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Bibliography on the Measurement of Gas Temperature

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Preface

This Circular presents an introductory review of the various temperatures that are of interest in hot gases moving at high velocities, and a bibliography of published information on the measurement of gas temperatures in general, grouped for convenience in accordance with various instrument types. These temperatures are of considerable interest in connection with the development, operation, and control of gas turbines and jet engines.

E. U. CONDON, *Director*.

Contents

	Page
Preface	iii
Introduction	1
Scope and arrangement of the bibliography	3
Bibliography	3
100. Books, 1936 through 1950	3
200. Periodical reports, 1930 through 1950	4
201. Thermocouples	4
202. Resistance thermometers and thermistors	8
203. Conventional optical pyrometry	9
204. Conventional radiation pyrometry	10
205. Spectroscopic methods	11
205.1 Line reversal	11
205.2 Band and line spectra	11
206. Pneumatic or thermodynamic methods	12
207. Indicating paints	13
208. Miscellaneous	13

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The various temperatures which are of interest in hot gases moving at high velocities, such as those constituting the working media of gas turbines and jet engines, are reviewed in an introduction to a bibliography of approximately 400 references on the measurement of gas temperatures in general. These references, grouped for convenience in accordance with instrument types, cover approximately the last 20 years.

Introduction

In the reaction zone of a flame where chemical changes are in progress, the individual molecules are in a wide variety of energy states that do not follow a Maxwellian distribution. Nevertheless, the "temperature" of such a reacting mixture has a practical significance, when considered in the sense of Maxwell's definition that "the temperature of a substance is its thermal state considered with reference to its ability to communicate heat to other substances." Even in the absence of equilibrium, spectroscopic methods may be used in the determination of significant temperatures of individual molecular species, and such temperatures are useful in studies of reaction mechanism and of the establishment of thermodynamic equilibrium. At chemical equilibrium, the thermal state of a gas can be expressed quantitatively on the basis of the kinetic theory. Unless otherwise stated, the present discussion of the measurement of gas temperature presumes the existence of such equilibrium.

In its familiar sense, the temperature of a stationary gas in thermodynamic equilibrium is a measure of the mean kinetic energy of random molecular translation. In fact, the mean translational energy of random motion in a perfect gas is the basis for the thermodynamic scale of temperature, and the translational temperature is adequate to describe completely the energy state of a quiescent perfect gas.

A gas with a directed velocity possesses not only the energy due to random molecular motion, but also some additional kinetic energy due to the mass motion in a single direction. It has been found convenient to express the total kinetic energy of both the random and the directed motion in terms of a temperature that has come to be called more specifically the total temperature. Where confusion might exist, the measure of random translational energy is usually designated as the static temperature.

The significance of the static and total temperatures can be illustrated by considering the acceleration of a perfect gas that is allowed to escape adiabatically from a large reservoir through a nozzle to a region of lower pressure. The gas in the reservoir has no directed velocity, so that its static temperature (T_s) and total temperature (T_t) are identical. For the adiabatic transformation of pressure head in the reservoir into velocity head in the throat of the nozzle, there is no change in the total enthalpy, and conservation of energy demands that the static and total temperatures of the gas in the throat of the nozzle be related by the equation

$$T_s = T_t - V^2/2gJC_p, \tag{1}$$

in which V is the velocity in the throat, g is the acceleration of gravity, J is the mechanical equivalent of heat, and all are expressed in consistent units.

For actual gases also, adiabatic acceleration (and deceleration) takes place at constant enthalpy, and eq 1 holds, provided that thermal equilibrium is maintained and that the proper value of the variable heat capacity is used. As will be shown, thermal equilibrium is not maintained during rapid accelerations of some actual gases, and for such cases eq 1 holds approximately, but not exactly.

When such temperature-sensing devices as thermometers and thermocouples, free of errors from conduction and radiation, are immersed in streams of high-velocity gas, they attain and indicate a temperature (T_i) intermediate between T_t and T_s. This characteristic of the instrument is frequently specified in terms of its recovery factor (r), defined as

$$r = (T_i - T_s)/(T_t - T_s). \tag{2}$$

The recovery factors of most instruments are essentially independent of the operating conditions.

In addition to the static and total translational temperatures already discussed, actual gases may possess energy in other forms, each of which may be described in terms of still other temperatures. Gases of major practical interest contain more than one atom per molecule, and thus the rotations and vibrations of the molecules may contribute to the total energy. As measures of these two kinds of molecular energy, the concepts of rotational and vibrational temperature have proved useful. Rotational and vibrational temperatures can be determined from the relative intensities of certain spectral lines.

For an actual gas in thermodynamic equilibrium, the total energy is partitioned among the various degrees of freedom in definite proportions which are invariant so long as equilibrium is maintained. Thus equipartition is said to exist at the equilibrium state. In certain processes to which gases are subjected in practical applications, equilibrium is established only after some finite interval known as the relaxation time. For example, rotational and vibrational temperatures are of practical interest in the case of molecules newly formed at high temperatures, as in the process of combustion. Such molecules may have abnormally high rotational and vibrational temperatures which decrease as equilibrium is approached. Since only the translational energy, and none of the rotational or vibrational energy, can be utilized in driving a turbine or in producing jet thrust, the desirability of attaining equipartition within the power plant is obvious.

Many problems have arisen in the measurement and control of the temperatures of the working media of gas turbines and jet engines. Satisfactory solutions to these problems, in the form of practical instruments, are required for evaluating the performance of power plants and their constituent parts, and for protecting them against overheating and overspeeding. Much research effort is being expended currently in the development of instruments that are more accurate and more rugged, in the perfection of various spectroscopic methods, in the extension of the theoretical background, and in the evolution of more exact knowledge of the real significance of the measured values.

The National Bureau of Standards is participating in this instrumentation program under sponsorship of the Bureau of Ships and the Air Matériel Command. One phase of this activity has been an examination of the literature applicable to this field. This Circular was prepared in the belief that a list of pertinent references, classified in accordance with instrument type, would prove useful to others who are interested in the measurement of gas temperature.

Scope and Arrangement of the Bibliography

Approximately 400 references to articles on and related to the measurement of gas temperature, covering the 20 years prior to January 1951, are included. These are classified topically, as shown in the table of contents. Within each topical subdivision, the reports are in chronological order and, within chronological sections, alphabetically by author. "Anonymous" articles are listed at the end of the chronological sections.

The journal abbreviations used are those employed in Chemical Abstracts, except that the abbreviation NACA is used for the National Advisory Committee for Aeronautics. Volume numbers are in boldfaced type, and the date of issue is given in cases where page numbers do not run consecutively throughout a given volume.

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