripts and superscript		
M_f	Mass flow rate of liquid	[g/s]	a	Air	
n	Hole number of liquid suppling hole		f	Fuel	
n	Hole number of atomizer		32	Volume / surface	
T_f	Temperature of liquid	[K]	’	Swirl angle	

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