models as Table 1 shows. The final entries in Table 1 show the results obtained using the dynamic programing least-squares filter. Although this filter does not use any second-order partial derivatives, the estimates are quite good for all the models investigated and are comparable to the TMV estimates. Of particular interest are the estimates based on the pure model, since, of the model-filter configurations considered, the combination of pure model and DPLS filter is the easiest to implement.

Finally, it was found that nonlinear measurements provided estimates comparable in quality to the estimates based on linear measurement. Results have been presented of a limited study of the application of linear and nonlinear filters to the problem of estimating the time delay of a simple hereditary system. In the case of the pure model, an iterated Kalman filter avoided the divergence problem. With the Padé approximate models, the Kalman filter convergence appears to improve as the order of the approximation is increased. Both of the investigated nonlinear filters provided good estimates regardless of the model chosen. In particular, the direct application of the simplest nonlinear filter to the original pure form problem resulted in estimates comparable to the estimates based on a more complex model and filter.

References

[1] Ray, W. H. and Soliman, M.A., "The Time Optimal Control of Processes Containing Pure Time Delays," *Proceedings of the 11th Joint Automatic Control Conference of the American Automatic Control Council,* Atlanta, Ga., 1970.

[2] Schiess, J. R., Wells, W. R., and Roland, V. R., "Estimation of Nonlinear Pilot Model Parameters Including Time Delays," *Proceedings of the Second Symposium on Nonlinear Estimation Theory and Its Applications,* San Diego, Calif., Sept. 1971.

[3] Koivo, A. J. and Stoller, R. L., "On Least Squares Estimation in Nonlinear Dynamical Systems With Time Delay," *Proceedings of the 9th Joint Automatic Control Conference of the American Automatic Control Council,* Univ. of Michigan, Ann Arbor, Mich., June 1968.

[4] Kwakernaak, H., "Optimal Filtering in Linear Systems With Time Delays," *IEEE Transactions on Automatic Control,* Vol. AC-12, No. 2, April 1967.

[5] Mehra, R. K., and Tyler, J. S., "Modeling the Human Operator Under Stress Conditions Using System Identification," *Proceedings of the 13th Joint Automatic Control Conference of the American Automatic Control Council,* Stanford Univ., Stanford, Calif., Aug. 1972.

[6] Schwartz, L., and Stear, E. B., "A Computational Comparison of Several Nonlinear Filters," *IEEE Transactions on Automatic Control,* Vol. AC-14, No. 2, April 1968.

Nitrogen Temperature Determination in Arc Tunnel Air Flows

S. S. Lazdinis* and R. F. Carpenter†
Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio

Introduction

An instrument known as the Rotational Temperature Device (RTD), which employs the electron-beam diagnostic technique originated by Muntz,[1] has been constructed at the Air Force Flight Dynamics Lab. It has been used to obtain radial profiles of nitrogen rotational temperatures in an arc tunnel air flow and its results have been compared with standard spectrographic electron-beam measurements. Since the nitrogen rotational temperature and the static translational temperature are in equilibrium for the flows analyzed in this study, the RTD serves as an on-line monitor of the static temperature. A similar instrument was constructed by Muntz and Abel[2] to measure rotational temperatures in short duration, shock tunnel flows. However, the degree of accuracy between their measurements and those obtained using the usual electron-beam technique has never been experimentally determined.

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* Aerospace Engineer, Flight Mechanics Division. Member AIAA.

† Physicist, Flight Mechanics Division.

Rotational Temperature Device

Details concerning the electron-beam method and the optical properties of the instrument have been given in Refs. 3 and 4. Briefly, the device functions in the following manner. Radiation induced by the electron-beam is imaged on its entrance aperture by an external lens, which is placed approximately 7 ft from the beam. The light is then collimated within the instrument and is divided by a partially reflecting beam splitter in the ratio 30/70. Each beam passes through one of two narrow band pass filters which have a nominal centerpass wavelength of 3910 Å and a half-width of approximately 12 Å (the location of the centerpass of each channel is set at the desired wavelength by tipping the filters). The filtered radiation is then chopped by a dual frequency chopper and focused onto a single photomultiplier.

