

Measurement of Lubricating Oil Flow Rate in a Circular Pipe Simulating a Discharge Pipe of an Air-Conditioning Compressor

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ABSTRACT

A non-contact measurement technique for the volumetric flow rate of oil droplets in compressor discharge pipes is proposed to improve the quantitative evaluation of oil carryover in air-conditioning compressors. Oil carryover reduces lubrication performance and may cause mechanical failure; therefore, accurate measurement of oil circulation is essential. The proposed method utilizes scattered light intensity from oil droplets illuminated by a laser sheet. The droplet size distribution is assumed with the Nukiyama–Tanasawa distribution, and volumetric flow rate of droplets is estimated by the size distribution derived from the light intensity scattered from droplets passing through the cross-section of the pipe. To validate the proposed technique, the volumetric flow rate of oil droplets was measured in a transparent acrylic circular pipe used as a substitute for the discharge pipe of an actual compressor. Oil droplets were generated by pressure atomization and introduced into the pipe by airflow under various velocity conditions ranging from 6 to 21 m/s. The volumetric flow rate of the droplets rate was measured by collecting the droplets using a mist trap to compare it with that estimated by the proposed technique, and droplet size distributions were obtained using a shadowgraph technique to determine parameters of the Nukiyama–Tanasawa distribution. The proposed technique was applied to the volumetric flow rate of the droplets, and a clear correlation between scattered light intensity and oil droplet volumetric flow rate was confirmed. The estimated values agreed with those obtained by a mist trap method within a range of +40% overestimation and –20% underestimation. Overall, the proposed technique demonstrates feasibility as a non-contact technique for measuring oil droplet flow rate and has potential for application to actual compressor systems.

1. Introduction

Air-conditioning compressors significantly influence the overall performance of air-conditioning systems. Therefore, further improvements in their efficiency are strongly demanded. On the other hand, in such compressors, refrigerant oil is discharged together with the refrigerant through the discharge pipe to the outside of the compressor, a phenomenon generally referred to as oil carryover. When refrigerant oil is discharged from the compressor, the oil supply to sliding components becomes insufficient, which may lead to seizure. Moreover, oil contamination to

refrigerant negatively affects the performance of Air-conditioning systems by decreasing the heat transfer coefficient and increasing the pressure drop (McMullan et al.). Hence, reducing oil carryover is an important issue.

As an index for quantitatively evaluating oil carryover, the oil circulation ratio (OCR) is commonly used. OCR is defined as the ratio of the circulating mass flow rate of refrigerant oil to the total circulating mass flow rate of refrigerant and refrigerant oil. To calculate OCR, it is necessary to determine the mass flow rate of refrigerant oil discharged from the compressor.

Several studies have been reported to evaluate the mass flow rate of refrigerant oil discharged from compressors. A typical technique for measuring refrigerant oil concentration is the sampling method. In this method, mass of a collected refrigerant–oil mixture is measured, and the refrigerant is evaporated from the mixture. Subsequently, the oil concentration is determined from the residual mass (e.g. Baustian et al.). Wada et al. proposed a method for measuring the instantaneous OCR of oil passing through the flow path. Specifically, they focused on the ultraviolet (UV) absorption characteristics of refrigerant oil. By irradiating UV light into refrigerant containing dissolved oil and evaluating the absorption from the intensity ratio of incident and transmitted light, the oil concentration was determined. This method was shown to have higher accuracy than the gravimetric method specified by JIS. However, this approach has only been validated for local measurements, and its applicability to the total oil flow rate across a pipe cross-section has not been clarified.

Image-based measurement techniques have also been proposed. Xu et al. installed a transparent PFA tube at the compressor discharge and captured oil droplets using high-speed shadowgraph imaging. The droplet diameter and velocity were obtained through image processing to evaluate the droplet flow rate. Furthermore, for the liquid film adhering to the pipe wall, the film thickness was determined from the size of elliptical patterns formed by laser reflection and refraction, and the film flow rate was calculated based on a theoretical model proposed by Hurlburt et al. However, as the droplet number density increases, overlapping droplet images make it difficult to distinguish individual droplets, which limits the measurement of droplet size and velocity.

