Journal of the Arkansas Academy of Science

Volume 45 Article 33

1991

Radiometer for the Investigation of Infrared Emissions from Flames and Rocket Plumes

Kathy Underhill
University of Arkansas at Little Rock

M. Keith Hudson
University of Arkansas at Little Rock

Jason Willis
University of Arkansas at Little Rock

Mokhtar Mofidi
University of Arkansas at Little Rock

Matthew J. Russo

Recommended Citation

Underhill, Kathy; Hudson, M. Keith; Willis, Jason; Mofidi, Mokhtar; and Russo, Matthew J. (1991) "Radiometer for the Investigation of Infrared Emissions from Flames and Rocket Plumes," *Journal of the Arkansas Academy of Science*: Vol. 45 , Article 33.
Available at: http://scholarworks.uark.edu/jaas/vol45/iss1/33

A RADIOMETER FOR THE INVESTIGATION OF INFRARED EMISSIONS FROM FLAMES AND ROCKET PLUMES

KATHY UNDERHILL, M. KEITH HUDSON,
JASON WILLIS, and MOKHTAR MOFIDI
Department of Electronics and Instrumentation
University of Arkansas at Little Rock
Little Rock, AR 72204

MATTHEW J. RUSSO
Hercules Aerospace
1101 Johnson Avenue
McGregor, TX 76657

ABSTRACT

A prototypical radiometer using standard one inch interference filters and a lead selenide detector was constructed for use in flame and rocket plume studies. This radiometer was designed to employ a 600 Hz chopper and chopper frequency/phase reference circuit for signal processing. Bandpass filters centered for either 2.7 µm or 4.45 µm were placed in the optical path. The passed carbon dioxide or water vapor band energy irradiated the lead selenide detector, resulting in an output voltage. This signal was then fed into a dedicated synchronous detector. The signal was then recorded by a computer system equipped with an analog-to-digital converter board. Infrared emission data was collected from two inch rocket motors and from a special burner based flame.

INTRODUCTION

Since the end of World War II, emissions from hot gases have been of major importance in scientific study. Early interest was in the area of missile guidance. Typically, model systems were used to simulate emissions found in jet exhaust (Plyler, 1948). However, in more recent times, investigations have been undertaken on infrared emissions from rocket plumes (Ambruso and Slack, 1983). The spectral area of most interest was the 1 to 5 µm region. This area is very important because of the large water band centered at 2.7 µm and the intense carbon dioxide band at 4.4 µm. Fig. 1 shows the spectra for a hydrogen/air and an acetylene/air flame, demonstrating that the 4.4 µm band is absent in the H_2/Air flame and that it is intense in the C_2H_2/Air flame.

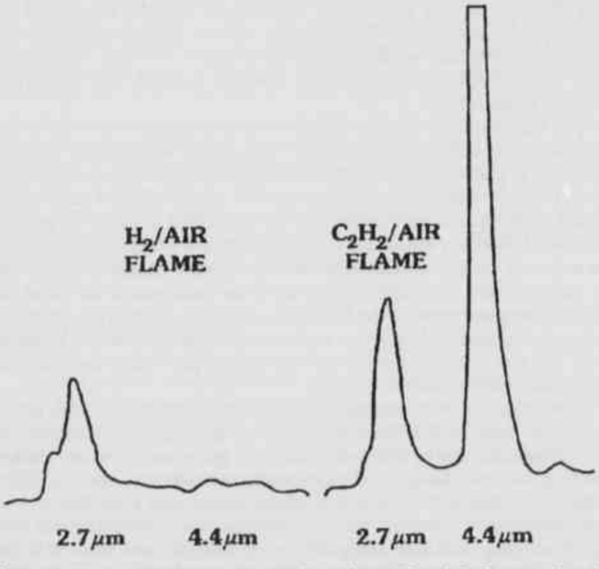

Figure 1. IR spectra for hydrogen/air and acetylene/air flames showing the 2.7 and 4.4 gaseous emission bands.