The signals of each channel are separated by two lock-in amplifiers, locked to the two chopping frequencies. A reference signal for the lock-ins is obtained from the same chopping wheel by the use of infrared light emitting diodes and matched photodiodes. The amplifier output is fed into a ratio computer and two strip chart recorders which record the filtered intensity seen by each of the channels and the relative intensity ratio as determined by the ratio computer. The latter device also drives a nonlinear scale voltmeter calibrated to permit observation of the instantaneous value of the static temperature. The time constant of each channel is set at 1 sec to provide a reasonable signal-to-noise ratio. A schematic of the RTD is given in Fig. 1.

The advantage of this system over the instrument developed by Muntz and Abel[2] is the use of a single photomultiplier tube to record the output of both channels. This feature eliminates problems associated with relative phototube drift and the need for prerun and postrun phototube calibrations. The instrument can thus be used to monitor static temperatures on-line and in real time.

To deduce a rotational temperature from the RTD measurements, the behavior of the filtered intensity ratio as a function

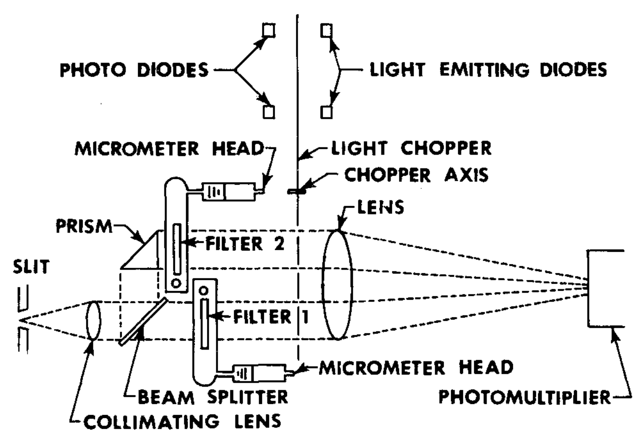

Fig. 1 Schematic of rotational temperature device.

of temperature must be analytically derived. This was accomplished by machine calculating the expected intensities for the first 45 rotational lines of both the P and R branches of the (0, 0) and (1, 1) vibrational bands of the N_2^+ First Negative System. The line intensities thus obtained were multiplied by experimentally determined relative transmission factors for each of the filters and the resulting filtered intensities were then summed and their ratio taken. The inclusion of the (1, 1) band in the calculations, dictated by the wide band pass of the filters, made the intensity ratios slightly nitrogen vibrational temperature dependent.

Experimental Procedure

Nitrogen rotational temperature measurements of the flow produced by the 2 Ft Electrogasdynamics Facility (EGF) of the Air Force Flight Dynamics Lab. were made both with the RTD and a 1-m Czerny-Turner spectrograph. The tunnel configuration consisted of a direct current arc-heater and a convergent-divergent nozzle with the flow exiting as a freejet in a pressure controlled test cabin. A $19\frac{1}{2}$ in. exit diameter conical nozzle of 7.5° half-angle was used for all tests. The temperature profiles were obtained 4.0 in. downstream of the nozzle exit, from the nozzle centerline through the higher temperature boundary layer. The position of the optical axis of the RTD with respect to the nozzle centerline was continuously monitored and was allowed to stabilize at each point for at least 10 sec so that the readings would represent the steady-state values. Because of the long time needed to obtain a spectral scan, the spectrograph monitored only one point during each run.

The spectrograph had 100 μ entrance and exit slits set parallel to the electron-beam and a 2160/mm grating which had a reciprocal linear dispersion of 4.6 Å/mm resulting in an instrument line-width of 0.46 Å. The portion of the flowfield viewed by the two instruments was not exactly the same with the spectrograph observing radiation from the flow 1.1 in. along the electron-beam and the RTD accepting radiation from a region 0.4 in. along the beam. It was felt that in the uniform core region of the flow, where the spatial temperature gradients are small, this difference would have little effect on the measurements. The spectrograph scanned the (0, 1) or (0, 0) band of the First Negative System of N_2^+ and the resulting traces were reduced with the Muntz model[1] applied to the line-slope procedure suggested by Hunter.[5]

Although the RTD is an on-line temperature measuring device, the data in this study were reduced after the runs to allow more accurate comparison with the spectrographic results. In addition, a static calibration of the RTD was performed before each run to insure that the instrument was functioning properly. This was done by making a spectral temperature measurement and relating the result to an intensity ratio from the theoretically calculated intensity-temperature curve. The value of this intensity ratio was then compared with the filtered intensity ratio obtained with the RTD and, if the two were different, a calibration factor was obtained. RTD run data were multiplied by this factor to obtain true intensity ratios which were then used to obtain the rotational temperatures. All RTD data were reduced assuming a nitrogen vibrational temperature of 2500°K. Complete details of both the calibration and data reduction procedures may be found in Ref. 3.

