Spectra of Rayleigh-Brillouin scattering in supersonic gas flows measured with a wide aperture spectrometer

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Abstract. We applied spontaneous Rayleigh-Brillouin scattering for measuring kinetic coefficients and velocity of flows. A kinetic model was used for spectral line shape calculation in case of wide aperture Fabri-Perot spectrometer. The calculation well corresponds to experimental spectra for stationary nitrogen and atmospheric air flow up to 3 Mach number.

1. Introduction
Laser Rayleigh-Brillouin scattering is useful tool for diagnostics of gases [1,2]. Scattered signal has spectral features reflecting the pressure, temperature and internal energy states of the gas. The method achieves high precision with using narrowband continuous wave lasers and thermostatic gas cell. Long collection of scattered radiation gives low level noise/signal ratio. Some kinetic models [3-5] predict spectral line shapes and define pressure macroscopic transport coefficients, such as the shear viscosity, the heat conductivity. The last S6 Tenti model [5] allows defining bulk viscosity, but also needs new approach for gas mixtures. In the work we used previous kinetic model [3] and applied it for interpreting of supersonic gas flows. Instability of real flows requires a short-time registration of spectrum and wide aperture.

2. Calculations based on theory of the scattering
Kinetic model describes spectral line shape for differential scattering cross section. The line shape depends on parameter $y$, which is the ratio of the scattering wavelength to the mean free path between collisions.

$$ y = \frac{p}{k v_0 \eta} = \frac{n k_B T}{k v_0 \eta} $$

where $k = |K_s - K_0|$ is the scattering wave vector, $n$ is the number density $T$ – temperature, $v_0$ is the thermal velocity, $k_B$ is the Boltzmann constant, $\eta$ is shear viscosity. Value $y$ depends on the scattering angle of the cross section, so it needs to take into account the angular dependence of the differential scattering cross-section. An elliptic line is the place in the plane of input diaphragm where $y$ is the same. A parabolic line is place of the same Doppler shift.
Differential scattering cross section can be express:

\[ DS(\vec{K}, \omega) = \left[ \frac{\sin \theta}{4\pi} \left( \frac{\partial \varepsilon}{\partial \rho} \right)_r \right]^2 K_0^4 S(\vec{K}, \omega) \]  

(2)

where \( \theta \) is the scattering polarization angle, \( \varepsilon \) is the dielectric constant, \( \rho \) is the gas density, \( S(\vec{K}, \omega) \) is the Van Have correlation function. Using wide aperture permits to get high intensity signal. The intensity is proportional square of the diaphragm; however the large area causes spectral line changing.

Figure 1. Forming lines of Doppler shift and the model parameter in the input plane.

Figure 2. Calculation of line shape changing in stationary gas (left) and gas flow (right) by using round wide aperture.

Figure 2 shows line shape changing in the case of stationary gas (left). In the case of gas flow (right) the spectral line changes. Calculations were made by integrating scattering cross-sections in the input diaphragm plane.

3. Experimental result
We used experimental setup, consist of low power 50 mW Ar+ laser with wavelength \( \lambda = 0.488\mu m \) in a typical scheme of direct spectral analysis [6]. The frequency composition of the scattered light
collected within the receiving aperture of a fast lens is analyzed with a high-resolution scanning spherical Fabry–Perot interferometer. The instrument function of the method coincides with the instrument function of the interferometer, whose width is 35 MHz at a free spectral interval of 1524 MHz. A photomultiplier tube operating in the photon-counting mode is used as a detector. The spectrum of the light scattered in moderate-density gases at small observation angles looks like a triplet of the central, or Rayleigh, peak and two Brillouin satellites.

![Graph showing experimental spontaneous scattering spectra](image)

**Figure 3.** Experimental spontaneous scattering spectra (solid curve) (a) in steady-state nitrogen obtained under the normal conditions, with a scattering angle of 22°, a round aperture of 40 mm, at a distance of 150 mm and (b) in a supersonic (580 m/s) jet of rarefied (88 Torr) nitrogen at T = 140K, with a scattering angle of 16°, a special diaphragm, at a distance of 150 mm from the scattering point as compared to model numerical calculations (dotted curve) and the spectrometer instrument function (dashed curve).

We will consider the experimental spectrum of the scattering at a subsonic nitrogen flow under the normal conditions ($p = 1$ atm, $T = 265$ K), which is shown in Fig. 3(a). The scattered light was collected at the angle 22° to the incident radiation within the round aperture 35 mm in diameter, set at the distance $L = 150$ mm from the scattering point. The Brillouin components are separated by $260 \pm 10$ MHz from the fundamental harmonic. This corresponds to the local sonic speed $332 \pm 15$ m/s. It follows from Eq. (1) that the parameter $\gamma = 3.1 \pm 0.1$ corresponds to the shear viscosity $\eta = (16.7 \pm 0.5) \times 10^{-6}$ Pa s, which is in agreement with the tabulated value of $16.65 \times 10^{-6}$ Pa s for nitrogen at the atmospheric pressure. The mean free path found from the spectral data is equal to $6.6 \times 10^{-7}$ m, which is also in agreement with the tabulated data ($\sim 10^{-7}$ m for most gases under the normal conditions). The spectral signal of the scattering at the supersonic nitrogen jet (Fig. 3 b) was obtained through the collection of the scattered light at the angle $\theta = 16$° within the special diaphragm at the distance $L = 150$ mm. The scattering volume was $V = 0.3$ mm$^3$. The triplet as a whole is shifted with respect to the zero frequency by $325 \pm 5$ MHz, which corresponds to the forward flow speed equal to $575 \pm 10$ m/s. The mean distance between the Brillouin peaks is $132 \pm 10$ MHz. Hence, the local sonic speed is $231 \pm 20$ m/s, and the flow temperature is equal to $130 \pm 15$ K. The parameter $\gamma$ is $1.2 \pm 0.1$, the static pressure is 88 Torr, and the viscosity is $\eta = (9.8 \pm 0.8) \times 10^{-6}$ Pa s as compared to the reference value.
of $9.45 \times 10^{-6}$ Pa s at 140 K (the reference data correspond to the pressure no lower than the atmospheric pressure). The mean free path is equal to $2.3 \times 10^{-7}$ m.

**Figure 4.** Spectrum of scattering in supersonic air flow (short-time registration within 10 sec).

**Figure 5.** Optimal form of diaphragm is the cross section of parabolic and elliptic strips.

4. **Conclusion**

Laser-illuminated Rayleigh-Brillouin scattering is rapidly becoming an important diagnostic tool for study of statistical fluctuations in gases [7]. However small scattering signal demands special design of experimental setup, based on kinetic model calculations.

5. **References**

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