

Seedless nonresonant gas-flow velocimetry with single-shot coherent Rayleigh-Brillouin scattering

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We demonstrate neutral gas-flow velocimetry by exploiting the optical dipole forces exerted by precisely tailored high-intensity laser fields on polarizable particles, in the form of single-shot coherent Rayleigh-Brillouin scattering (CRBS). This enables mapping of the velocity distribution function of the particles in a single laser shot of approximately 200 ns duration, allowing us to perform spectroscopic measurements in the time, rather than the frequency, domain. Importantly, CRBS results in a coherent signal beam, which renders the technique ideal for measurements in optically noisy environments. By correlating the time shift of the resulting spectrum to the Doppler shift caused by the bulk motion of particles, we perform neutral gas-flow velocimetry without the need to seed the flow, nondestructively, for a variety of gases, atomic or molecular. We demonstrate gas-flow velocimetry at flow velocities as low as 1 m s^{-1} , with similar velocity resolution, while temperature and gas density can also be estimated from the same single-shot spectra. To prove the effectiveness of the measurement technique, we benchmark it against Pitot tube measurements, which show excellent agreement.

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I. INTRODUCTION

Accurate gas-flow velocimetry has been an integral part of the development and advancement of a plethora of fields in science and engineering, ranging from turbulence [1–3] and aerodynamics [4–7] to plasma physics [8] and nanotechnology [9,10]. The ability to characterize the gas-flow field in terms of temperature, number density, and flow velocity magnitude and direction around a structure provides the input necessary to validate and verify codes and theories, respectively, that govern the gas-flow structure. It is thus important that the measurement technique employed to characterize the flow field conforms to certain standards, enabling it, in turn, to provide the most accurate measurements. It should thus (1) be nonperturbative,

so that it does not alter the medium it seeks to measure; (2) be fast, to probe high gas-flow velocities as well as gas dynamics; (3) work with as many gas species as possible; and (4) require no additional seeding to the flow.

The current state of the art in gas-flow velocimetry still relies largely on mechanical probes, such as the Pitot tube [11–13] and hot-wire anemometer [14–16]. Although relatively cheap, commercially available, and simple to set up, these techniques are largely perturbative to the flow they measure, and introduce a source of uncertainty in the validity and accuracy of their measurements. Pitot tubes also require incompressible inviscid flow, complicating their use in some environments, such as supersonic regimes. Another method to perform visualization of the flow field is particle image velocimetry (PIV); here the flow is seeded with small (micrometers to nanometers) particles, which are illuminated by a laser beam and imaged using fast cameras [17–19]. By digitally tracking the particles in fast frame sequences, flow velocimetry measurements can be obtained [20–22]—apart from gas flows, this method finds important applications in liquid flows [23,24]. Alternatively, an interference pattern can be projected onto the flow particles and its Doppler shift,

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resulting from the motion of the particles, measured. This process is known as laser Doppler velocimetry (LDV) [25–27]. Although undoubtedly successful, PIV and LDV require the flow to be seeded with particles; this could damage the models under flow testing, while the technique relies on the assumption that the particles accurately follow the flow pattern of the gas particles. Gas pressure measurements can be made using pressure-sensitive paints applied on the surface of test models; however, gas pressure can only be estimated on the surface and not above it [28–30].

To address these well-known issues with mechanical probes, a wide variety of laser-based diagnostics have been developed, all of which aim to characterize thermodynamically the flow field (temperature, pressure, flow velocity vector), while adhering to the requirements mentioned earlier.

In this article, we demonstrate single-shot coherent Rayleigh-Brillouin scattering (CRBS) as an effective technique for nonintrusive, nonresonant gas-flow velocimetry, capable of resolving, within a single ≈ 200 ns duration laser pulse, the flow velocity vector for a variety of both atomic and molecular gases. This measurement capability adds to the already demonstrated capabilities of single-shot CRBS for nonresonant temperature, density, and polarizability measurements within a laser shot of the order of approximately 200 ns [31–33]. CRBS is also capable of retrieving other thermodynamic properties, such as bulk and shear viscosity [34], thermal conductivity, diffusivity, Mach speed, and compressibility, owing to their influence on the CRBS spectral profile.