On the other hand, Sugiura et al. conducted a fundamental study toward the development of a lubricating oil measurement technique by measuring the scattered light intensity from oil droplets. Laser light was irradiated onto oil droplets generated in a gaseous refrigerant, and the scattered light intensity was measured as voltage using a photosensor. Their results showed that the scattered light intensity increases with increasing lubricating oil quantity. However, they did not quantitatively estimate the oil droplet flow rate from the scattered light intensity, and the validity of the method as a flow measurement technique has not been verified.

Furthermore, Fukuda et al. proposed a refractive index-based method to measure the amount of lubricating oil dissolved in refrigerant over time. By measuring the change in optical path length of laser light, the refractive index was determined and used to calculate OCR. The results showed good agreement with those obtained by a sampling method. However, this method has difficulty measuring dispersed phases such as oil droplets that are not dissolved in the liquid refrigerant.

As described above, although various studies on measuring refrigerant oil flow rate have been conducted, it remains difficult to measure the instantaneous oil flow rate passing through an arbitrary cross-section in a discharge pipe as a time series. Since compressors compress refrigerant through rotational motion, pulsation occurs in the discharge flow. Therefore, the oil circulation rate in the refrigerant is also expected to fluctuate over time, and it is important to capture the temporal variation of OCR.

Based on this background, the present study focuses on establishing a fundamental measurement technique as a preliminary step toward the development of a time-resolved measurement method for the oil droplet flow rate passing through a cross-section in the discharge pipe. Specifically, a non-contact measurement technique based on scattered light intensity from oil droplets is developed to estimate the flow rate. Its applicability is then evaluated using a transparent acrylic circular pipe simulating the discharge pipe by comparing the estimated flow rate with directly measured values for a view toward application to compressor testing.

2. Experimental set-up

The volumetric flow rate of oil droplets flowing in a transparent circular pipe made of acrylic, which simulates the discharge pipe of an actual compressor (hereafter referred to as the test section), was measured.

A schematic of the experimental apparatus is shown in Fig. 1. The setup mainly consists of an oil supply unit and the test section. The oil supply unit was installed upstream of the test section to

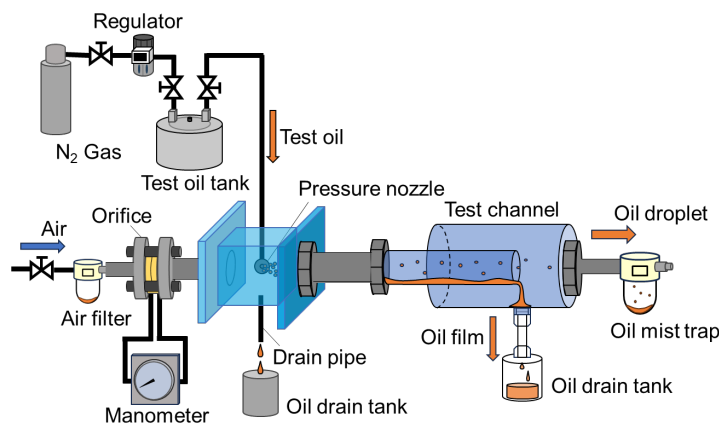


Figure. 1 Experimental apparatus for flow rate measurement

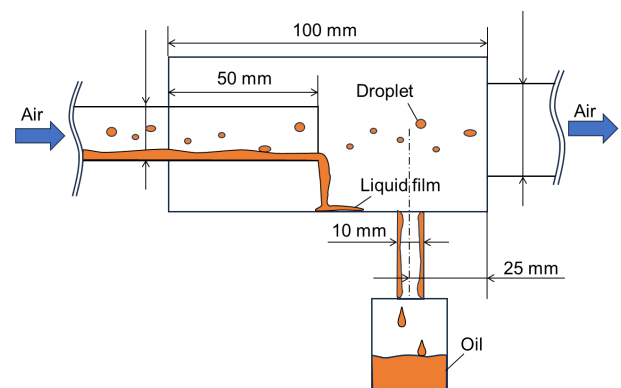


Figure. 2 Schematics view of test channel

introduce the test oil into the flow as droplets. The test oil was injected into the flow channel using a pressure nozzle (Ikeuchi Co., J-series) mounted on the side wall of a rectangular channel (depth 30 mm $\times$ height 30 mm $\times$ length 80 mm). The oil in a tank pressurized by nitrogen gas at a constant injection pressure of $P_{inj} = 200\text{kPa}$ was sprayed into the channel. As the test oil, silicone oil was used as a substitute for compressor lubricating oil. A kinematic viscosity of $5\text{ mm}^2/\text{s}$ was selected to simulate the viscosity of refrigerant oil under high-speed compressor operation.

