A Fiber LDV System for Measurement of Atomized Droplets away from the Trailing Edge of a Fixed Blade in Two-Phase Flow*

Kuniyoshi TSUBOUCHI**, Shohei YOSHIDA**,
Takeshi SATOH** and Kazuo IKEUCHI**

The presence of particles or water droplets in the flow of turbomachinery, especially in the low-pressure stages of steam turbines, leads to erosion of the moving blades and causes additional loss. This report describes a measurement technique for droplet sizing and velocity in atomized droplet flow by using a two-color, four-beam fiber laser doppler velocimeter (LDV) system. The optical probe system forms two coaxial measurement volumes with different diameters in which droplet sizes are evaluated by light scattering intensity. Measurements are performed for atomized droplet flow in the wake of a fixed blade. Test results demonstrate that relatively large droplets concentrate in the wake and are slowly accelerated by the stream. While the droplet velocities are influenced by the wake profile, the droplet sizes tend to be particularly affected by wetness rather than by stream velocity.

Key Words: LDV, Flow Measurements, Multiphase Flow, Cascade, Steam Turbine

1. Introduction

In the internal stages of turbomachinery containing solid or liquid droplets in working fluid flow, particle behavior exerts a harmful effect on blade reliability and stage flow performance. For instance, as low-pressure stages of a steam turbine are operated under wet steam conditions, the impact of large droplets which are atomized in the wake of fixed blades on moving blades with large peripheral speed leads to erosion and causes additional energy loss⁽¹⁾⁽²⁾. Therefore, there is a growing demand for direct measurement of these droplet sizes and velocities. Several investigators⁽²⁾⁽³⁾ have previously described the behavior of droplets torn away from the trailing edge of a blade and the atomization of liquid film in gas flow, but microscopic measurements and optical sizing still need to be discussed. Recently, a laser doppler velocimeter (LDV) was used in a two-phase flow to measure the distribution of particle sizes and

velocities simultaneously. But it is difficult to apply this LDV system to the internal flow of turbomachinery. A LDV with an optical fiber connected to the laser light source and a small probe head can extend applications to various internal flow problems because of its easy handling and setting up.

In this study, a two-color, four-beam optical probe for a backward-scattering-mode-type LDV system has been developed to measure atomized droplets in high subsonic flow such as in the last stage of low-pressure steam turbines. The optical system, using the basic design of Hishida and Maeda⁽⁴⁾⁽⁵⁾, forms two coaxial volumes with different diameters in order to obtain high resolution of droplet sizing⁽⁶⁾. The LDV system was applied to measurement of a two-phase flow at the exit of a test cascade and droplet behavior in the wake near the trailing edge of the fixed blade was evaluated.

Nomenclature

C, C_x : chord length, blade width
 d_p : droplet diameter
 U, V : stream and droplet velocities
 X, Y : axial and tangential directions

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** Mechanical Engineering Research Laboratory, Hitachi Ltd., 3-1-1 Saiwai-cho, Hitachi, 317, Japan

Y_0 : wake axis as shown in Fig.7

y : wetness

2. Mechanism of Droplet Atomization

During the expansion of the steam through the latter stages of low-pressure steam turbines, moisture condensation occurs spontaneously in the supersaturated conditions and fine droplets are initially formed. Their sizes are up to a few microns, so most follow the steam flow. However, some are deposited on the fixed and moving blades, forming a thin film of water on the blade surfaces. Generally, the water film on the moving blades is splashed towards the casing by centrifugal force, but that on the fixed blades is moved along the surfaces by the shear force of the steam flow. Finally, it is torn from the trailing edge and broken up to form large droplets, between several tens and hundreds of microns in diameter. As the velocity of these droplets are smaller than that of steam (Fig. 1), they strike the leading edge of the moving blade from the back side at a relatively high speed. Impingement of droplets on the moving blade causes mechani-

Fig. 1 Velocities of steam and droplets in steam turbine

Fig. 2 Optical system of the fiber LDV

cal material removal due to the large impact pressure. Therefore, it is important to understand droplet behavior in the wake in order to prevent such erosion damage.

3. Optical System and Signal Processing

Generally, the scattering intensity of a single sphere in uniform monochromatic light (wavelength = λ) is proportional to the square of the diameter as is given by the Mie theory for the particle parameter α ($\equiv \pi d_p / \lambda$) > 5 . The principle of this theory can be applied to the scattering intensity of a particle crossing through the middle of a Gaussian laser beam⁽⁴⁾. The present system with a two-color, four-beam fiber LDV is based on the above theory. The optical system uses two coaxial volumes with different diameters to distinguish between the middle of the Gaussian beam and other areas.