Most laser-based techniques usually follow a resonant excitation scheme, targeting a specific atom or molecule of the flow that could be naturally present (e.g., N_2 in the case of air flow) or would need to be seeded to the flow (e.g., Kr or NO). Examples of such resonant techniques include planar laser-induced fluorescence (PLIF) [35–39], coherent anti-Stokes Raman scattering (CARS) [40–44], femtosecond laser electronic excitation tagging (FLEET) [45,46], molecular tagging velocimetry (MTV) [47,48], krypton tagging velocimetry (KTV) [49–51], and vibrationally excited nitric oxide monitoring (VENOM) [52,53]. PLIF, FLEET, MTV, KTV, and VENOM are used to measure flow velocity by resonantly exciting the target flow species using a laser sheet, thus tagging or writing a resonant line on the flow and subsequently monitoring its propagation in the flow with high-speed cameras. PLIF, VENOM, and CARS can be used for flow thermometry by measuring the ratio in signal strengths between different rotational or vibrational states and, assuming Maxwellian (i.e., equilibrium) conditions, derive the rotational or vibrational temperature. The fact that all these techniques are resonant automatically limits their application to mainly one atmospheric flow configuration, thus limiting their thermometry application to, e.g., only one entry flow scenario in a wind tunnel. Additionally, their reliance on thermal

equilibrium to derive rovibrational temperatures can lead to erroneous estimates in measurements, especially in conditions where thermal nonequilibrium is anticipated, such as in those encountered in planetary entry. Finally, we note that none of these techniques can provide information about the translational temperature of the gaseous ensemble.

Translational temperature and flow velocity measurements can be performed with spontaneous Rayleigh scattering (SRS) [54–56] or filtered Rayleigh scattering (FRS) [57–59]: both techniques are nonresonant and can be used with a multitude of gases and gas mixtures. Since in both techniques the signal is scattered in a 4π solid angle, signal acquisition in an optically noisy environment (e.g., when plasma is present) is challenging. Finally, since the Rayleigh scattering cross sections are relatively low, neither Rayleigh scattering techniques operate well in low pressure or density environments, such as those encountered in supersonic or hypersonic wind tunnels.

A. Single-shot coherent Rayleigh-Brillouin scattering: The technique

Single-shot CRBS has been presented in detail elsewhere [31–33]; here, we are only presenting its main operating principles. In CRBS, two intense laser beams of the same polarization and with relative frequency difference $\Delta\omega$, called the *pumps*, interfere within a medium to produce an optical interference pattern of wavelength $\lambda_g = \lambda_{\text{pump}} / (2 \sin(\phi/2))$, where λ_{pump} is the pump wavelength and ϕ is the pump crossing angle; the pattern's phase velocity v_g is given by $v_g = (\Delta\omega \lambda_{\text{pump}}) / (2 \cdot \sin(\phi/2))$.

Owing to the optical dipole force $F_{\text{OD}} = \frac{1}{2} \alpha_{\text{eff}} \nabla I_{\text{pump}}$, where α_{eff} is the effective polarizability of the medium's particles and I_{pump} the intensity of the pump beams, particles in the medium feel an attraction toward the high-intensity nodes of the interference pattern, thus forming an *optical lattice*. A third, *probe* beam is then incident on the lattice at the Bragg angle [$\lambda_{\text{probe}} = 2\lambda_g \sin(\theta)$, where λ_{probe} is the probe beam wavelength and θ the Bragg angle] and is Bragg reflected by the optical lattice, resulting in a fourth, *signal*, beam. Figure 1(a) shows a typical CRBS beam geometry.

Only particles with a velocity v_{particle} matching v_g can interact with the lattice; this means that the intensity of the signal I_{signal} will be proportional to the square of the particle density perturbation at that velocity manifold of the velocity distribution function (VDF). By scanning $\Delta\omega$, and thus v_g , the lattice interacts with different velocity components of the VDF; by recording I_{signal} as a function of $\Delta\omega$ or lattice phase velocity, the VDF can be measured, contained in the CRBS spectral lineshape, as shown in Fig. 1(b). The CRBS lineshape is the summation of three peaks: the Rayleigh peak, at the center of