Details of the test section are shown in Fig. 2. The test section consists of an inner circular pipe (inner diameter 18 mm, length 50 mm) inserted into an outer circular pipe (inner diameter 38 mm, length 100 mm). In actual compressors, the working fluid is a refrigerant such as HFC; however, in the present experiment, air was used instead. Air mixed with oil droplets supplied from the oil supply unit flows into the inner pipe (18 mm diameter), and subsequently flows through the outer pipe (38 mm diameter) before exiting the test section.

A portion of the oil droplets flowing from the supply unit to the test section detaches from the gas flow and adheres to the pipe wall, forming a liquid film. This phenomenon is also observed in actual compressor discharge pipes, and the presence of such a liquid film is expected to interfere with the measurement of scattered light intensity. By adopting the test section structure shown in Fig. 2, oil droplets and the liquid film are separated at the exit of the inner pipe. As a result, only oil droplets are present in the region between the exit of the inner pipe and the outlet of the test section, enabling measurement of scattered light originating solely from oil droplets.

Since compressor rotational speed varies depending on operating conditions, experiments were conducted while varying the airflow velocity entering the test section. The air velocity at the inlet of the test section, V_{air} , was set to five conditions: 6, 9, 12, 18, and 21 m/s. These velocities were controlled by adjusting the differential pressure measured with a manometer, as shown in Fig. 1.

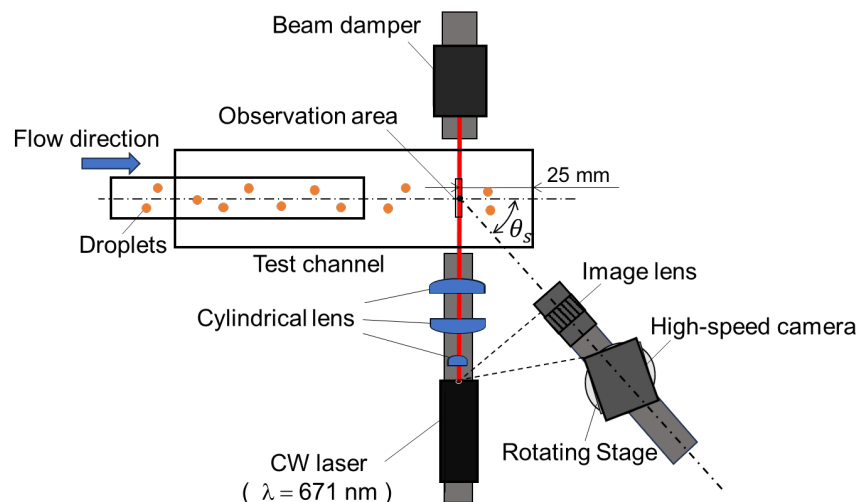


Figure. 3 Optical arrangement for flow rate measurement based on scattering light from oil droplets

All experiments were conducted under atmospheric pressure and at a room temperature of 27°C, regardless of the airflow velocity.

To validate the volumetric flow rate of oil droplets estimated by the proposed method, the results were compared with the flow rate of oil droplets collected using a mist trap installed downstream of the test section (Fig. 1). The collection time was fixed at 15 minutes for all airflow conditions.

Figure 3 shows the optical setup for acquiring scattered light from oil droplets passing through the cross-section of the flow. A continuous-wave (CW) laser (output: 2 W, wavelength: 671 nm) was used as the light source, and a laser sheet with a thickness of less than 1 mm was formed using three cylindrical lenses. The measurement region was located 25 mm upstream of the test section outlet, and the laser sheet was introduced from the side to illuminate a cross-section perpendicular to the flow direction.

The scattered light from oil droplets passing through the illuminated cross-section was recorded using a high-speed camera (nac, MEMRECAM Q2m). The frame rate was set to 3000 fps, and the exposure time was 10 μ s. To observe the laser sheet plane, the camera must be positioned at an oblique angle relative to the sheet, which makes it difficult to keep the entire field of view in focus. Therefore, a Scheimpflug optical arrangement was employed, in which the lens plane and the image plane intersect along a common line. The stereo angle θ_s , defined as the angle between the lens plane and the normal to the image plane, was set to 60°.