Figure 2 shows a schematic diagram of the fiber LDV optical system. The light beam from an argon ion laser (4 W) is separated into two colors (0.5145 and 0.4880 μm wavelengths) by a color separator. After the two beams are split by their respective compensated beam splitters, the four beams are compressed into four single-mode polarization fibers. In the probe head, beam expander lenses are mounted at the end of each fiber to increase the light beam diameter. Finally, the four beams are focused and two coaxial volumes for droplet measurements are formed. As shown in Fig. 3(a), the coaxial volume (250 μm cross-sectional diameter) of the green beams envelopes that of the blue beams (30 μm cross-sectional diameter). A receiving lens is mounted behind the lens ($f=160$) for the backward receiving optics. The scattering signals are transmitted through the multimode fiber to the photomultipliers.

Figure 3(b) shows an illustration of output scattering signals. When droplet P_A passes through the center of the measuring volume, both doppler signals from blue and green are clearly received. But, when droplet P_B is passing away from the volume center, the doppler signal from the smaller blue volume cannot be received. In other words, droplets crossing through the blue volume will also cross through the region of maximum intensity of the green volume. These output signals from photomultipliers are then input to the signal processor, as shown in Fig. 4. Each of the doppler burst signals with high-frequency components from blue and green volumes is converted to velocities of two directions by frequency counters. The pedestal signal, which is output with the low-frequency component from the green volume, is input to the pulse height detector (P.H.D) and is put into the memory when the envelope of two doppler burst signals coincides with the pulse height peak. Then the peak intensity of the pedestal signal, which is proportional to the square of the droplet diameter, is measured. However, as the probability of the number count to be captured by the center of the blue volume depends on the droplet diameter passing through the measuring volume, the density of droplets must be corrected by the cross-sectional area which is formed by the view area for the blue beams and the surrounding area bounded by the size of the droplet diameter.

Fig. 3 Droplet path in measurement volume and output signals from photomultipliers

Fig. 4 Block diagram of signal processing

Standard droplets with known diameters are generated by a monodispersal aerosol generator and are used for the calibration of this system. An example of droplet sizes measured with the present fiber LDV system is shown in Fig. 5. The measured Sauter mean diameters d_p (SMD) are in good agreement with those of microscopic measurements. The results indicate that droplet size can be precisely estimated within an accuracy of several percent of the mean square errors.

4. Experimental Apparatus and Approach

The experimental work on droplet atomization in the wake of the fixed blade was carried out in the two-phase flow tunnel, as shown in Fig. 6. Either steam from the boiler or air from a 600 kW blower was supplied through an expansion and contraction

Fig. 5 Comparison of droplet sizing by the fiber LDV and microscopic measurements

Fig. 6 Experimental apparatus of two-phase flow tunnel with cascade

duct to a test section including a two-dimensional cascade. Wetness of both fluids was regulated and controlled by cooling water from the spray nozzle. According to the cascade geometric data summarized in Fig. 6, the blade mounted in the cascade was a two-fifths scale model of a typical fixed blade designed for the tip section of the last stage in fossil-fueled steam turbines.

Experiments in wet steam flow were conducted under the same conditions as those in the last stage of the steam turbine. Also, simulation experiments in wet air were carried out in order to study the basic behavior of atomized droplets which directly affect the size limit in the wake. The experimental conditions are shown in Table 1. Figure 7 illustrated the two-dimensional cascade and coordinates. The droplet size and velocity along the wake axis of the center blade of the cascade were measured by the

Table 1 Experimental conditions

Fluid type	wet steam	wet air
Inlet pressure	0.030 MPa	0.110 MPa
Inlet moisture	4.0 %	0.27–1.01 %
Exit pressure	0.025 MPa	0.102 MPa
Velocity	330.0 m/s	79.6–172.3 m/s
Reynolds number	1.4×10^6	$0.7 - 1.5 \times 10^6$
Weber number	84	40–180

The Reynolds number $= U_\infty C / \nu$, and the Weber number $= \rho_s (U_0 - V_0)^2 d_p / \sigma$, assuming that $(U_0 - V_0) \equiv U_\infty$ and d_p = trailing edge thickness at the exit of the blade.

Fig. 7 Schematic diagram illustrating the cascade setup

optical probe.

5. Experimental Results and Discussion

Experimental results from the cascade test showing mean droplet direction and their size and velocity distributions up to 250 m/s in wet steam are plotted in Fig. 8. The measured droplets increase slightly in velocity and decrease in diameter between point A ($X/C=0.21$) and point B ($X/C=0.36$) downstream of the fixed blade. The results indicate that the present technique, backward-scattering-mode-type LDV system with a small probe, is one of the effective methods for droplets sizing in high-subsonic two-phase flow in turbomachinery because of its easy handling and setup.