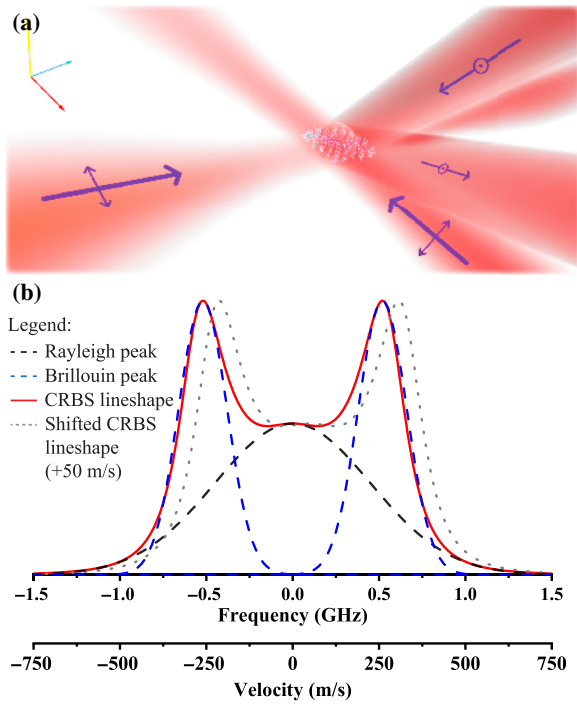


FIG. 1. (a) Single-shot, single-color coherent Rayleigh-Brillouin scattering (CRBS) geometry used in the experiments presented in this article: the two *pump* beams of the same polarization interfere to create an optical lattice. A third, *probe*, beam of orthogonal polarization intersects the optical lattice at the Bragg angle from the orthogonal plane, resulting in the CRBS *signal* beam. (b) Typical single-shot CRBS lineshape (solid red line), which results from the summation of three peaks: the Rayleigh peak in the center (dashed black line) and the two Brillouin peaks (centered at the speed of sound). Also shown is the Doppler-shifted CRBS lineshape due to the bulk flow of the gas medium (gray dotted line).

the lineshape, which is a direct representation of the VDF, and, equidistant from it, the two Brillouin peaks, centered at the speed of sound of the medium. By scanning $\Delta\omega$ across the duration of the pumps, i.e., by scanning all the velocity components resulting in the CRBS spectrum, single-shot spectral acquisitions of the order of approximately 200 ns can be achieved [32]. This practically translates to single-shot CRBS spectra being recorded on the time, rather than the frequency, domain, since I_{signal} can be detected on a photodiode for the duration of the pump beams and displayed on an oscilloscope [60]. Importantly, the fact that the signal beam is another laser beam vastly reduces any optical background, since the optical background scales according to $1/r^2$ with distance r from the measurement location. In fact, in CRBS, the signal-to-noise ratio (SNR) increases with increased distance of the detector, contrary to what happens with linear optical diagnostics.

For quiescent gases, the CRBS lineshape is centered at 0 m s^{-1} , while for a gas bulk flow, the lineshape should be Doppler shifted, as a linear function of the flow velocity [Fig. 1(b)]. The sign of the spectral shift $\Delta f_{\text{Doppler}}$ will be proportional to the flow direction, while the magnitude of the shift will be linearly proportional to the flow velocity v_{flow} . Importantly, single-shot CRBS is not only a nonperturbative method but also highly localized: even for supersonic flows, the displacement of the flow during the scanning of the phase velocity of the optical lattice does not exceed tens of micrometers.

B. Single-shot coherent Rayleigh-Brillouin scattering: The laser system

The laser system developed to obtain single-shot CRBS spectra has been presented in detail elsewhere [61]; here, we are only providing its main output characteristics. The laser system provides two laser pulses with energies up to approximately 400 mJ per pulse. The intensity of the pulses at the measurement point (focal points of the beams) is kept below the optical breakdown of air (approximately 10^{12} W/cm^2 [62]). The measurement volume is dictated by the focal point of the lens (0.046 mm^2) and the overlap between the pump beams ($\approx 100 \text{ }\mu\text{m}$). The lattice sites are separated by a distance of approximately $\lambda/2$ ($\approx 532 \text{ nm}$). The achievable chirp between the two pulses can reach up to 10 GHz, while the pulse duration can be varied between 10 and 1000 ns. Although the CRBS geometry utilized here uses the single-color CRBS scheme, where the pumps and probe are all operating at 1064 nm, the laser system is also capable of frequency-doubling the probe, hence enabling measurements at lower densities, as demonstrated in detail in Ref. [33].