Existing systems which can be used for this application require very sophisticated equipment, including Fourier Transform Infrared (FTIR) instruments and imaging systems. Albrechcinski and Wurster (1979) reported rapid scanning instrumentation for both spatial and spectral measurements in rocket plumes. Spatial scanners were set atop a chamber, and were used to map the infrared region from 1 to 5.5 µm. The spatial scanners used indium antimonide detectors arranged in a six element array. These detectors had to be liquid nitrogen cooled. Four arrays were set up so there were 24 channels of information. The unit employed a spun grating monochromator for fast scanning. In order to detect the 4 to 10 µm band, a mercury cadmium telluride detector was used.

Scott *et al.*, (1978) and Ridout and Webb (1980) both used an infrared imaging system for spatial plume scanning. This system employed an indium antimonide detector (liquid cooled), and a raster scanning prism system. The raster encoded signal could be displayed on a monitor, or be recorded on video tape. Scott *et al.* (1978) also used a commercial Fourier Transform Infrared Spectrometer for wavelength scanning.

Most existing systems are calibrated for temperatures below 1000°C, however, most rocket plumes are at temperatures greater than 3000°C. A general problem with imaging systems is that they give no spectral information. At this time there is no economical means of monitoring the IR emissions from plumes. This is especially true when dealing with new propellant formulations or new rocket designs and configurations, which are prone to catastrophic failure and can damage or destroy expensive equipment. Also, as tactical weapon systems become more sophisticated, spectral information for rocket motors and propellants becomes increasingly more important to those using them on and above the battlefield. The instrument we will describe is very simple and inexpensive compared to existing systems and provides useful spectral information. It can be used to characterize various rocket propellants and allow more insight into propellant combustion phenomena.

EXPERIMENTAL

The computer equipment used in our experiments included a Metrabyte DAS-20 analog-to-digital converter board installed in a COMPAQ 286 portable computer. The electronics-IR detector system was constructed based on designs first used by Hudson and Busch (1987, 1988), and later modified by Hudson *et al.* (1990). The radiometer used a lead selenide (PbSe) photoconductive cell as the sensing element (Hamamatsu P791-01). The sensitive area was arranged in a 1X3 mm slit shape. The radiometer employed a 600 Hz chopper motor and chopper frequency/phase reference circuit, one inch diameter Optical Coating Laboratories narrow bandpass filters, with the bandpass centered for either 2.7 µm or 4.45 µm, an aperture for field-of-view limitation, a preamplifier circuit, and a dedicated synchronous detector of our own design (Mofidi, *et al.*, 1991). The radiometer was mounted on a rigid metal base which serves as an optical rail. This enabled the accurate aiming of the overall system. Fig. 2 shows the experimental arrangement for the filter radiometer.