Conclusions

The spectral scan and RTD measurements were found to be repeatable and consistent as long as flow within the nozzle core was viewed. Once outside the core and in the boundary layer, the data points were found to scatter significantly not only during a particular run, but also from run-to-run. It is felt that the scatter was due to each instrument's difference in

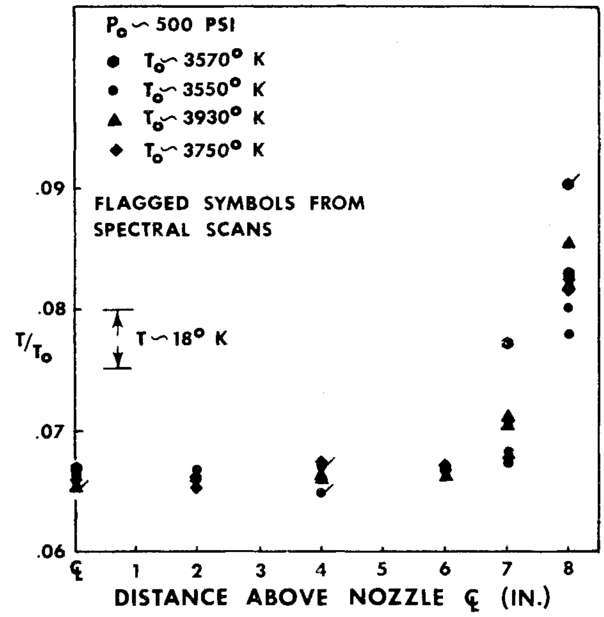

Fig. 2 Summary of normalized RTD and spectral scan temperature data.

resolution of the high-temperature gradients in the boundary layer. However, the flow quality of the core was sufficiently uniform to make a valid assessment of the accuracy of the RTD as compared to spectrographic electron-beam measurements.

Figure 2 summarizes the static temperature distributions obtained with both instruments. All temperatures have been normalized with respect to reservoir temperatures which were calculated using experimentally determined run-average heat balance enthalpies and the assumption of thermochemical equilibrium. The results show that the run-to-run variation for RTD measurements performed in the flow core is within 5%, or 10°K, of the average value of the temperature. The scatter in the data within any particular run however, is much less. In addition, except for measurements performed in the high temperature boundary layer, the agreement between the spectral scan and RTD measurements is within 10%. It must be pointed out that for normalized plots of the type given in Fig. 2 a portion of the run-to-run variation can be due to the slightly different reservoir conditions for each run. With this in mind, it is seen that not only the repeatability and consistency of the RTD measurements, but also their agreement with spectrographic results, are very good, thus lending a high degree of confidence in the future use of the instrument as an on-line temperature monitoring device.

References

[1] Muntz, E. P., "Static Temperature Measurements in a Flowing Gas," *The Physics of Fluids*, Vol. 5, No. 1, Jan. 1962, pp. 80–90.

[2] Muntz, E. P. and Abel, S., "The Direct Measurement of Static Temperature in Shock Tunnel Flows," GE Rept. R645D25, April 1964, General Electric Co., Valley Forge, Pa.

[3] Lazdinis, S. S. and Carpenter, R. F., "Nitrogen Temperature Determination in Arc Tunnel Air Flows," AIAA Paper 72-1022, Palo Alto, Calif., 1972.

[4] Carpenter, R. F., "A Device for the On-Line Measurement of Nitrogen Rotational Temperature in Low Density Flows," *5th Symposium on Temperature, Its Measurement and Control in Science and Industry*, Instrument Society of America, Washington, D.C., June 1971.

[5] Hunter, W. W., "Investigation of Temperature Measurements in 300° to 1100°K Low-Density Air Using an Electron Beam Probe," TN D-4500, May 1968, NASA.