II. RESULTS

To demonstrate single-shot CRBS as an effective gas-flow velocimetry technique, two different experimental setups were developed: the first one, presented in Sec. II A, demonstrates open air flow measurements, while the second one, presented in Sec. II B, demonstrates CRBS's capability for performing velocimetry in a variety of gases, atomic or molecular. A Pitot tube was used for validation in both campaigns, as it is a well-established diagnostic tool in comparable environments. The Doppler shift represents the average velocity of the particles in the interaction region. Owing to the relatively small size of the interaction region, the particle velocity therein is assumed to be uniform and the region is treated as a point. It should be noted that, for the spectra demonstrated in this article, a total of 20 shots of the single-shot CRBS lineshapes are averaged to reduce lineshape distortion inherent from the fluctuating nature of the flow between shots and to increase the signal strength, thus enabling a better comparison with the flow velocity measured by the Pitot tube.

A. Open air gas-flow velocimetry

To demonstrate the proof of concept for gas-flow velocimetry, an experiment was designed and conducted as shown in Fig. 2(a). Here, the CRBS optical lattice is formed in open air, on top of an optical table. Two nozzles were set up to have their outputs at close distance (approximately 1 cm) from the location of the lattice. Both nozzles were connected to the same inlet, fed with pressurized air from the supply of the building. The air flow to each nozzle was directed by a three-way valve, while the backing pressure was controlled via a regulator. To benchmark the accuracy of single-shot CRBS, Pitot tubes were installed on the opposite side and in close proximity to the optical lattice. Note that the optical lattice was located 6.3 cm downstream from the nozzle exits and the Pitot tubes were 7.6 cm downstream from the nozzles to avoid overlapping between the two methods. Prior to the CRBS velocimetry,

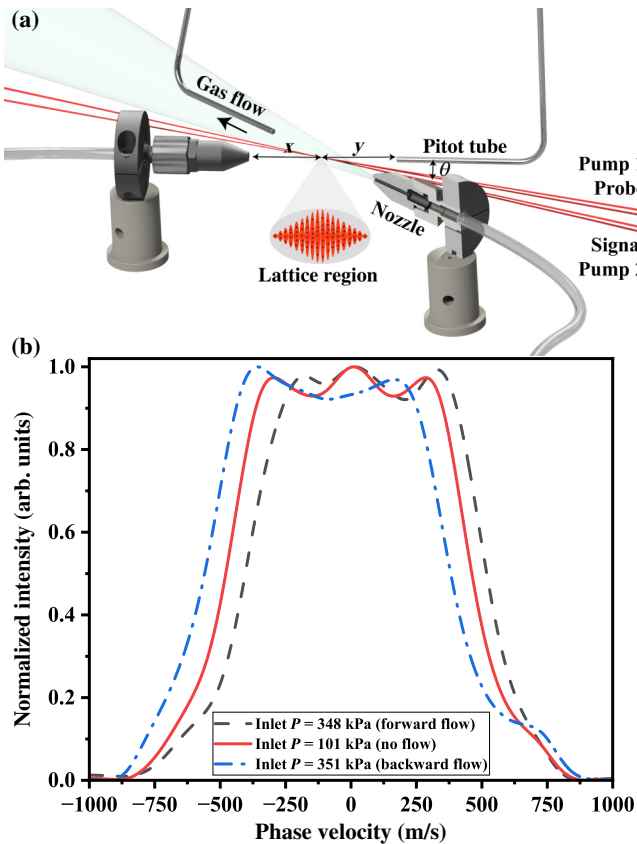


FIG. 2. (a) Experimental setup used for open air velocimetry experiments. Two open air nozzles eject high pressure air, provided by the building, at an angle on the optical lattice. Pitot tubes are also deployed to validate the coherent Rayleigh-Brillouin scattering (CRBS) measurements. (b) Experimental single-shot CRBS results for air in this configuration. The solid red line is a measurement of quiescent air without any flow, while the dashed gray and dash-dotted blue lines are the CRBS Doppler-shifted spectra for forward and backward flows, respectively. Refer to Ref. [63] for a video presentation of this measurement.

the flow velocity along the center axis of the nozzle at the lattice location was characterized by the Pitot tubes. The flow at the lattice location was 22% higher than that at the nominal Pitot location during CRBS velocimetry, which was taken into account when comparing the simultaneous Pitot and CRBS results.

