Study of Cluster Formation and its Effects on Rayleigh and Raman Scattering Measurements in a Mach 6 Wind Tunnel

by

B. Shirinzadeh,* M. E. Hillard,* A. B. Blair, ** and R. J. Exton***
NASA Langley Research Center
Hampton, VA 23665

ABSTRACT

Using a frequency-doubled Nd-YAG pulsed laser and a single-intensified CCD camera, Rayleigh scattering measurements have been performed to study the cluster formation in a Mach 6 wind tunnel at NASA Langley Research Center. These studies were conducted both in the free stream and in a model flow field for various flow conditions to gain an understanding of the dependence of the Rayleigh scattering (by clusters) on the local pressures and temperatures in the facility. Using the same laser system, we have also performed simultaneous measurements of the local temperature using the rotational Raman scattering of molecular nitrogen and determined the densities of molecular oxygen and nitrogen by using the vibrational Raman scattering from these species. Quantitative results will be presented in detail with emphasis on the applicability of the Rayleigh scattering for obtaining quantitative measurements of molecular densities both in the free stream and in the model flow field.

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*Physicist, Optical Spectroscopy Section, Instrument Research Division.
**AeroSpace Technologist, Supersonic-Hypersonic Aerodynamics Branch, Applied Aerodynamics Division. Senior member AIAA.
***Head, Optical Spectroscopy Section, Instrument Research Division.

INTRODUCTION

With recent increased activity in hypersonics, the demand for multi-point, quantitative, non-intrusive measurements of flow parameters such as density, temperature, and velocity have risen in order to obtain experimental data for computational fluid dynamics (CFD) code validation. We have considered a combination of the Rayleigh and Raman scattering techniques to simultaneously measure, in a Mach 6 facility, the total density using the Rayleigh scattering (multi-point), species concentration using the vibrational Raman scattering of molecular nitrogen or oxygen (single-point), and the rotational temperature (single-point) using the rotational Raman scattering of molecular nitrogen. The motivation was, by using a single laser system, to develop an instrument capable of measuring all these quantities simultaneously and accurately. Because the Rayleigh cross section is about three orders of magnitude larger than the Raman cross section, higher signal levels are expected in Rayleigh scattering measurements.[1,2] As a result, based on signal level consideration only, it is possible to obtain multi-point measurements of the local densities in a Mach 6 facility, where density is expected to vary from 2×10^{17} to 2.5×10^{18} molecules/cm^3. The major difficulty with the Rayleigh scattering technique, however, is its lack of specificity. That is, it cannot distinguish between the molecular scattering and the stray laser light scattered by windows and walls, light scattered by particles in the flow, or scattering by flow generated clusters. The stray light can be minimized by proper design of the collection optics. By using a short duration laser pulse, the effect of particles on the Rayleigh signal may be reduced. In addition, since the density of particles in the flow is usually low and the signal generated by them is very large, they produce a distinct signature in the image and can be identified and rejected from data analysis. Under our experimental conditions, the signal generated by clusters, which are generated as a result of the cooling which takes place as the gas is expanded into the test section,[3,4] cannot however be distinguished or rejected from the molecular signal. In a previous publication,[5] it was shown that this signal is strongly dependent on the thermodynamic parameters, namely, pressure and temperature. This strong dependence of the signal level on the pressure and the temperature, presents a difficulty in interpretation of the Rayleigh results obtained in the presence of clusters.

In this paper, we will present the results of our simultaneous measurements of the Rayleigh signal levels both in the free stream and in a model flow field, the free stream rotational temperature using the rotational Raman scattering of molecular nitrogen, and the free stream density using vibrational Raman scattering of molecular nitrogen or oxygen. We will show that with the present setup, these measurements can be performed with low background levels. The pressure and the temperature dependence of the Rayleigh signal in the free stream and in the model flow field will be discussed. We will show that, in the absence of clusters, Rayleigh measurements which are in good quantitative agreement with the expected values both in the free stream and in the model flow field can be obtained.