3. Experimental results

Oil droplet flow rate through the test section

To evaluate the flow rate of oil droplets passing through the test section, the relationship between the airflow velocity and the volumetric flow rate of oil droplets was first investigated using the experimental apparatus shown in Fig. 1. The mass flow rate of oil droplets was determined by measuring, with an electronic balance, the mass of oil collected over a fixed period using a mist trap installed downstream of the test section. Since the density of the test oil is known, the mass flow rate was converted into a volumetric flow rate.

Figure 4 shows the volumetric flow rate of oil droplets with respect to the airflow velocity. Although some scatter is observed at airflow velocities below 12 m/s, the volumetric flow rate remains approximately constant. In contrast, at higher velocities, an increase in the volumetric flow rate is observed. If the supply rate of oil droplets from the injection unit is constant and all droplets perfectly follow the airflow, the volumetric flow rate of oil droplets passing through the test section would be expected to remain constant regardless of airflow velocity. However, the experimental results exhibit a clear dependence on airflow velocity.

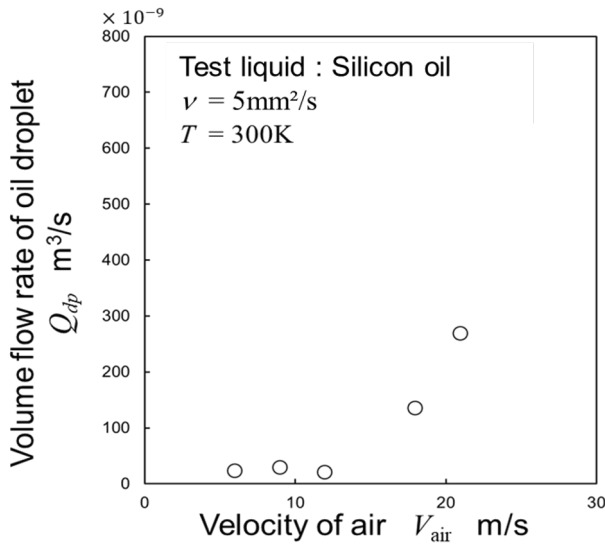


Figure. 4 Volume flow rate of oil droplets with respect to velocity of air flow in the test channel

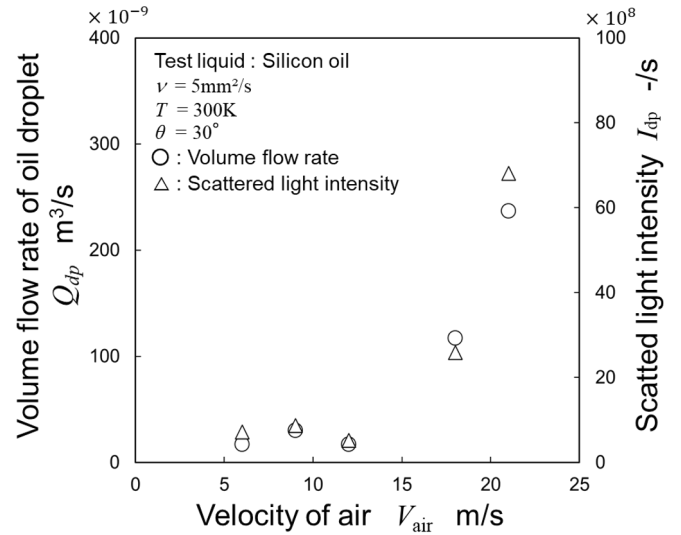


Figure. 5 Volume flow rate of oil droplets and light intensity scattered from oil droplets

This behavior can be attributed to the fact that, under low-velocity conditions, some oil droplets adhere to the pipe wall due to inertia and gravity, forming a liquid film and thereby reducing the number of droplets suspended in the airflow. In contrast, under high-velocity conditions, the ability of oil droplets to follow the airflow improves, resulting in an increased number of droplets transported within the gas stream. Consequently, the volumetric flow rate increases with airflow velocity.

Next, the relationship between the scattered light intensity obtained from oil droplets using the optical system shown in Fig. 3 and the volumetric flow rate is presented in Fig. 5. In the scattered light measurements, imaging was performed three times for 2 seconds each at a specified frame rate, yielding a total acquisition time of 6 seconds. The recorded signals were integrated and then divided by the total acquisition time to obtain the scattered light intensity per unit time.

