

Low atmospheric density measurement based on Rayleigh scattering of an ultraviolet laser

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The qualitative measurement of low atmospheric density in the air flow field has been investigated in this paper. The supersonic flow field with Mach number of 1.5 around the NACA0006 aerofoil has been numerically simulated and the transient slight pressure and low density atmosphere have been experimentally determined based on Rayleigh scattering of a 266 nm ultraviolet laser. The scattering patterns have been effectively captured under different atmospheric pressure of 4.5, 92, 470 and 710 Pa with laser energy of only 0.5 mJ. It has been demonstrated that in the pressure range from 4.5 to 1100 Pa, corresponding to the atmospheric density from $4.8105 \times 10^{-5} \text{ kg/m}^3$ to $1.279 \times 10^{-2} \text{ kg/m}^3$, the scattering intensity of an ultraviolet laser is linear to the pressure and density with the slope coefficient of 0.00968 a.u./Pa and 0.83226 a.u./($\text{kg/m}^3 \times 10^{-3}$). It has been proved that Rayleigh scattering is a promising technology for observation of instantaneous and multi-dimensional distribution of a supersonic flow field.

Keywords: atmospheric density measurement, Rayleigh scattering, ultraviolet laser.

1. Introduction

The measurement of atmospheric density is of great importance in many application fields, such as aerodynamics, combustion engineering, meteorology and atmospheric physics [1, 2]. Thus the monitoring devices have a great value and extensive prospects for development [3, 4]. With the development of laser and relevant technologies, many optical flow field diagnostic technologies with their high spatiotemporal resolution [5] have been employed for the investigation on the distribution of the characteristic parameters, such as pressure, density, velocity, temperature as well as species concen-

trations for combustion flows, which are of great guiding significance for a theoretical design and practical application of the high-speed flight vehicle. In particle image velocimetry (PIV) [6], the fluid motion is made visible by adding small tracer particles to infer the flow velocity field. Methods based on laser-induced fluorescence (LIF) [7] and planar laser induced fluorescence [8] can produce large signals with the help of trace amounts of seeded species. BALLA and EXTON described the LIF method to obtain instantaneous measurements of atmospheric density with the seeded species I_2 in the range of $(0.1-6.5)\times 10^{17} \text{ cm}^{-3}$ [9]. As the seeded material may introduce unacceptable corrosion or undesirable influence on the flow field, the applications of molecular tagging techniques such as coherent anti-Stokes Raman spectroscopy (CARS) [10] and Raman excitation-laser induced electronic fluorescence (RELIEF) method [11] are developed for nonintrusive flow field diagnoses. CARS is a coherent third-order nonlinear process to perform temperature and concentration measurements in practical combustion systems. RELIEF is accomplished by tagging oxygen molecules through vibrational excitation and imaging them after a short period of time to obtain velocity profiles in unseeded air flows. However, the measurement process of two unseeded techniques above depends on the specific tagging molecules (*e.g.*, oxygen) and could not reflect the overall parameter information of the flow field, which severely limits the practical application of the measurement. Additionally, all the methods mentioned above always measure the two-dimension planar distribution of flow fields at normal atmospheric environment (density and pressure) with a complex optical system. As the aircrafts always fly in high altitude, it is more desirable to verify the measurement of slight pressure and low density air flow fields with a simpler structure for the practical application, which has little been researched through traditional methods.