CRBS spectra were initially recorded without any gas flow in this setup. Depending on which nozzle is turned on, the CRBS lineshape would be expected to shift in a different direction, with the magnitude of the shift proportional to the backing pressure and, ultimately, the flow velocity. Figure 2(b) presents sample experimental CRBS spectra for three cases; no flow, forward flow, and backward flow. Since the nozzle output is at an angle with respect to the optical lattice axis, the Doppler shift that is observed is for the velocity component parallel to the optical lattice axis.

Gas-flow measurements using single-shot CRBS are obtained by monitoring the Doppler shift of the CRBS lineshape on an oscilloscope. The measurement takes place in the time, rather than the frequency, domain, where high-resolution measurements can trivially be made with easily accessible experimental tools. To give an example, a flow velocity v_{flow} of 10 m s^{-1} along the optical axis would equate to a spectral Doppler shift $\Delta f_{\text{Doppler}}$ of approximately 20 MHz through the relation $\Delta f_{\text{Doppler}} = 2 \cdot v_{\text{flow}} / \lambda_{\text{probe}}$. Assuming that a total chirp of, e.g., 1.5 GHz is applied across a pulse duration of 150 ns, this would equate to a temporal shift of 2 ns for the single-shot CRBS lineshape on the oscilloscope for this assumed v_{flow} . This measurement is easily attainable with standard commercial laboratory equipment and the measurement accuracy is practically limited by the bandwidth of the oscilloscope and photodiode used for the measurement. In this work, both devices used had a bandwidth of 1 GHz. The measurement techniques used to obtain the flow velocities are described in detail in Ref. [60]. In summary, depending on the flow direction, the temporal shift of the rising or falling slope was used to derive the magnitude of the flow velocity. The direction of the temporal shift provides the direction of the flow; the two together provide the flow velocity vector in the axes of the optical lattice.

Figure 3 shows the comparison of the neutral air gas-flow velocimetry results, using the experiment shown in Fig. 2(a), between both the Pitot tube and single-shot CRBS as a function of the inlet pressure in the nozzle. It is evident that there is very good agreement between the two methods, while any small differences in the measurements can be attributed to the slightly different measurement locations of the two methods, as well as to the dimensions of the overall measurement volumes. It is clear though that single-shot CRBS can be used to make the same measurement as the current state of the art, without, however, perturbing the flow. Note that there is fundamentally no upper limit to the velocities that can be measured with this method, rendering its application to supersonic and

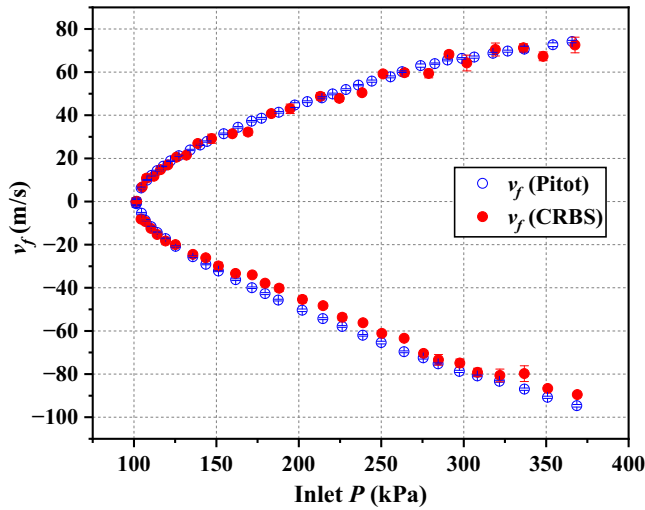


FIG. 3. Comparison between the velocities estimated with the single-shot coherent Rayleigh-Brillouin scattering (CRBS) method presented in this article (solid red circles) versus those measured using a Pitot tube (hollow blue circles), for the experimental setup shown in Fig. 2(a).

hypersonic flows ideal, especially considering the short acquisition time available for these measurements.

B. Nonresonant seedless gas-flow velocimetry

Since single-shot CRBS is achieved for polarizable particles in a medium, it can be applicable to all atomic or molecular gases. So long as the pump beams are detuned far from the resonant electronic and vibrational frequencies (of molecules), there are no fundamental differences in the measured spectral features. Hence, this removes the need to seed the flow with particles or any gas with which the lasers will be resonant. This renders single-shot CRBS an ideal velocimetry technique in gas flow scenarios where flow in different gas atmospheres needs to be studied, e.g., in planetary entry conditions. To demonstrate this capability, a gas-flow chamber was constructed, as shown schematically in Fig. 4.

