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RAYLEIGH-BRILLOUIN SCATTERING FOR HIGH-PRESSURE GAS TEMPERATURE MEASUREMENTS

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The spectrum of laser light scattered by density fluctuations in a gas is a function of the molecular velocity distribution function. The distribution function is characterized by the macroscopic gas parameters, including temperature. For low density gases, where the molecular mean-free-path l_{mfp} is much longer than the wavelength λ_s involved in the scattering, the molecular motions are uncorrelated, and the spectrum of the scattered light is Gaussian for a gas with a Maxwellian velocity distribution. (The ratio λ_s/l_{mfp} is usually given the symbol y; so, by low density, we mean $y<<1$). The width of the spectrum for low density gases is thus proportional to the square root of the ratio of the gas temperature to the molecular weight. If we know the molecular weight of the gas, we can use the width of the spectrum as a measure of gas temperature. An example of the application of Rayleigh scattering in this regime is given in reference 1.

On the other hand, for high density gases ($y>>1$), the molecular motions are correlated and the spectrum of the scattered light consists of 3 parts - a central peak at the laser wavelength and 2 side peaks. The side peaks can be thought of as arising from scattering of laser light from random thermally excited acoustic waves in the gas. This is usually referred to as Brillouin or Rayleigh-Brillouin scattering[2]. For this high density situation, the frequency shift of the Brillouin peaks relative to the laser frequency is proportional to the speed of sound in the gas. Because the speed of sound is proportional to the square root of the gas temperature, the position of the Brillouin peaks provides a measure of gas temperature.

The spectrum of Brillouin scattering in high density gases ($y>>1$) can be calculated using a relatively simple continuum (hydrodynamic) theory[3]. In this theory, the spectrum is a function of two non-dimensional parameters. The first parameter is a non-dimensional frequency, $x=2\pi f/aK$ where f is the frequency shift from the laser frequency, $a=(2\kappa T/m)^{1/2}$ is the "most probable" molecular velocity, and $K=(2\pi/\lambda_s)=(4\pi/\lambda)\sin(\theta_s/2)$, with θ_s being the scattering angle. The other parameter is y (same parameter as discussed above), which can be written as a function of the pressure and shear viscosity of the gas as $y=p/\mu Ka$. The frequency shift corresponding to the Brillouin peaks is only a weak function of y for high pressure gases; for nitrogen it occurs at $x=x_p=(\gamma/2)^{1/2}=0.837$. Measurement of the frequency shift of this peak from the laser frequency allows us to determine the gas temperature.

An experiment has been set up to evaluate the feasibility of using Rayleigh-Brillouin scattering as a diagnostic technique for measuring gas temperature in high pressure environments, such as the SSME preburner. A high-pressure furnace (rated for 3000 psia at 1300 K) is used as the scattering chamber. Either nitrogen or hydrogen may be used. An argon-ion laser beam ($\lambda=514.5$ nm, 1W) is focused into the furnace. Light backscattered from the gas in the furnace is collected and analyzed with a 5-pass scanning Fabry-Perot interferometer[4] and photon counting electronics. The multi-pass configuration provides the high frequency selectively needed to measure the Brillouin peaks in the presence of large amounts of spuriously scattered light at the laser frequency.

Preliminary measurements have been made at room temperature in nitrogen at pressures up to 2000 psia. The free spectral range of the interferometer and frequency separation of the Brillouin peaks are determined from measured spectra. Temperature measurements are then obtained using the simple continuum theory with low frequency values of specific heat ratio and shear viscosity. The measured temperatures are within 10% of the true value. It is anticipated that the accuracy will be significantly better if a more refined theory[5,6] is used.

At high temperatures, large thermal gradient occurs in the transition region between the high temperature at the center of the furnace and the cooler parts near the windows. The gradients cause severe beam distortion and prevent focusing of the beam. To eliminate this problem, sapphire cylinders (110 mm long x 12 mm dia.) will be placed in the furnace adjacent to the windows. This will provide an optical path to the hot zone with much less distortion. Tests are planned for both nitrogen and hydrogen.