To solve the problem above, ultraviolet Rayleigh scattering [12] from the atmospheric molecules is particularly promising for observing the structure of complex and low-density flow fields due to its higher measurement efficiency and simpler structure. It is a non-intrusive method and the measurement process has no influence on the distribution of the flow field. As it occurs by all kinds of small-scale particles in atmosphere, Rayleigh scattering could reflect the overall density information of the flow field rather than some specific particles. According to the Rayleigh scattering theory, the cross-section of ultraviolet Rayleigh scattering is tens of times stronger than that at visible light due to the fourth-power dependence on frequency. Additionally, the interference from background scattering of optical surfaces as well as particles in the flow is significantly reduced due to the poor reflectivity in an ultraviolet band, which provides higher signal-to-noise ratio and could be applied in the situation of low atmospheric density. In combination with laser spectroscopy, the spectrum of the scattered light could recover multi-parameters involving density, velocity and the temperature of the flow field [13]. The intensity of Rayleigh scattering is directly proportional to the molecular density while the Doppler frequency shift of the center frequency and the broadening of spectral lines associated with the motion of molecules reflect the velocity and the temperature, respectively. With the development of wavelength tuning, frequency stabilization, ultra-short pulse and the gated intensified

charge coupled device (ICCD) techniques, Rayleigh scattering will achieve higher temporal and spatial resolution for the application in the extreme conditions such as hypersonic and instantaneous flow fields [14].

In this paper, we have considered the potential for low atmospheric density measurement based on Rayleigh scattering of an ultraviolet laser. The distribution of Mach number and the density of the supersonic atmosphere flow field at Mach number of 1.5 around the NACA0006 aerofoil have been numerically investigated for the demonstration of the extremely inhomogeneous density profile and the necessity of the precision measurement. Additionally, the transient slight pressure and low density atmosphere have been experimentally measured for a qualitative illustration of the flow field detection. The linear relationship between the signal intensity and the atmospheric density is remarkably consistent with the Rayleigh scattering theory and the experimental results indicate that this technique proves to be a promising optical method for qualitative measurements of low-density conditions.

2. Theory and numerical simulation

In the process of the interaction between the electromagnetic wave and the medium, the incident radiation is attenuated by absorption as well as scattering out of their straight path. If the frequency of the incident wave is well removed from any resonant frequency of the medium, the absorption is negligible and only scattering needs to be taken into account. Rayleigh scattering is considered as the elastic scattering of electromagnetic radiation by particles (individual atoms or molecules) with the dimension much smaller than the wavelength of the incident wave [15, 16]. The Rayleigh scattering intensity for N particles is given by the following expression [17]:

$$I = I_0 \frac{8\pi^4 N \alpha^2}{\lambda^4 R^2} [1 + \cos^2(\Phi)] \quad (1)$$

where N is the number of scattering molecules, α is polarizability, R is the distance between the observer and the scattering molecules, I_0 is the intensity of the incident optical wave, and Φ is the angle between the incident and the scattered light.

As we can see from Eq. (1), the strong wavelength dependence of the scattering intensity ($\sim \lambda^{-4}$) signifies that the scattering cross-section at far ultraviolet is tens of times stronger than that at visible light. Additionally, the background scattering from other optical surfaces in the flow field is obviously depressed due to the poor reflectivity in ultraviolet, which provides a higher signal-to-noise ratio for measurement.

The simulation of a supersonic flow field with a software package Fluent 6.3 considers the two-dimension constant compressible flow around a NACA0006 airfoil [18], the geometric parameters of which are easy to be retrieved on the Internet. The flow field is described by Navier–Stokes equations in combination with Spalart–Allmaras turbulence model. It has been simulated by the finite volume method with structure grids and the pressure-based coupled solver at a free stream Mach num-

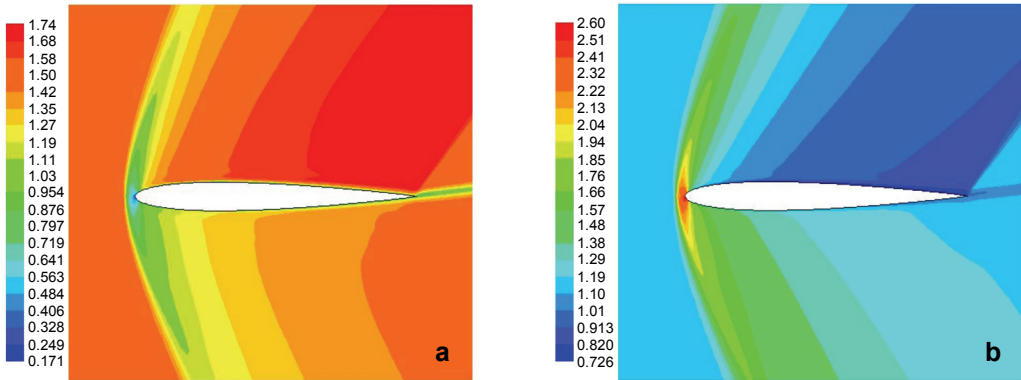


Fig. 1. Distribution of Mach number (a) and density around a NACA0006 airfoil (b).