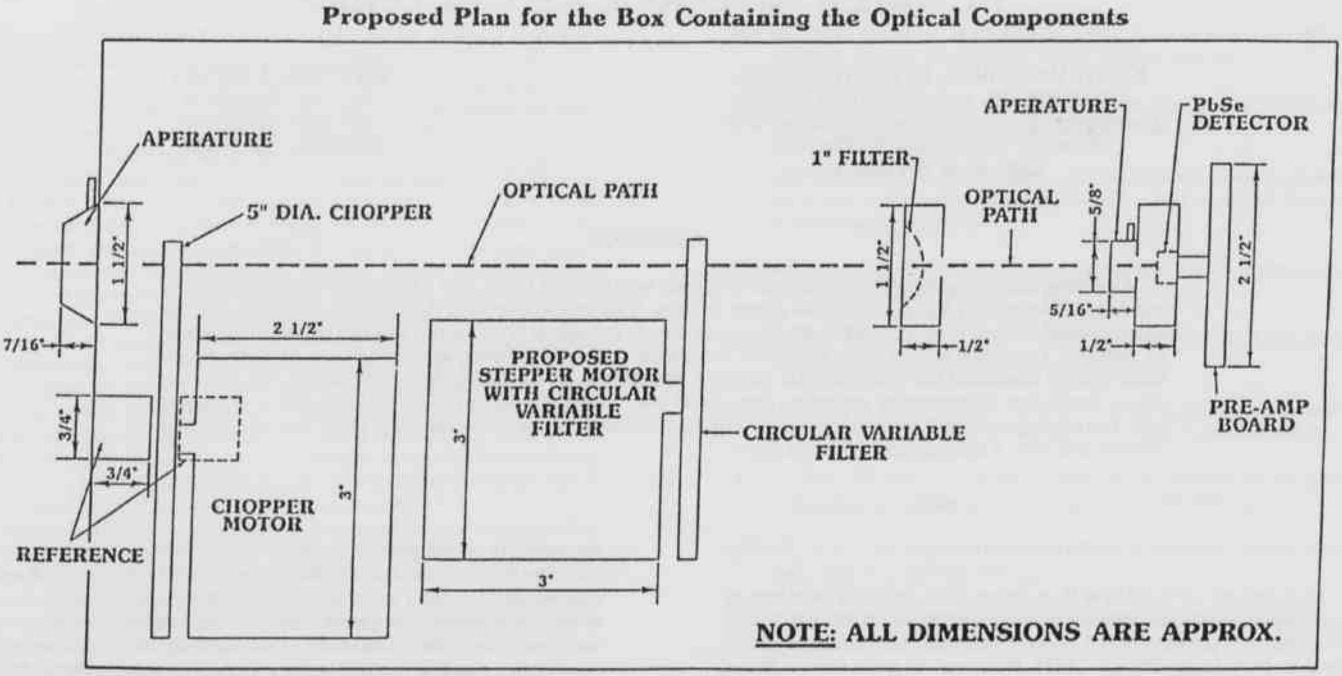

Figure 2. Dimensioned drawing of the IR radiometer, including proposed circularly variable filter placement.

The building where the rocket test motors were fired was approximately 100 ft. from the control bunker. The motors were mounted in a steel cradle, parallel to the ground, and connected to ignition cables stretched from the bunker for computer controlled firing. An approximately 36 volt pulse was sent from a control board in the bunker to the rocket motor to start the ignition process. This same pulse was used to trigger the analog-to-digital board to begin sampling data. The data were stored in a voltage vs. time (in seconds) format. Data were also obtained simultaneously from a pressure transducer on the rocket motor. All of the data were then saved to disk. Data were collected for several rocket propellants including: a "low smoke" formula, a high specific impulse formula, and an experimental formula. The experimental formulation was the subject of 15 experimental trials.

A Perkin-Elmer atomic absorption burner was modified to allow the introduction of organic compounds via its nebulizer, into an acetylene/air based flame (other fuels may be used such as hydrogen/air). Flame fuel and oxidant were controlled using Cole-Parmer flow meters with integral flow valves. The burner system was used to ascertain the response of the radiometer to specific functional groups and also to solutions of inorganic compounds.

RESULTS AND DISCUSSION

RADIOMETER DESIGN AND PERFORMANCE

The purpose for building this prototype radiometer was to show the feasibility of using a lead selenide detector, in conjunction with relatively simple electronic circuits, to inexpensively detect spectral emissions from flames and plumes. The PbSe IR detector has several advantages for detection of the 1.5 to 5.5 µm region, when compared to other IR detectors. A PbSe detector is a photoconductive cell, which works on the basis of the photoelectric effect. As the cell is irradiated, electrons are promoted from the valence band to the conduction band. This increase in charge carries is sensed as a voltage difference across the cell, when a constant bias voltage is applied across the cell through a fixed resistor in series with it. The PbSe detector can be used at room temperature with high sensitivity. This eliminates the need for expensive and bulky cooling methods. The detector is housed in a standard TO-5 transistor case, and was readily installed in the radiometer system. The radiation is chopped via mechanical chopper (600 Hz), so the resulting voltage is detected using AC circuits, and a dedicated synchronous detector substituted for the usual lock-in-amplifier. The chopping rate was chosen to be above the flicker noise threshold of the PbSe detector (about 500 Hz). The system could be operated in the DC mode, however, stability and sensitivity would be compromised.