REFERENCES

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RAYLEIGH-BRILLOUIN SCATTERING

$$P_s(f)\,df\,d\Omega = I_o\, n\, V_{sc} \left(\frac{d\sigma}{d\Omega}\right) \sin^2\chi\; S(f)\,df\,d\Omega$$

I_o = irradiance of incident beam
n = molecular number density
V_{sc} = scatteringvolume
χ = polarization direction
$\left(\frac{d\sigma}{d\Omega}\right)$ = Rayleigh scattering cross section
$S(f)$ = normalized spectrum of scattered light

RAYLEIGH SCATTERING NOMENCLATURE

$$\boldsymbol{K} = \boldsymbol{k}_s - \boldsymbol{k}_o$$

$$K = |\boldsymbol{K}| = \frac{4\pi}{\lambda}\sin\frac{\theta_s}{2}$$

$$a = \sqrt{\frac{2\kappa T}{m}}$$

NONDIMENSIONAL PARAMETERS

$$x = \frac{2\pi f}{aK}$$

$$y = \frac{p}{\mu K a}$$

μ = shear viscosity

EXAMPLE OF NITROGEN AT 1000 psia

Mirror spacing d = 21.8 mm

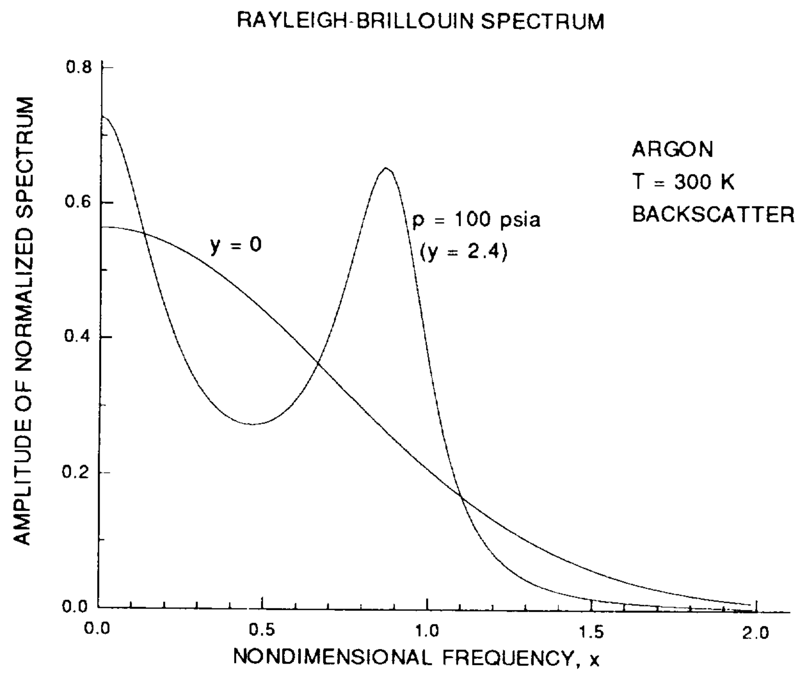
Free Spectral Range FSR = 6.88 GHz

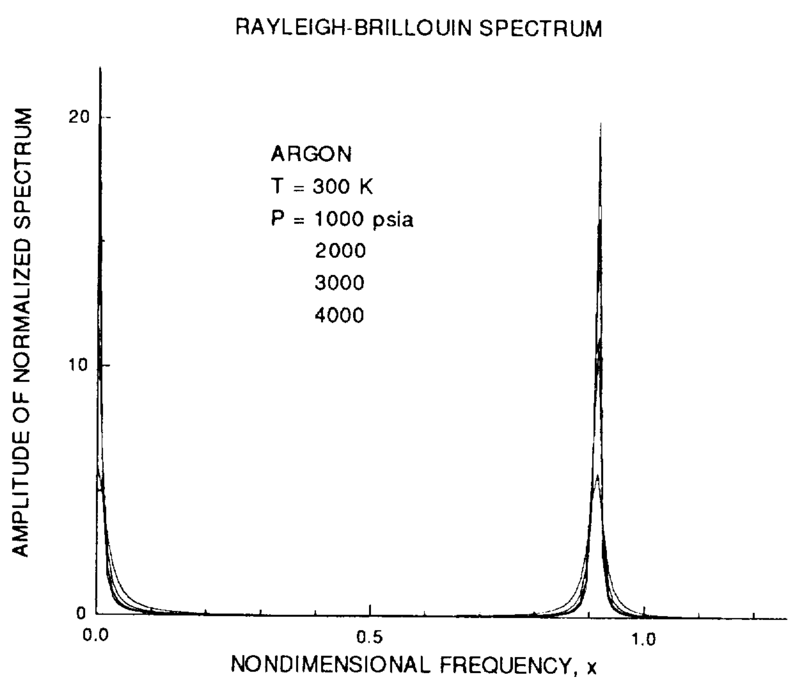
$x_p = (\gamma/2)^{1/2} = 0.837$

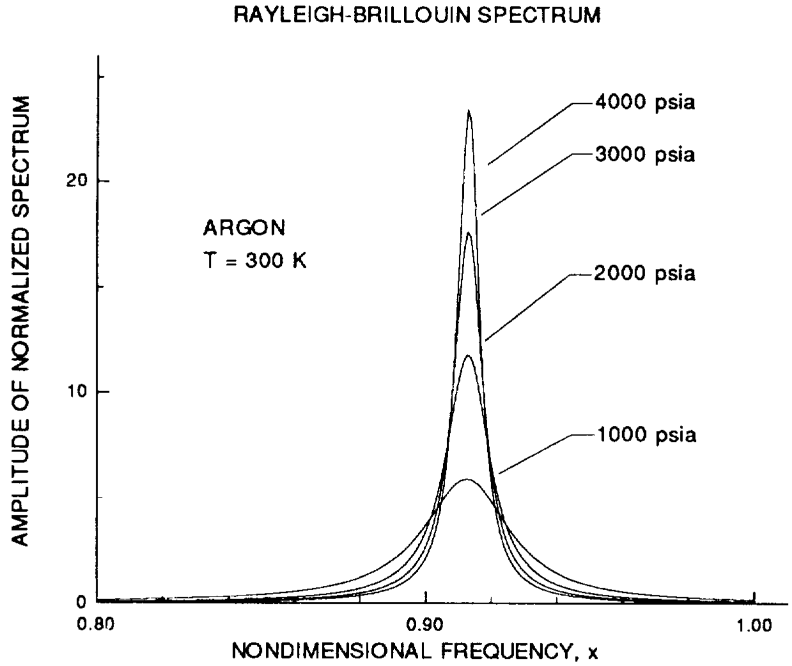
$K = 2.44 \times 10^7\ m^{-1}$

a = 399 m/sec

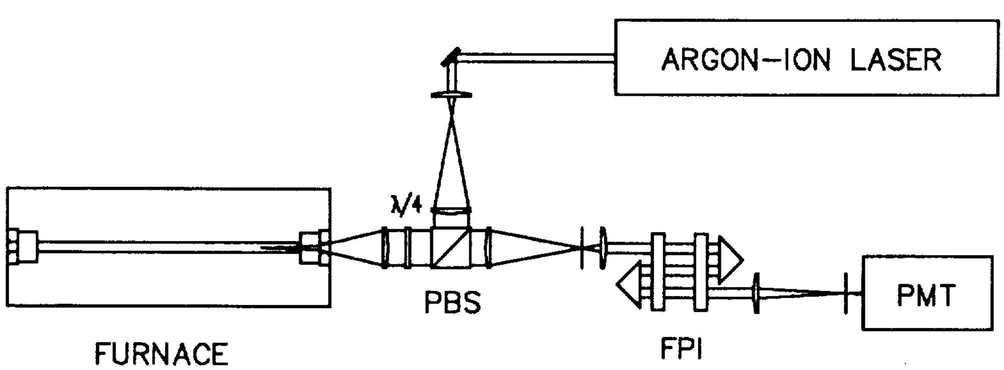
T = 317 K

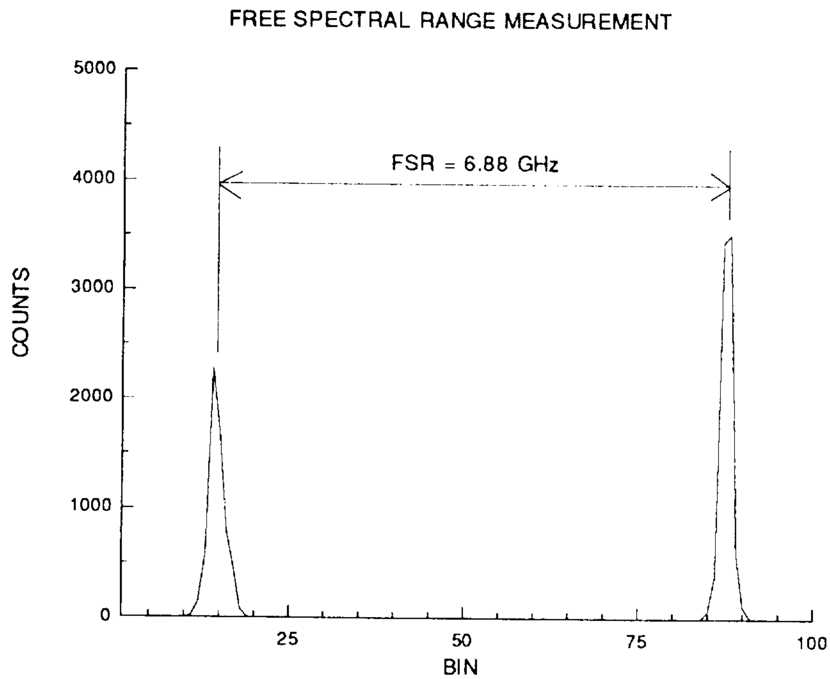

RAYLEIGH-BRILLOUIN SPECTRUM
AMPLITUDE OF NORMALIZED SPECTRUM
0.8
0.6