ber of 1.5 and angle of attack $\alpha = 4^\circ$, under normal conditions (the default values of the software Fluent 6.3 as $T = 300$ K, standard atmosphere pressure at 101.325 kPa and ideal-gas density at 28.9×10^{-3} kg/mol). The distribution of the supersonic flow field is as follows.

Figure 1 illustrates obviously that the detached shock wave exists in front of the blunt-body airfoil, across which there is an extremely rapid decrease in Mach number and a severe increase in density of the atmosphere. As the extremely inhomogeneous distribution around the vehicle is due to the high Mach number, it is necessary to develop an effective method for the precision measurement of the density profile for the theoretical design and practical application of the high-speed flight vehicle. With an optical window opening on the edge of the airfoil, it is possible to detect the density distribution of atmosphere based on Rayleigh scattering of 266 nm ultraviolet laser. To a special time and space, the instantaneous flow field can be considered as transient atmosphere, the measurement of which provides a qualitative illustration for diagnose of the supersonic flow field, as the illumination in the following section.

3. Experiment and discussion

To give a qualitative demonstration for the flow field diagnose with an ultraviolet laser, a confirmatory experiment has been implemented to measure the slight pressure and low density of transient atmosphere. Assuming that the temperature can be approximated as a constant, the density is in a direct proportion to the pressure according to the perfect gas equation:

$$PV = nRT = \frac{m}{M} RT \Rightarrow PM = \rho RT \quad (2)$$

where P is the pressure, M is the atmospheric mole mass, ρ is the density, R is the gas constant, taking 8.31441 J/(mol·K), and T is the room temperature of atmosphere at 300 K. So the density distribution could be interpreted as a pressure field.

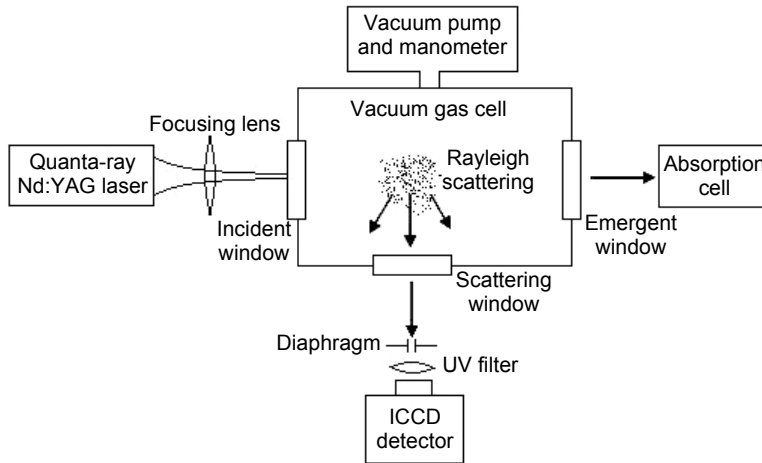
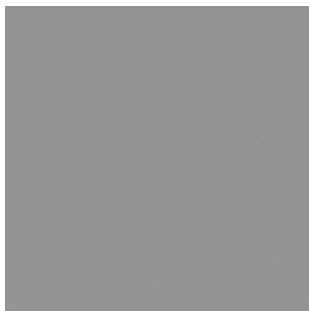


Fig. 2. Schematic diagram of the experimental setup.