EXPERIMENTAL

Figure 1 shows a schematic of the experimental setup. As before,[5] the frequency-doubled output of a Nd-YAG pulsed laser was used as the light source. This output near 532 nm was focused to the region of interest in the test section using a 40 cm focal length lens (L1). The beam was dumped after a traversal path through a half-wave plate, a brewster window (BW), a series of apertures, and a hole in the floor of the test section. This minimized the amount of stray light scattered by the laser entrance window into the test section. On one side of the test section, the scattered light was collected at an angle of 60^o with respect the flow by a lens system (L3), which consisted of two achromatic lenses each having a focal length of 50.8 cm (f/5). The magnification obtained using this lens system was equal to one. A combination of the half-wave plate and the brewster window ensured that the polarization of the laser beam was rotated in such a way to maximize the Rayleigh and the vibrational Raman signals, while reducing the effect of Rayleigh scattering on the rotational Raman signal. The Rayleigh scattered light was reflected by a dichroic mirror (DM), underwent spatial aperturing, and was imaged using a lens system (L4) onto a single-intensified charge-coupled device (CCD). The video signal from the camera was digitized using a frame grabber and stored in a computer. This configuration enabled us to obtain a line image of the Rayleigh signal with much reduced background level. The vibrational Raman signal transmitted through the dichroic mirror was processed by a color filter (CF) and an interference filter (IF), whose output after spatial aperturing was detected by a photomultiplier tube (PMT). The signal from the PMT was processed by a boxcar, the output of which was digitized and stored in a computer. In this way, a single-point measurement of the vibrational Raman signal due to molecular nitrogen or oxygen was obtained and recorded. On the other side of the test section, the scattered light was collected by a lens system (L2) and imaged onto a slit of a double-monochromator. The double-monochromator was designed, by using a dual intermediate and dual exit slit assembly, to resolve rotational Raman lines of $J = 4$ ($\Delta J = +2$) and $J = 6$ ($\Delta J = -2$) of molecular nitrogen. These two signals were simultaneously detected by two photomultiplier tubes, processed by boxcars, and were digitized and stored in the computer. In this way, a single-point rotational temperature measurement was obtained.

For these experiments, the laser was operated at a repetition rate of 10 pulses per second with an energy of about 120 mJ/pulse. The pulse duration was 7 ns. The laser and all the optics were mounted on a schlieren support yoke to reduce vibrations. To minimize the effect of the laser energy fluctuations, a small portion of the beam was split and detected by a photodiode. The output of the photodiode, after sample and hold detection, was digitized and stored in the computer. This facilitated shot-to-shot normalization of the Rayleigh and the Raman signals by the laser energy.

To minimize uncertainties associated with the photon-flux, the volume of the interaction, the solid angle of collection, the transmission of the optics, the quantum efficiency of the detectors, and the gain differences for different detectors, it was necessary to calibrate each detector. This calibration, as before,[5] was performed by pumping the tunnel down to a known static pressure and obtaining the data. In this way, linear plots of the signal level as a function of the static pressure were obtained. The slopes and the intercepts deduced from these plots were used to determine densities from the Rayleigh and the vibrational Raman signals, and to account for the gain differences between the two PMTs used to detect the rotational Raman signals.

RESULTS AND DISCUSSION

To obtain the rotational temperature, the scattered light was imaged using a lens system (L2), which consisted of two spherical lenses each having a focal length of 50.8 cm and a diameter of 7.6 cm, onto an entrance slit of a double-monochromator. The double-monochromator with a dual intermediate and dual exit slit assemblies was designed to resolve the rotational Raman lines of (4 -> 6) and (6 -> 4) of molecular nitrogen. The combination of the grating and the slit assemblies provided a triangular line shape with a full-width at half-maximum (FWHM) of 4 cm^{-1}. This resolution is sufficient to minimize the effect of the oxygen line (e.g. (7 -> 9)) which is separated by about 5 cm^{-1} from the nitrogen line. High gain PMTs used for these experiments, were matched in gain and exhibited a dark current of about 50 nA. To reduce the sensitivity of the signal level to small gate drifts in the boxcars, gate-widths were set to 40 ns. The output of the boxcars with and without any signal present were compared in order to account for the baseline drift in the electronics. To do so, an electronic shutter was placed on the entrance slit of the double-monochromator. This shutter was remotely closed after acquiring about 250 laser shots so that the electronic baselines could be determined and subtracted from the signals. As was mentioned previously, before each run a calibration set was obtained to take into account the gain differences in the electronics. Using a linear least-squares fitting procedure, the slopes and the intercepts were determined for both detectors from linear plots of signal level as a function of $X = P.\exp(-E_J/kT)/T^2$, where P is the static pressure, T is the temperature, E_J is the energy of the rotational level, and k is the Boltzmann constant. The deduced intercepts were found to be zero, and the slopes accounted for differences in gain between the two channels. In this way, a single-point measurement of the rotational temperature of molecular nitrogen can be obtained by taking the ratio of the deduced quantities X for both Raman transitions from the observed signal levels. One should add here that, if experiments were performed using a long pulse duration or a cw laser where photon counting techniques could be implemented and the two channels were optically the same, the calibration procedure described above may not be required.[6,7]