0.4
0.2
0.0
ARGON
T = 300 K
BACKSCATTER
p = 100 psia
(y = 2.4)
y = 0
0.0
0.5
1.0
1.5
2.0
NONDIMENSIONAL FREQUENCY, x

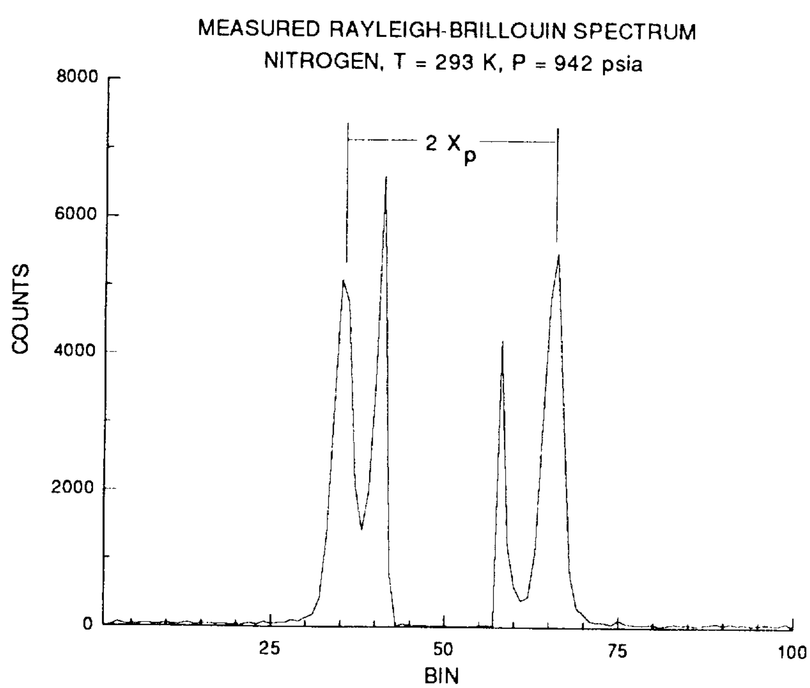

RAYLEIGH-BRILLOUIN SPECTRUM
AMPLITUDE OF NORMALIZED SPECTRUM
20
10
0
ARGON
T = 300 K
P = 1000 psia
2000
3000
4000
0.0
0.5
1.0
NONDIMENSIONAL FREQUENCY, x



RAYLEIGH–BRILLOUIN SCATTERING DIAGNOSTIC FOR HIGH PRESSURE FURNACE




FREE SPECTRAL RANGE MEASUREMENT
FSR = 6.88 GHz
COUNTS
5000
4000
3000
2000
1000
0
25
50
75
100
BIN


MEASURED RAYLEIGH-BRILLOUIN SPECTRUM
NITROGEN, T = 293 K, P = 942 psia
2 X_p
COUNTS
8000
6000
4000
2000
0
25
50
75
100
BIN