One inch narrow bandpass filters were used because of ready availability and ease of replacement. Center frequencies were chosen to match as closely as possible the gas emission band maximums for carbon dioxide and water vapor at plume temperatures. Bandwidths at both wavelengths were chosen as narrow as were available in order to achieve maximum blackbody emissions rejection. Particles from the solid propellant materials emit a continuum spectrum, normally of less intensity than the gaseous band emissions. However, if the bandpass is too large the PbSe will respond more to the blackbody emission, since it integrates the total signal incident on its active surface. A 2.7 µm filter with a bandpass of 0.2 µm was used for water vapor and a 4.45 µm with a bandwidth of 0.5 µm was used for carbon dioxide.

Two problems were encountered with the use of the one inch filters. To change bands, the radiometer had to be disassembled, therefore the radiometer could not be scanned to record a spectrum. To allow spectral scanning and the changing of wavelengths without disassembly, future systems will replace the one inch bandpass filters with a circular variable filter. These filters are constructed in a circular shape, with different coatings of varying thickness along the curve. The effect is somewhat like that of a filter wedge, except that wavelength is varied linearly with angular displacement. These filters will be placed in a circular mount turned by a computer controlled stepper motor. This arrangement will give a great deal more versatility to the radiometer.

Apertures to limit field-of-view were used at the entrance to the radiometer and directly in front of the PbSe detector. Due to the slit shape of the PbSe active area and because of the placement of the rear aperture, it was expected that its use would change the shape of the viewed solid angle of the plume of flame. The smallest opening was about 1.2 mm in diameter. Considering the 1X3 mm detector area, this would allow a circular image to be viewed. Opening the aperture would allow the entire 1X3 area to view the plume, and would correspond to a rough oval image, giving about a 3x increase in signal level. The front aperture would modify the size of the image, or viewed area. This aperture could vary in opening diameter between about 1.2 and 6 mm, allowing a large effect on viewed solid angle, and therefore, available light. It was found during the experimental trials that the front aperture did have a great effect, seen as apparent changes in orders of magnitude of signal level. With the high intensities from the rocket plumes, this aperture was set at about 2 mm. This allowed the use of most of the electronic circuit's dynamic range. The rear aperture was set at 3 mm, giving an oval viewed field.

The electronic circuits used in the radiometer were designed to be rugged, small, and offer good performance as an overall package. The circuit board was mounted to the side of the optical bench, near the PbSe device. This enabled short leads to be used in connections to the detector, minimizing noise pick-up. The circuit included a signal pre-amplifier, chopper reference comparator, and a synchronous detector. This circuit replaced a lock-in-amplifier, giving a radiometer package that was truly portable. Operation of the circuitry gave sufficient sensitivity for the moderate to high intensity emissions viewed by the radiometer, while allowing sufficient dynamic range for all rocket firing after initial settings were made. All of the experimental trials were run with a time constant of 250 milliseconds (msec) hardwired on the circuit board. A shorter time constant would have revealed more plume intensity detail. This fact was not apparent until rocket motor data was taken using the radiometer in conjunction with the existing pressure system. Analysis of pressure data indicates changes occurring on a time scale closer to 10 msec. Future studies will characterize an optimum time constant. This circuitry is described in more detail in another submission to this Journal (Mofidi, *et al.*, 1991).

FLAME COMBUSTION STUDIES

The atomic absorption burner was used to initially test the radiometer and assess its performance. Burner studies were done with a front aperture diameter of about 5 mm. The acetylene/air flame was adjusted to give fuel rich, stoichiometric, and lean flames. The emission from the burner was monitored using each filter, allowing a comparison of the water and carbon dioxide bands. Also, organic compounds containing various functional groups were aspirated into the flame for combustion. The relative contribution of functionality to the emission in each band was noted. In addition, several aqueous solutions of metals were aspirated, at levels from 250 to 1000 ppm. These metals had no effect on IR signal, under these conditions. Metals are commonly used to modify rocket plume signatures and propellant burn rates. Effects of organic groups and metals will be investigated further.