As shown in Fig. 5, the scattered light intensity per unit time increases with increasing airflow velocity, exhibiting a trend similar to that of the volumetric flow rate of oil droplets. In general, the scattered light intensity from a group of droplets depends on both the droplet diameter and the number density of particles. Therefore, the present results are considered to reflect an increase in the total amount of oil droplets passing through the measurement cross-section. These findings indicate a clear correlation between the scattered light intensity and the volumetric flow rate of oil droplets, suggesting that the volumetric flow rate can be estimated based on the scattered light intensity.

Estimation of volumetric flow rate based on scattered light from oil droplets

Since the droplet group passing through the circular pipe is generated by pressure atomization at the supply unit, it exhibits a broad size distribution. Let $f(x)$ denote the number-based size distribution for droplets of diameter x . The total scattered light intensity from the droplet group, I_{total} , is expressed as Eq. (1).

$$I_{\text{total}} = \int_0^{\infty} I(x) f(x) dx \quad (1)$$

Here, $I(x)$ denotes the scattered light intensity from an oil droplet of diameter x . Equation (1) indicates that the total scattered light intensity from oil droplets passing through the laser-sheet-illuminated cross-section depends on the droplet number distribution.

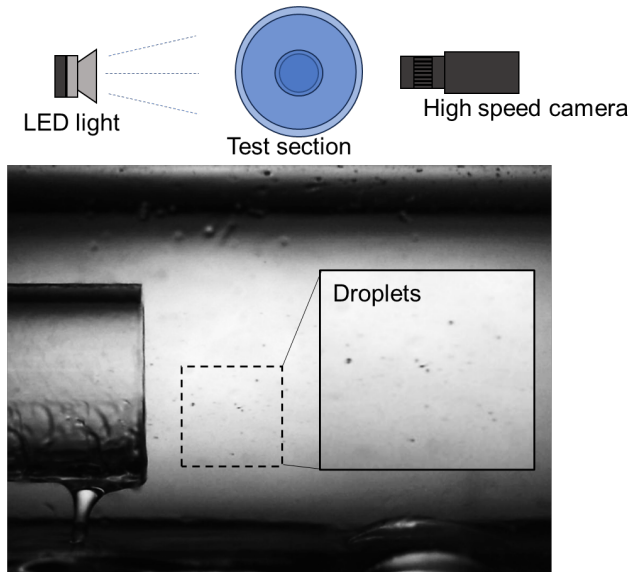


Figure. 6 Optical arrangement of shadow imaging for oil droplets and the captured droplets image

To evaluate the number distribution of oil droplets at airflow velocities of 6 m/s and 21 m/s, droplet images were obtained using a shadowgraph technique, as shown in Fig. 6, and the number distributions were calculated. The results are presented in Fig. 7. Regardless of the airflow velocity, the most frequent droplet diameter is found to be in the range of 150–200 μm , and all measured droplet diameters are greater than 50 μm .

Since the droplet diameters are sufficiently larger than the wavelength of the laser used in this study, the size parameter is much greater than unity, and diffraction scattering is considered to be dominant. Therefore, the scattered light intensity from a droplet can be approximated as being proportional to the square of the droplet diameter. Accordingly, the scattered light intensity $I(x)$ from a droplet can be expressed as Eq. (2), where C is an optical constant.

$$I(x) = Cx^2 \quad (2)$$

Furthermore, Toyama et al. determined the number-based size distribution of oil droplets in a scroll compressor using image-based measurements, and demonstrated that the distribution can be well described by the Nukiyama–Tanasawa distribution given in Eq. (3).