The schematic diagram of the experimental setup has been shown in Figure 2. The 266 nm ultraviolet laser from Quanta-Ray Nd:YAG laser is focused into the vacuum gas cell, the pulse width and repetition rate of which are 5 ns and 10 Hz, respectively. The lens in front of the vacuum gas cell is a 1 m-long-focal-length ultraviolet quartz lens. The gas cell is filled with N_2 to avoid the Mie scattering from the larger particles in the air and assembled with a vacuum pump to control the atmospheric pressure. The intensified charge coupled device (ICCD) camera (Andor iStar DH734i-18F-03), with the image intensifying response spectrum ranging from 180 to 880 nm, collects the photons scattered in the vacuum gas cell. Compared with the common photoelectric detection system, the ICCD could capture the distribution profile of a two-dimensional flow field. The diaphragm is used to restrict the collecting angles, which causes that the ICCD only receives the scattered signal in the vertical direction. The ultraviolet filter, with the central wavelength and the bandwidth of 266 and 10 nm, in front of the ICCD filters the background noise and enhances the signal-to-noise ratio.

The background image of the vacuum gas cell without the input laser has been plotted in Fig. 3 with the laser energy of 0.5 mJ. As seen from the picture, the uniform



◀ Fig. 3. Background image of the vacuum gas cell without the input laser.

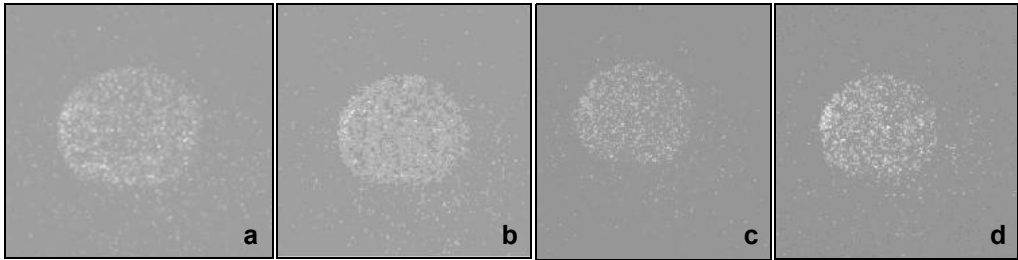


Fig. 4. Patterns of scattered light at different air pressures with laser energy of 0.5 mJ: 4.5 Pa (a), 92 Pa (b), 470 Pa (c) and 710 Pa (d).

background image proves that the interference light could be filtered effectively with the 266 nm ultraviolet filter and the experimental system is working properly. The background image will be subtracted from the patterns of the scattered light captured by the ICCD for the background correction.

The scattering patterns of 266 nm ultraviolet laser have been effectively captured during the experiment under different atmospheric pressures of 4.5, 92, 470 and 710 Pa with the subtraction of the background image in Fig. 4. It has been proved that the ICCD can effectively capture the distinct two-dimensional scattered signal in barometric depression as low as 4.5 Pa with the laser energy of only 0.5 mJ. According to the system parameters in the instruction, the stability of the laser is $\sim 1\%$. For the correction of the fluctuation of the light source, the average values from multiple measurements are used to correct the instability of the light source, for 10 times at each air pressure. It needs to be emphasized that with the self-adaptive image and data post-processing software of the ICCD, the contrast and the resolution of each picture are regulated to the optimum visibility. As a result, the gray gradient in the same picture represents the quantitative density distribution, while the gray discrepancy between pictures does not represent the absolute intensity and they are not comparable with each other.

Table 1. Functional relationship between scattered signal intensity and air pressure.