ROCKET PLUME STUDIES

The radiometer was positioned with the entrance aperture located 18 inches from the plume. For this preliminary set of experiments, the radiometer was mounted on a wooden box under the plume and "looked" up into the plume. Concerns that particles or burning pieces of insulation might fall into the radiometer were unfounded. Evidently, the combination of high burn velocity and temperature caused any particulate matter to be ejected forcefully out of the test stand. The radiometer location was varied from two to approximately 30 inches from the rocket nozzle, in order to view different portions of the plume. The curves generated were very similar, with a decrease in IR intensity seen as the unit moved further from the rocket nozzle. It was expected that the 4.4 µm, CO_2 signal would have gone through a maxima as the distance to the nozzle was increased, due to afterburning with atmospheric oxygen. It is possible that this was not observed because of the aperture size and image resolution employed, or because of the formulation of the propellant mixtures used. This effect will be more thoroughly studied in future work.

Several pressure vs. IR plots were made and analyzed. These plots illustrate that the IR emissions at 4.4 µm generally agree with the internal pressure data. As the pressure rises, the thrust increases, and the overall burn time decreases. Figs. 3-5 generally show this behavior. Note that the

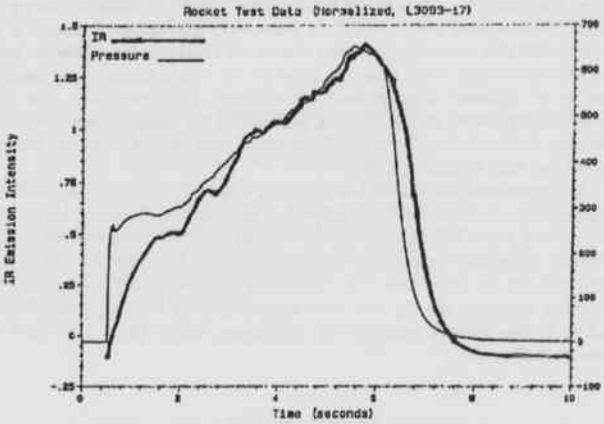

Figure 3. Normalized pressure/IR rocket test data (L3093-17).

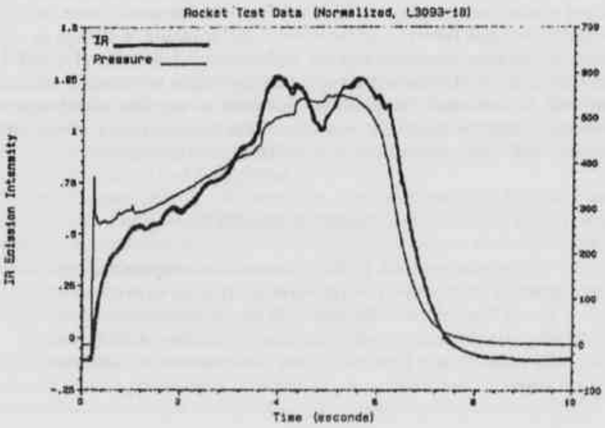

Figure 4. Normalized pressure /IR rocket test data (L3093-18).

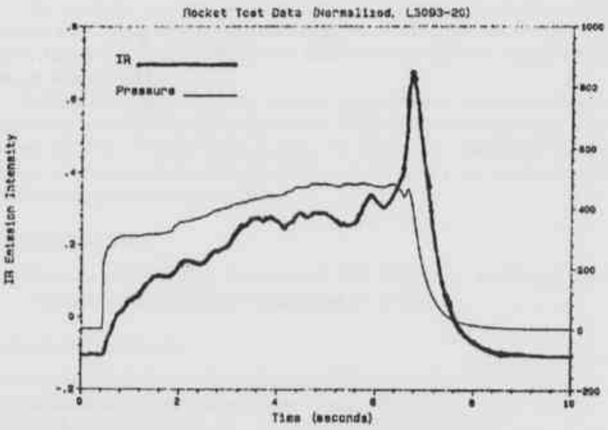

Figure 5. Normalized pressure/IR rocket test data (L3093-20).