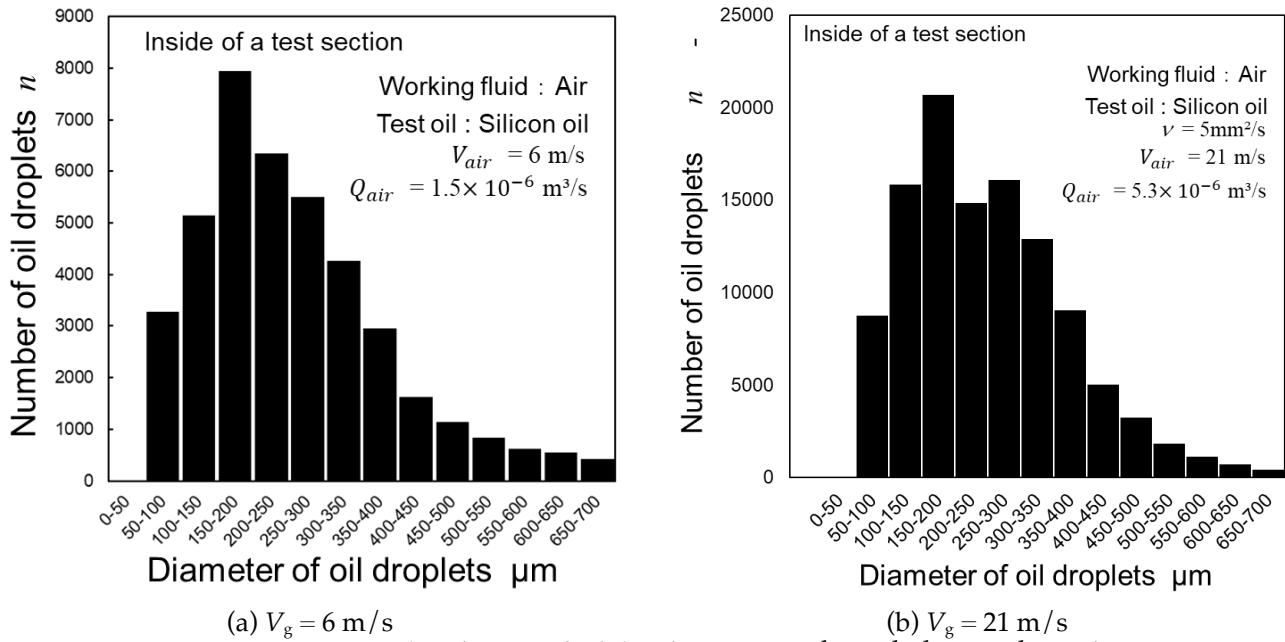


Figure 7 Size distribution of oil droplets passing through the test channel

$$f(x) = A x^\alpha \exp(-Bx^\beta) \quad (3)$$

Accordingly, assuming that the droplet size distribution $f(x)$ in the present study is described by the Nukiyama–Tanasawa distribution, the total scattered light intensity I_{total} can be expressed as Eq. (4).

$$I_{\text{total}} = \int_0^{\infty} I(x) f(x) dx = AC \int_0^{\infty} x^{\alpha+2} \exp(-Bx^{\beta}) dx \quad (4)$$

Furthermore, the integral of Eq. (4) can be evaluated using the gamma function, and the total scattered light intensity I_{total} is expressed as Eq. (5).

$$I_{\text{total}} = AC \frac{1}{\beta} B^{-\frac{\alpha+3}{\beta}} \Gamma\left(\frac{\alpha+3}{\beta}\right) \quad (5)$$

In these equations, α and β are constants, and A and B are parameters defined by these constants, as given in Eqs. (6) and (7).

$$A = N\beta B^{\frac{\alpha+1}{\beta}} / \Gamma\left(\frac{\alpha+1}{\beta}\right) \quad (6)$$

$$B = \left[\frac{1}{x_{32}} \frac{\Gamma(\alpha+4/\beta)}{\Gamma(\alpha+3/\beta)} \right]^{\beta} \quad (7)$$

Here, N denotes the total number of oil droplets, and x_{32} is the Sauter mean diameter. Since the droplet size distribution is assumed to follow the Nukiyama–Tanasawa distribution, the total number of droplets N can be obtained by integrating the distribution function.

$$N = \int_0^{\infty} f(x) dx = \int_0^{\infty} Ax^{\alpha} \exp(-Bx^{\beta}) dx = A \cdot \frac{1}{\beta} B^{-\frac{\alpha+1}{\beta}} \cdot \Gamma\left(\frac{\alpha+1}{\beta}\right) \quad (8)$$

Therefore, from Eqs. (5) and (8), the relationship between the total number of droplets N and the total scattered light intensity I_{total} can be derived as Eq. (9).

$$N = I_{\text{total}} \cdot \frac{B^{\frac{2}{\beta}} \cdot \Gamma\left(\frac{\alpha+1}{\beta}\right)}{C \cdot \Gamma\left(\frac{\alpha+3}{\beta}\right)} \quad (9)$$