Here, different gases at up to a pressure of 760 torr can be introduced. The pressure inside the chamber remains constant through the operation of a flow check valve, ensuring that when the pressure inside the chamber rises above 760 torr, the residual gas outlets into the atmosphere. Similar to the experiment in Sec. II A, the CRBS beams intersect the gas flow at an angle.

Measurements were made in this chamber for a variety of gases, atomic and molecular. Similar to the case with air flow, the Doppler shift of the single-shot CRBS lineshape was quantified for different flows, and the measurement was validated using a Pitot tube that was also pointed in the direction of the flow. The Pitot tube results were corrected by 10%, taking into account the location being 5 mm downstream from the lattice location. Figure 5

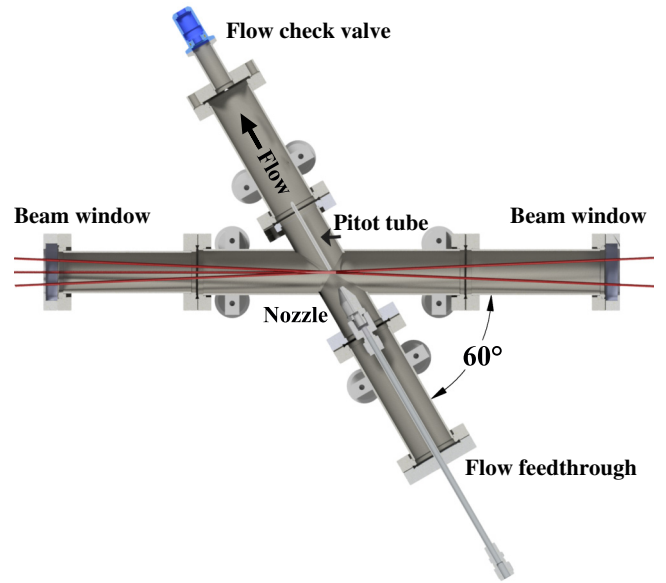


FIG. 4. Experimental setup used for gas-flow velocimetry measurements of atomic and molecular gases. The pressure in the chamber is kept constant, at 760 torr, through the use of a flow check valve. The coherent Rayleigh-Brillouin scattering flow measurements are benchmarked against those from a Pitot tube inside the chamber.

shows experimental flow velocimetry results from this chamber for air, argon, CO_2 , and SF_6 gases, demonstrating the CRBS capability in operating with different gases, atomic or molecular, without the need to seed the flow or alter the laser wavelength or configuration. Discrepancies in the results between the Pitot tube and CRBS methods in this chamber are attributed to the different measurement locations and to reflections of different waves within the chamber. Further information on the density structure resulting from the nozzle flow is found elsewhere [64,65]; however, this goes beyond the scope of this article and hence is not discussed in detail. Additionally, errors in the Pitot tube measurement might occur, owing to differences in static pressure between the static and dynamic ports of the tube [66] and from any shift in the alignment between the tube and the flow field [67]. The uncertainty in the CRBS measurement results primarily from resolving the Doppler shift in the signal, as this is dependent on the signal strength.

III. CONCLUSION

In this article, the capability of single-shot CRBS in performing velocimetry in a variety of gases is demonstrated, to the best of our knowledge, for the first time. This capability adheres to the requirements for nonperturbative, seedless, nonresonant optical diagnostics to perform accurate gas-flow velocimetry in a variety of flows, regardless