Figure 2 shows a comparison between the deduced rotational temperatures and the expected temperatures computed from isentropic expansion for a Mach number of 5.94 appropriate for the free stream of this tunnel. In these plots, the temperature is depicted as a function of the sequence in which the data were taken. For ease of reference, the stagnation pressures, P_t, for each run are posted next to the data points. Error flags represent the statistical uncertainty in the deduced temperatures obtained for 240 laser shots. This uncertainty is obtained by calculating the standard deviation of the mean value for 240 laser shots and it also includes the calibration uncertainty. The data presented in Figs. 2(a) and 2(b) show that a good agreement is obtained between the deduced and the computed temperatures in the beginning of each day; however, suddenly after some time elapse, disagreements as high as 20 K in temperature are observed. For the data obtained on August 29, 1990, a calibration set was obtained at the end of the session. This calibration set was different from the one obtained in the beginning of the session and, when it was applied to the points from 11 to 18 of the same data (results are shown in Fig. 2(c)), it removed the disagreement shown in Fig. 2(b) for those last data points. The reason for this change in the calibration is not clear, since no change was made to the optics or the electronics during this period. The above results indicate that, with further improvements, this system can be made into a reliable instrument for measuring the rotational temperature.

To measure the density of molecular nitrogen (or oxygen), the scattered light which constituted both the Rayleigh and the vibrational Raman signals was collected by the lens system L3. The Raman signals were transmitted through a dichroic mirror which exhibited a transmission of about 2% near 532 nm, 84% near 580 nm, and 91% near 607 nm for a 45^{o} angle of incidence. The output of the dichroic mirror was processed by a color filter which transmitted about 89% and 91% of the light near 580 nm and 607 nm, respectively, and passed about one part in 10^4 near 532 nm. To separate Raman signals due to molecular nitrogen or oxygen, 2 nm bandpass interference filters were used. These filters exhibited peak transmissions of T ~ 72% near 580 nm and T ~ 74% near 607 nm. Typical transmission near 532 nm was about one part in 10^5. To minimize the amount of the stray light on the PMT, a slit was placed at the image plane of the lens L3. With the laser light blocked, the current output of the PMT was essentially the dark current thus indicating that the room light was eliminated in this setup. A slit height of 1 cm determined the spatial resolution of the measurement. The signal from the PMT was processed by a boxcar with a gate width of 40 ns. The output of the boxcar was then digitized and stored in the computer. As was mentioned earlier, the detection system was calibrated before each run. No evidence of any background light was ever observed on the calibration data (the intercept was zero within the uncertainty). In this way, the vibrational Raman signals due to molecular nitrogen or oxygen were detected and the density of these species in the free stream were deduced.

Figures 3 and 4 show a comparison between the deduced air density from the measured vibrational Raman signals and the expected density as computed from isentropic expansion in the tunnel. A Mach number of 5.94 is assumed for the free stream. In these figures, each data point was obtained by averaging 200 laser shots. The error flags represent the statistical uncertainties of the data (standard deviation of the mean value for 200 laser shots) and they include the uncertainty in the calibration. The data depicted in Figs. 3 and 4 are deduced from the measured Raman signal due to molecular nitrogen and oxygen, respectively. As it is seen in Fig. 3, an excellent agreement between the deduced and the expected free stream air densities is obtained, while in Fig. 4, for an unknown reason, a few points do not agree within the statistical uncertainty of the measurement. Figs. 3(a) and 4 cover a large range of stagnation pressures from 0.69 to 2.93 MPa with a maximum stagnation temperature of 490 K. Under the high pressure conditions, the Rayleigh scattered light is predominantly due to clusters with signal levels as high as one order of magnitude larger than the Rayleigh signal due to molecular scattering. The agreement observed here for the Raman results and the consideration of the transmission of the filters, indicate that this scheme is capable of rejecting the Rayleigh scattered light even in the presence of clusters. From Fig. 3, one should also note that, the uncertainties in the deduced densities here are about a factor of two smaller than the previously reported result,[5] thus indicating a factor of four better signal-to-noise ratio. This improvement is due in part to the higher laser energy (about a factor of two) and to a higher throughput (another factor of two). The use of interference filters to separate Raman signals has several advantages over a conventional monochromator. First of all, a higher throughput (visible wavelength) and thus more signal can be obtained. Secondly, by using a lens system with a flat field of view, imaging of the Raman signal onto a linear detector may become possible and thus render spatial information. Finally, the alignment of the filter optics can be accomplished easier and faster. From the above discussion, it is clear that, within the uncertainty of our measurements, good agreements between the expected and deduced temperatures and densities were obtained.