Figures hereafter show experimental results for a wet air cascade. They provide basic and detailed information on the behavior of atomized droplets, especially in the wake region.

Figure 9 shows the velocity profiles of the air stream along the Y direction with different X values from the fixed blade, which were measured by a conventional five-hole Pitot tube. Mainstream velocity U_∞ is approximately 121 m/s at the cascade exit. The velocity profiles of the wake change typically as the wake is reenergized downstream of the blade.

Figures 10 and 11 show the velocities and diameters of droplets in wet air flow, which are measured by the present optical system. Experiments were performed for wetness values of $y=0.27, 0.45$ and 1.01% at constant stream velocity ($U_\infty=120.7$ m/s). Taking into account the density difference between wet air and steam condition, these are equivalent to the wetness values of $y=2.4, 4.0$ and 9.0% in wet steam.

Fig. 8 Mean droplet directions and their velocity and size distributions measured in wet steam flow

Near the trailing edge, the mean droplet velocity profiles are similar to the wake profile of the blade, meanwhile the Sauter mean diameters of droplets in the wake axis are larger than those of the wake edge. Thus, relatively large droplets are concentrated in the wake region and slowly accelerated by the stream. These experimental results indicate that the behavior of atomized droplets depends heavily upon the wake profile and wetness. Furthermore, these droplets are rapidly dispersed in smaller sizes and accelerated far

away from the fixed blade which can be seen, for instance, at locations of $X/C_x=0.17$. Then, finally, profiles of velocity and diameter have relatively uniform distributions at $X/C_x=0.39$.

Figures 12 and 13 show the variation of mean velocities and mean diameters along the wake axis. Also, in Fig. 12, stream velocities along the wake axis without the atomized droplets are shown for comparison. Clearly, mean droplet sizes decrease rapidly in the region from $X/C_x=0$ to $X/C_x=0.05$, as the relative velocity difference between stream and droplets becomes larger. Thus, droplets traveling near the trailing edge are subjected to the largest aerodynamic shear force so that the large droplets are disrupted into smaller droplets, that is to say, 'secondary atomization' occurs. It is interesting to note in Fig. 13 that the mean droplet diameters tend to increase with higher wetness at constant stream velocity. This suggests that the droplet formation is influenced by the water film on the trailing edge, because of increasing film thickness of the water deposited on the blade surface at higher wetness.

Other experimental measurements were performed while varying the mainstream velocity as $U_\infty=79.6, 120.7$ and 172.3 m/s at approximately constant wetness, as shown in Figs. 14 and 15. The acceleration of atomized droplets near the trailing edge becomes

Fig. 9 Velocity profiles of wake at $U_\infty=120.7$ m/s

Fig. 10 Mean droplet velocity profiles at $U_\infty=120.7$ m/s

Fig. 11 Mean droplet diameter distributions at $U_\infty=120.7$ m/s

Fig. 12 Mean droplet velocity along the wake axis at $U_\infty=120.7$ m/s

Fig. 13 Mean droplet size along the wake axis at $U_\infty=120.7$ m/s

Fig. 14 Mean droplet velocity along the wake axis at constant wetness

Fig. 15 Mean droplet size along the wake axis at constant wetness

slower, although the mainstream increases in velocity. This is explained by the droplet velocities which are strongly influenced by the wake profile, because the velocities along the wake axis increase slowly with the higher mainstream velocity as a result of momentum transfer and are smaller near trailing edge ($X/C_x < 0.03$) than those of the smaller mainstream velocities. Although the mainstream increases in velocity, the mean diameters of droplets along the wake axis are kept in a similar size range. Thus, it is concluded that the final atomized droplet sizes are strongly affected by wetness.

6. Summary and Conclusions

A fiber LDV system with a compact two-color, four-beam optical probe has been developed to measure atomized droplets in high subsonic flow. This system was successfully applied to measure droplet sizes and velocities up to 250 m/s under the same conditions as those of the last stage in low-pressure steam turbines.

Detailed measurements were performed for the atomized droplets in a two-phase flow tunnel with a cascade. The results obtained clearly indicated the basic characteristics of droplet behavior in the wake near the trailing edge of the blade. Relatively large droplets were concentrated in the wake of the fixed blade and were slowly accelerated by the stream. In particular, while the droplet velocities were influenced by the wake profile, the droplet size tended to be affected by wetness. This knowledge of droplet behavior should make a useful contribution to the development of erosion criteria for blades and erosion preven-

tion techniques.

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