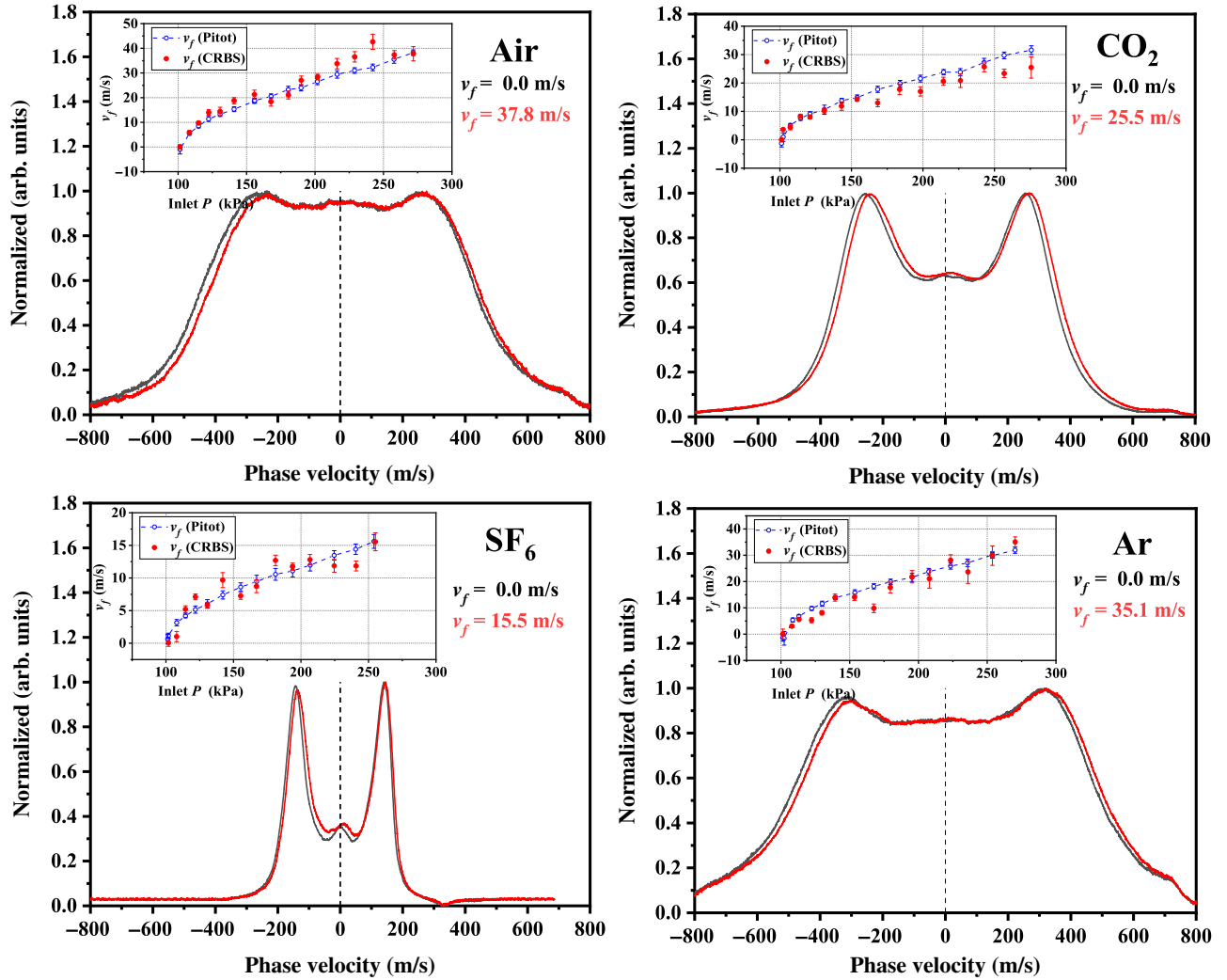


FIG. 5. Gas-flow velocimetry performed in the chamber shown in Fig. 4 for air, CO₂, SF₆, and argon gases. Shown are single-shot coherent Rayleigh-Brillouin scattering (CRBS) lineshapes for quiescent gas at 0 m s⁻¹ (black lines) and for gas flows at various speeds (red lines). In the insets, measurements made using CRBS (solid red circles) and the Pitot tube (hollow blue circles) are presented, for each gas.

of optical noise in the vicinity of measurement. We estimate that the current achievable velocity resolution is of the order of 1 m s⁻¹, while the densities at which the technique can be applicable range from approximately 1 torr, depending on the gas, using the dual-color CRBS scheme demonstrated in Ref. [33], while an upper limit does not exist. The achievable resolution can trivially be improved with the use of faster photodiode or oscilloscope combinations.

These characteristics render single-shot CRBS an ideal flow velocimetry technique for a variety of flow scenarios, ranging from aerospace applications (e.g., supersonic or hypersonic flows, propulsion, planetary entry) to flame, combustion, and plasma flow applications. Coupled with density and temperature estimates from the CRBS lineshapes, as demonstrated in Ref. [33], single-shot CRBS can provide density, temperature, and flow velocity vector

measurement, in a single laser shot of approximately 200 ns duration.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors on reasonable request.

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