To obtain the Rayleigh images, the signal reflected by the dichroic mirror was processed by a slit, the L4 lens system (magnification of four), and a single-intensified CCD camera. The line image thus obtained, was digitized using a frame grabber and was stored in the computer. With the improvements made in this setup, a background-free detection of the Rayleigh signal has become possible. As before,[5] to minimize the uncertainties associated with the photon-flux, solid angle of collection, volume of interaction, and differences in the quantum efficiency and the gain between different pixels in the camera, a calibration procedure was performed by pumping the tunnel down to known static pressures and acquiring data at each level. Figure 5 shows a plot of the Rayleigh signal for a pixel as a function of the static pressure in the tunnel. Each data point represents an average of 100 laser shots with an statistical uncertainty (standard deviation of the mean value) depicted as the size of the points. It is seen from this plot that the data follow a linear dependence with a slope and an intercept which are posted in the figure. The deduced intercept of zero in this figure indicates that the spatial aperture used in this experiment provided us with a background-free detection of the Rayleigh signal. This procedure was used to calibrate a row of pixels in the camera, where the slopes and the intercepts with their corresponding uncertainties were determined and used to convert the observed Rayleigh signal levels to density. To see how well this calibration procedure works, Fig. 6 presents a plot of the deduced pressures for a row of pixels as a function of the pixel number or position. In this figure, the static pressure in the tunnel was adjusted to 17.47 kPa and each data point represents an average of 100 laser shots. The uncertainties associated with the deduced pressures appear as a band around the data. This uncertainty, which is about 1.5% of the mean value, is obtained by calculating the standard deviation of the mean value for 100 laser shots and it includes the uncertainty in the calibration (slope and intercept). In this figure, the line is drawn to intercept the ordinate at an average value of 17.47 kPa which was obtained by considering all the pixels plotted here. The excellent agreement between the deduced and the expected pressures indicates that this calibration procedure works well and it successfully removes all the uncertainties discussed above. One should also add that, in these experiments, the Rayleigh data were obtained with higher spatial resolution at no expense to the signal level. This stems from the fact that the lens systems used in these experiments are all matched in étendue and they provide larger solid angle of collection than the previous setup.[5] The effective spatial resolution obtained in this setup was about 0.3 mm in the plane of observation. Each pixel shown in Fig. 6, represents .06 mm in the object plane, thus we have a resolution of 5 pixels.

In supersonic or hypersonic facilities, it is well known that as a gas expands into the test section, one or more of its constituents may condense and form clusters. The Rayleigh signal generated by these clusters is much higher than the signal level expected for molecular scattering. Since in Rayleigh scattering experiments with low spectral resolution, it is not possible to distinguish between these two signals, the Rayleigh signal generated by clusters interferes with the Rayleigh signal generated by gas molecules thus making the interpretation of the results difficult. In a previous publication,[5] it was shown that the Rayleigh signal generated by clusters strongly depends on the local conditions of the flow, namely, pressure and temperature. The purpose of these Rayleigh measurements was to extend the previous investigations of the pressure and the temperature dependence of this signal. To do this, measurements were performed both in the free stream as well as behind a shock wave where higher pressures and temperatures are achieved. We first conducted the measurements in the free stream to obtain simultaneously the vibrational and rotational Raman data. These measurements showed a flat signal level similar to Fig. 6 and no systematic behavior beyond the statistical uncertainty of the measurement was ever observed. Later, we placed a wedged model at an angle of 10^{o} with respect to the flow (Fig. 7). In this setup, the laser beam was placed behind the model and, as in the free stream case, it traversed a hole in the floor of the test section. No increase in the background was detected as a result of this arrangement. The oblique shock wave generated by the model was probed by our Rayleigh setup in such a way to simultaneously obtain data both in the free stream and behind the shock.