The total volume of the droplet group, V_{total} , can be expressed based on the Nukiyama–Tanasawa distribution as shown in Eq. (10), from which the relationship with the total number of droplets N can be derived.

$$V_{\text{total}} = \int_0^{\infty} \frac{\pi}{6} x^3 \cdot f(x) dx = N \cdot \frac{\pi}{6} B^{-\frac{3}{\beta}} \cdot \frac{\Gamma\left(\frac{\alpha+4}{\beta}\right)}{\Gamma\left(\frac{\alpha+1}{\beta}\right)} \quad (10)$$

Finally, from Eqs. (9) and (10), the total volume of oil droplets can be derived as shown in Eq. (11).

$$V_{total} = \frac{\pi}{6C} B^{-\frac{1}{\beta}} \cdot \frac{\Gamma\left(\frac{\alpha+4}{\beta}\right)}{\Gamma\left(\frac{\alpha+3}{\beta}\right)} \cdot I_{total} \quad (11)$$

To estimate the volumetric flow rate using the equation, it is necessary to determine the parameters α , β , and B . Accordingly, α and β in the Nukiyama–Tanasawa distribution were estimated using the number distributions at airflow velocities of 6 m/s and 21 m/s, as shown in Fig. 7. Specifically, by taking the common logarithm of the Nukiyama–Tanasawa distribution, the relationship can be linearized as shown in Eq. (12).

$$\log_{10} \left(\frac{1}{x^\alpha} \cdot \frac{dn}{dx} \right) = \log_{10} A - \frac{B}{2.3} x^\beta \quad (12)$$

α and β were determined such that the number distribution obtained from shadow images was fitted to Eq. (12). Figure 8 shows a comparison between number distributions obtained by the shadow imaging technique and the Nukiyama–Tanasawa distribution. The measured distributions at airflow velocities of 6 m/s and 21 m/s is shown as plots, and the solid lines indicate the linear relations derived from the Nukiyama–Tanasawa distribution. Regardless of the airflow velocity, by adapting $\alpha = 2.8$ and $\beta = 1.0$, the measured distributions were represented well by the Nukiyama–Tanasawa distribution when α and β were set to 2.8 and 1.0, respectively, with coefficients of determination R^2 greater than 0.96.

Next, based on the α and β , the Sauter mean diameter x_{32} was determined to approximate the number distributions obtained by the shadow imaging technique. Figure 9 shows the number distributions at airflow velocities of 6 m/s and 21 m/s. The measured distributions are shown as