pressure rises rapidly at rocket ignition, while the IR data slopes up more slowly. Much of this effect is due to the 250 msec time constant effectively smoothing out differences. This is also seen at burn-out. However, the IR data indicate greater magnitude fluctuations in each figure, especially in Fig. 5. The IR data for Fig. 5 indicates a sharp rise in emission just before burn-out. This was noted by the operators as an audible change in rocket exhaust note pitch, which is somewhat indicative of thrust. It is thought that this anomaly was seen due to the final portion of the propellant casting tearing loose from the front of the rocket motor inner casing, causing an increase in propellant surface area. It is interesting that this effect was indicated in the IR data, and not in the internal pressure data, and may indicate that the propellent piece may have exited the rocket nozzle just after breaking loose.

A comparison was also made between a "smoky" and a clean burning propellant formulation, as currently used in weapons systems, using two trial runs of each. While not entirely conclusive, these runs indicated that a visible difference in particle emissions, or smoke, does not allow the prediction of IR emissions. The evidently defacto industry standard of watching or video taping trial runs cannot predict the "signature" of a rocket. It also cannot quantify the emissions, either IR or UV-Visible, from the motor.

CONCLUSIONS

The authors feel that the radiometer with future improvements will provide an excellent and inexpensive basis for spectral data collection. Future studies will employ changes in the areas discussed above, mainly: circularly variable filters to allow wavelength scanning, a change in electronic circuit time constant, and the collection of data at the 4.4 and 2.7 μm carbon and hydrogen wavelengths during rocket burn. Also, emission data will be collected for particle emissions at another wavelength to investigate the blackbody IR signature. This type data may reveal more about the efficiencies of different propellant formulations.

ACKNOWLEDGMENTS

The authors wish to thank Hercules Aerospace for support of this project. Appreciation is also expressed to David Wankum and Reagan Cole for suggestions on optics and electronics, and to Armand Tomany and Lewis Neidhart of the Electronics and Instrumentation Machine Shop.

LITERATURE CITED

ALBRECHCINSKI, T.M. and W.H. WURSTER. 1979. Rapid scan instrumentation for spectrally and spatially resolved radiance measurements of short duration rocket plumes. ICIASF'79 Record. 57-71.

AMBRUSCO, R. and M. SLACK. 1983. Solid carbon oxidation and radiation in exhaust plumes. 14th JANNAF Plume Technology Meeting, Volume 1. CPIA 384:47.

HUDSON, M.K. and K.W. BUSCH. 1987. Infrared emission from a flame as the basis for chromatographic detection of organic compounds. Anal. Chem. 59:2603-2609.

HUDSON, M.K. and K.W. BUSCH. 1988. Flame infrared emission detector for gas chromatography. Anal. Chem. 60:2110-2115.

HUDSON, M.K., T. FAU, K. UNDERHILL, and S. APPLEQUIST. 1990. A flame infrared emission/flame ionization detector for gas chromatography. J. Chromatogr. 513:21-29.

MOFIDI, M., M.K. HUDSON, R. COLE, and J.D. WILSON. 1991. A simple synchronous detector for spectroscopic studies. Proc. Ark. Acad. Sci. (In press).

PLYLER, E.K. 1948. Infrared radiation from a bunsen flame. J. Res. Nat. Bur. Stand. 40:113.

RIDOUT, J.M. and B.C. WEBB. 1980. Dual waveband infrared scanning radiometer for use with rocket motor plumes. Proc. SPIE 234:32.

SCOTT, H.E., J.G. PIPES, J.A. ROUX, C.S. WELLER, and C.B. OPAL. 1978. Plume radiation measurements in a space simulation chamber. Proc. SPIE. 156:184.