Figure 8 shows the Rayleigh signal levels in the free stream and behind the shock as a function of the pixel number or position. This figure is obtained for a stagnation pressure of 0.86 MPa and a stagnation temperature of 555 K, a condition where scattering is due to only air molecules. Each data point represents an average of 100 laser shots. The band represents the statistical uncertainty of the data. From this figure, the presence of the shock wave is apparent and the signal behind the shock shows a slight decrease in level as the distance from the shock wave is increased. The ratio of the signal levels immediately behind the shock to those in the free stream agrees well with the expected ratio of 2.36 obtained for a shock wave generated by a 10^{o} wedge placed in a free stream with a Mach number of 5.94. This also demonstrates that, the Rayleigh scattering technique is very useful for determining the position of the shock wave. Similar results were obtained in the presence of clusters.

To understand how the Rayleigh signal due to clusters behaves in the free stream and behind the shock, the pressure and the temperature dependence of this signal was studied. Fig. 9 shows a logarithmic plot of the Rayleigh signal obtained in the free stream (no model) as a function of the stagnation pressure, P_t, and at constant stagnation temperatures, T_t. In Fig. 9(a), the stagnation temperature is 505 K and the line is drawn to have a slope of 3. As it is seen here, the Rayleigh signal levels show a cubic dependence on the stagnation pressure when the stagnation temperature is less than or equal to 505 K. We have confirmed this by obtaining similar plots at lower stagnation temperatures. This observation also agrees with the previously reported results.[5] As one increases the stagnation temperature to a higher value, namely, 533 K in Fig. 9(b) and 561 K in Fig. 9(c), a different behavior is observed. It is seen in Fig. 9(b) that the data can be fit to two slopes: a slope of three and a slope of one as is depicted. It is also seen that for the same adjusted stagnation pressure, there exists a considerable scatter in the data--some exhibit linear and some cubic dependence. This scatter is beyond the measurement uncertainty and is due to the reproducibility of the conditions of the tunnel for different runs. This stagnation temperature is at a level, where slight changes in the initial conditions, could either favor or inhibit the formation of clusters. In Fig 9(c), a range of stagnation pressures from 0.69 to 1.38 MPa at a stagnation temperature of 561 K is shown. It is seen from this figure that the data exhibit a linear dependence on the stagnation pressure (except possibly at the highest pressure) which is the expected behavior for molecular scattering.

We reversed the process by keeping the stagnation pressure constant and varying the stagnation temperature. Fig. 10 shows a plot of the Rayleigh signal in the free stream as a function of the inverse of the static temperature as computed from the isentropic expansion in the tunnel. In this plot we have also included the freestream data obtained in the model flow field to show the extent of the scatter in the data. The best fit to the data is plotted here as the dashed curves. Fig. 11 depicts the same graph for only two stagnation pressures (0.69 and 1.21 MPa) with the difference that, the data in the free stream and the data obtained immediately behind the shock are those obtained for the model flow field only. For the sake of comparison, in both figures, the expected Rayleigh signal as computed from the isentropic expansion is shown as a solid line for both conditions, namely, in the free stream and behind the shock. In Fig. 11, the signal level behind the shock tracks the signal level in the free stream, i. e., a higher signal in the free stream results in a larger signal behind the shock even for the same temperature. From Figs. 10 and 11, it is clear that as the stagnation temperature is increased, data approach the molecular scattering signal levels. The above results confirm all the previously[5] observed behavior in the free stream with the additional information obtained behind the shock.

To study the behavior of clusters as they encounter a shock wave, we have compared the cluster component of the Rayleigh signal in the free stream and immediately behind the shock. Let us denote the total Rayleigh signals immediately behind the shock by S_S and those in the free stream by S_F, and the computed Rayleigh signals expected for molecular scattering for each case by S_{SM} and S_{FM}, respectively. Then, the difference between the observed and the expected signal levels is the cluster contribution to the signal. In Fig. 12, we have plotted this contribution for the data behind the shock as a function of the data in the free stream. The data covers a range of stagnation pressures from 0.34 to 1.21 MPa, and a range of stagnation temperatures from 383 to 561 K. It is seen that the data can be fit by a line which intercepts both axes at zero and exhibits a slope of 1.42 ± 0.03. In other words, the ratio of the cluster component of the signal behind the shock to that in the free stream is a constant independent of stagnation pressure and temperature. This is a surprising result since we have demonstrated that in the free stream the cluster signal is strongly dependent on these thermodynamic parameters.