Air pressure [Pa]	Scattered signal intensity [a. u.]	Air pressure [Pa]	Scattered signal intensity [a. u.]
4.5	55.4	520	60
92	56	600	60.4
130	56.5	710	61.2
190	57	870	62.4
240	57.4	900	64
360	58.2	1100	66.6
470	59		

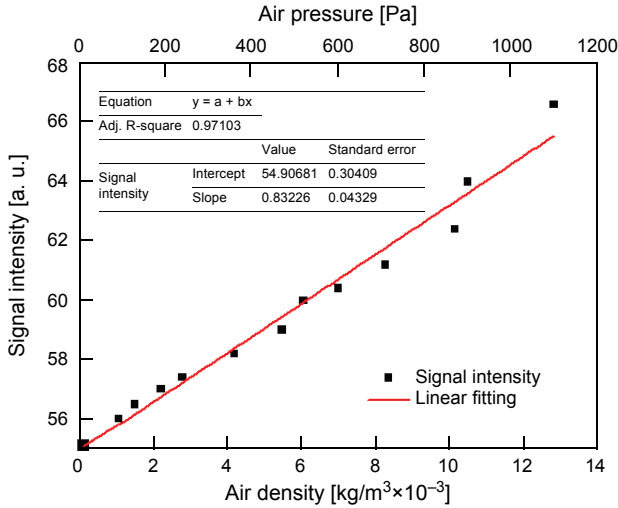


Fig. 5. Intensity of scattered light as a function of air density as well as pressure.

The functional relationship between the scattered signal intensity and the air pressure from 4.5 to 1100 Pa, which corresponds to the atmospheric density from $4.8105 \times 10^{-5} \text{ kg/m}^3$ to $1.279 \times 10^{-2} \text{ kg/m}^3$ according to the Eq. (2), has been listed in Table 1 and given in Fig. 5, according to the post-processing software of the ICCD.

It is observed that they are in an approximate direct proportion relationship within the range of tolerance and the *R*-squared value estimated with linear regression fits is 0.97103. The intercept and slope of the signal intensity are 54.90681 and 0.83226 a.u./($\text{kg/m}^3 \times 10^{-3}$) for air density (corresponding to 0.00968 a.u./Pa for air pressure) with the standard error 0.30409 and 0.04329, respectively. The linear fitting expressions are given as follows:

$$I = 54.90681 + 0.83226\rho \tag{3}$$

$$I = 54.90681 + 0.00968P \tag{4}$$

where *I* is the intensity of the received scattered light by the ICCD, ρ and *P* denote the atmospheric density and pressure, respectively. The fluctuation of the received intensity comes from the flow of the gas in the air chamber due to the continuous operation of the vacuum pump during the process of measurement. The experimental result shows that the linear relationship between scattered signal intensity and the atmospheric density proves approximately consistent with the fundamental theory of Rayleigh scattering in Section 2.

It has been proved experimentally that Rayleigh scattering of 266 nm ultraviolet laser could be effectively applied in the measurement of slight pressure and low density air flow field. With the calibration between the signal intensity and the atmospheric

density, this method can reflect not only qualitative but also quantitative information of the air flow field. Additionally, in combination with wavelength tuning, frequency stabilization, ultra-short pulse and the gated ICCD techniques, the time and spatial resolution of the system for online measurement will be further intensified and this diagnostic technology will be extended to a promising optical method for the instantaneous, multidimensional and multi-parameter measurement of supersonic flow fields.

4. Conclusions

In conclusion, we have numerically simulated the distributions of Mach number and density of the supersonic flow field around a NACA0006 aerofoil and experimentally measured the slight pressure and low density of transient atmosphere based on the Rayleigh scattering of 266 nm ultraviolet laser. The linear relationship between the signal intensity and the atmospheric density proves remarkably consistent with the Rayleigh scattering theory. It has been demonstrated that in the pressure range from 4.5 to 1100 Pa, corresponding to the atmospheric density from 4.8105×10^{-5} to 1.279×10^{-2} kg/m³, the scattering intensity of an UV laser is linear to the pressure and density with the slope coefficient of 0.00968 a.u./Pa and 0.83226 a.u./(kg/m³ × 10⁻³). With appropriate standardization of the measurement results, it is possible to obtain the quantitative determination of atmospheric density. Ultraviolet Rayleigh scattering has been proved practical and effective for analyzing comprehensive fluid dynamic phenomena.

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