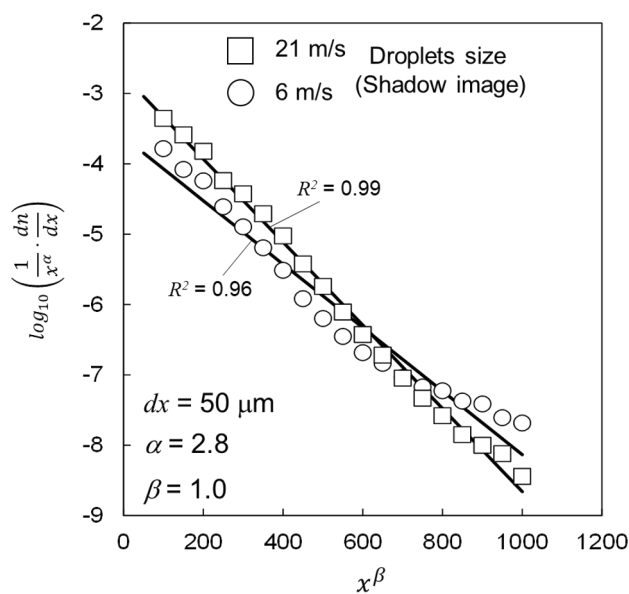


Figure. 8 Determination of α and β in the Nukiyama-Tanasawa equation

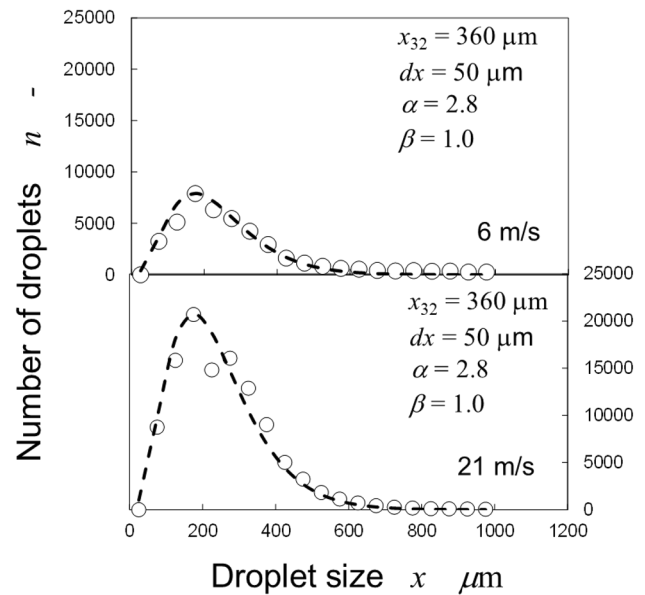


Figure. 9 Number distribution of oil droplets fitted with the Nukiyama-Tanasawa equation

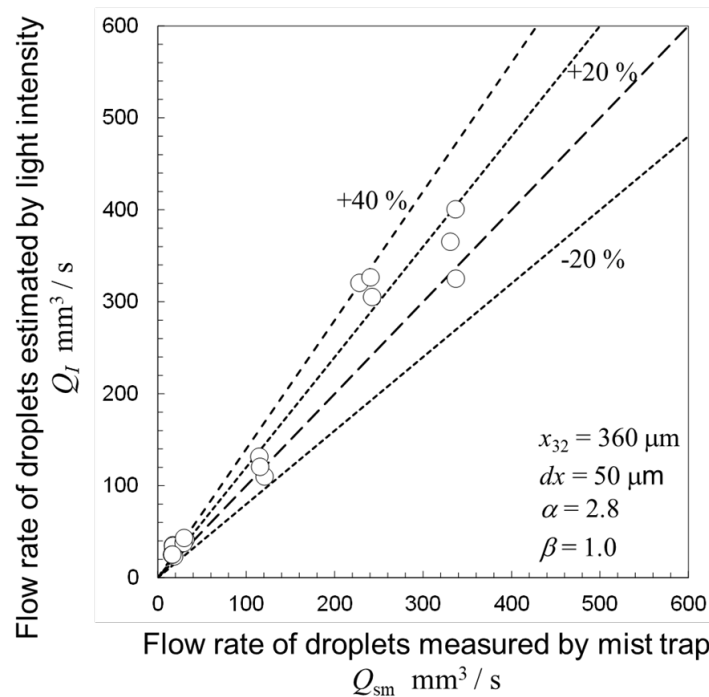


Figure. 10 Volumetric flow rate of oil droplets estimated by scattering light

the plots, and the dashed lines represent the distributions approximated by the Nukiyama-

Tanasawa equation shown in Eq. (3). It was found that the measured distributions can be reasonably approximated by setting the Sauter mean diameter x_{32} to $360\mu\text{m}$, regardless of the airflow velocity.

From these results, the coefficient B can be determined using the Sauter mean diameter with α and β via Eq. (7). Consequently, the total volume of the droplets V_{total} can be obtained from the total scattered light intensity I_{total} based on Eq. (11).

Using the proposed method described above, the volumetric flow rate was estimated from the scattered light intensity per unit time for each airflow velocity shown in Fig. 5, and compared with the volumetric flow rate obtained from the oil mass collected by the mist trap. As shown in Fig. 10, the estimated values agree with the measured values within a range of +40% overestimation to -20% underestimation, suggesting the feasibility of the proposed optical diagnostics technique for volumetric flow-rate estimation.

4. Conclusions

In this study, measurement technique for volumetric flow rate of oil droplets passing through a circular channel was developed. The main findings of this study are as follows;

1. A non-contact method was developed to estimate the volumetric flow rate of oil droplets based on scattered light intensity using a laser sheet.
2. The droplet size distribution based on the Nukiyama–Tanasawa equation was predicted by using total light intensity scattered from oil droplets.
3. The proposed method achieved agreement with reference measurements within +40% overestimation and -20% underestimation, suggesting the feasibility of the proposed optical diagnostics technique for volumetric flow-rate estimation.

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