An argument to explain this might go as follows: let us assume that near the shock boundary the shock wave simply "refracts" the clusters and that their size distribution remains constant across the shock wave. These assumptions simply reflect the concept that near the shock boundary, the clusters may not have time to fully respond to the local thermodynamic parameters. Now, if the clusters were "refracted" along the same stream lines as the gas molecules (10 degrees with respect to the free stream), the slope in Fig. 12 should equal the gas density ratio across the shock, namely 2.36. On the other hand, if the clusters simply passed through the shock boundary without any deflection, the slope should have been equal to one (since there is no change in the cluster component). So, the measured slope of 1.42 suggests a "refraction" which is less than the gas. In fact, a deflection of 5.2^o with respect to the free stream, in combination with the above assumptions, would generate Fig. 12.

CONCLUSIONS

In this paper, we have demonstrated an instrument utilizing a pulsed laser which is capable of measuring rotational temperature, concentration of oxygen and nitrogen molecules, and one dimensional Rayleigh images. Preliminary data obtained with this system indicates that quantitative measurements with negligible background level is possible. Temperature and density results obtained using Raman spectroscopy agreed with the expected free stream values in the tunnel within the uncertainty of the measurements. This indicates that cluster formation has no noticeable effect on the bulk properties of the flow. We also extended the previous study of pressure and temperature dependence of the Rayleigh signal (due to clusters) by performing the measurements at higher temperatures and in a model flow field. These studies indicate that, in the absence of clusters, it is possible to obtain quantitative measurements of the total density using the Rayleigh scattering technique both in the free stream and in a model flow field.

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REFERENCES

1. J. V. Beck and K. J. Arnold, "Parameter Estimation in Engineering and Science", John Willey & Sons, New York, 1977, pp. 213-219.

2. W. K. Bischel and G. Black, "Wavelength Dependence of Raman Scattering Cross Section from 200-600 NM", in AIP Conference proceedings, No. 100, Subseries on Optical Sciences and Engineering, No. 3, Excimer Lasers-1983, edited by C. K. Rhodes, H. Esser, and H. Pummer (AIP, New York, 1983).

3. G. D. Stein, "Angular and Wavelength Dependence of the Light Scattered from a Cloud of Particles Formed by Homogeneous Nucleation", J. Chem. Phys. 51, 938(1969).

4. P. P. Wegener, "Nucleation of Nitrogen: Experiment and Theory", J. Chem. Phys. 91, 2479(1987).

5. B. Shirinzadeh, M. E. Hillard, R. J. Exton, "Condensation Effects on Rayleigh Scattering Measurements in a Supersonic Wind Tunnel", AIAA Journal 29, 242(1991).

6. R. S. Barlow, R. W. Dibble, and R. P. Lucht, "Simultaneous Measurements of Raman Scattering and Laser-Induced OH Fluorescence in Nonpremixed Turbulent Jet Flames", Opt. Lett. 14, 263(1989).

7. C. M. Penney, R. L. St. Peters, and M. Lapp, "Absolute Rotational Raman Cross Sections for N_2, O_2, and CO_2", J. Opt. Soc. Amer. 64, 712(1974).

FIGURE CAPTION

Fig. 1. Schematic diagram of the experiment.

Fig. 2. Comparison between deduced and expected temperatures.

Fig. 3. Comparison between deduced density from Raman scattering of N_2 and expected air density.

Fig. 4. Comparison between deduced density from Raman scattering of O_2 and expected air density.

Fig. 5. Plot of the Rayleigh signal as a function of the static pressure in the tunnel for a single pixel in the camera.

Fig. 6. Plot of the deduced pressure as a function of the pixel number or position.

Fig. 7. Illustration of the model and the laser beam.

Fig. 8. Plot of the Rayleigh signal in the model flow field as a function of pixel number or position.

Fig. 9. Rayleigh signal vs stagnation pressure at three stagnation temperatures.

Fig. 10. Rayleigh signal as a function of the inverse of the static temperature.

Fig. 11. Comparison of the Rayleigh signals in the free stream and immediately behind the shock for two stagnation pressures.

Fig. 12. Plot of the cluster contribution to the Rayleigh signal immediately behind the shock as a function of those in the free stream.