Psychrometrics—Theory and Practice

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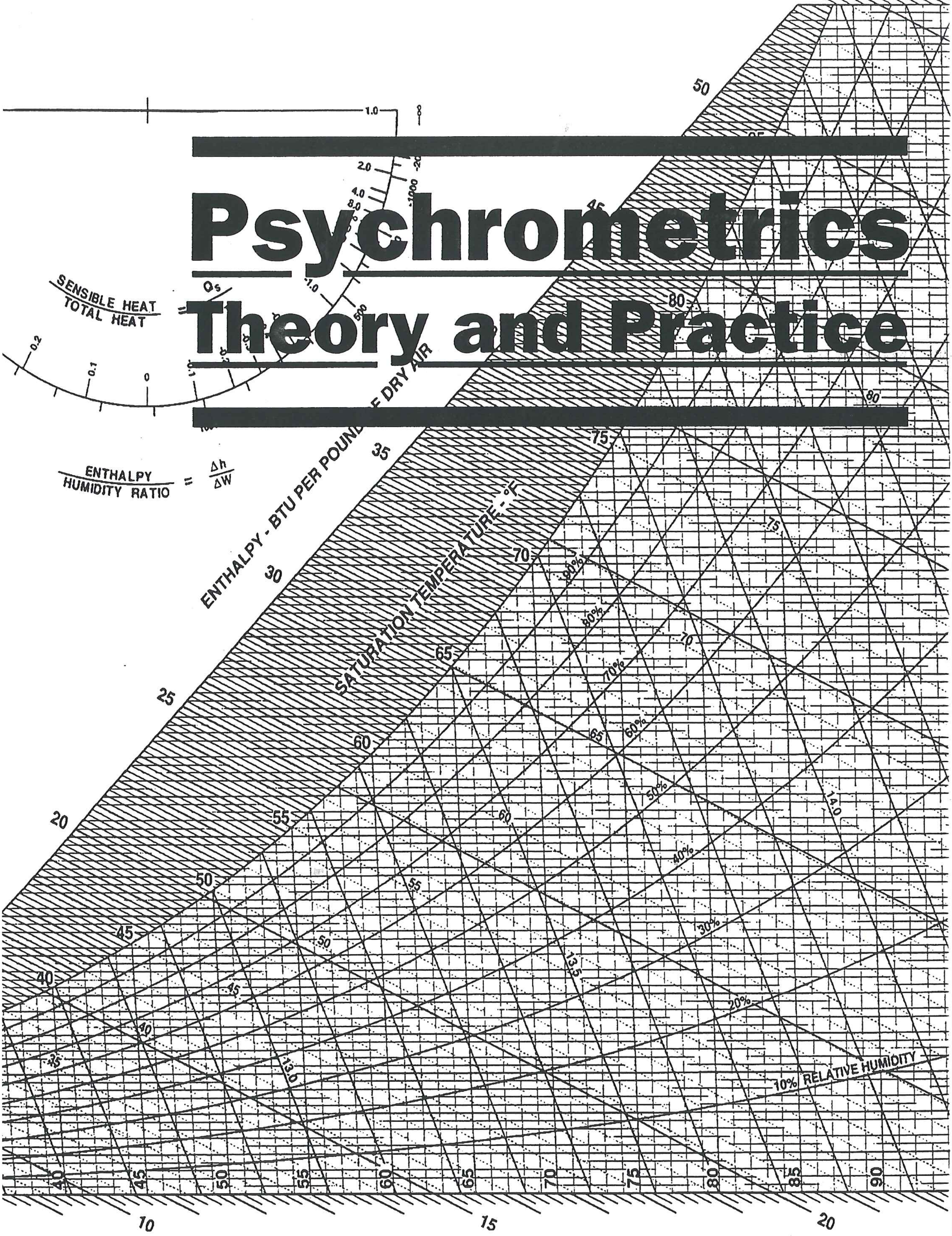

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INTRODUCTION

Moist-air properties in the atmosphere display periodic variations of a diurnal and seasonal nature associated with the rotation of the globe and the revolution of the earth in an elliptical orbit about the sun. Changes in atmospheric moist-air properties are also due to movements of air masses from different regions, such as the polar or tropical regions. These bodies of air bring with them characteristic meteorological properties and activities, depending upon the conditions over the source regions and over the various geographical areas traversed by the air masses. These bodies of air, constantly moving about, are capable of manifesting a wide range of activities. They can gain or lose heat, take up or yield water vapor, become clear or cloudy, flow past with light breezes or gales, give balmy weather or light to heavy rains and snows, sleet, and perhaps thunderstorms, tornadoes, or hurricanes, unleashing torrential precipitation attended by strong winds.

The degree of moisture in the air has a profound effect on our man-made structures. Moist air changes its properties or loses or gains water as it moves in and out of these structures and often causes damage. It plays a principal role, not only in the heating and cooling processes of these structures and the resulting comfort of the occupants, but in building insulation, roofing properties, and the stability, deformation, and fire-resistance of the building materials. The degree of moisture in the air has an effect on sound absorption, odor level, and ventilation.

Industry and agriculture, by necessity, must control the humidity of the air to fairly close limits. The paper industry, space industry, clothing manufacturing, hospital operating rooms, storage of fruit and grain, and growing of animals and plants are but a few examples.

An understanding of the principles involved is essential. To this end, presentation of the relationships involved, instrumentation, and some of the techniques used by the Weather Bureau, industry, and agriculture are given in this publication. Many of the facts given have been known for years. The theory of psychrometry was well developed by 1945 when Goff and Gratch prepared their tables. Since then, however, with the rapid growth of industry and universities, many new techniques for controlling, making use of, and measuring the properties of dry and moist air have developed rapidly. Yet most of the knowledge available is widely spread throughout literature, and sometimes the information cannot be found easily.

The underlying purpose in preparing this publication was to bring together, under one cover, most of the available knowledge so it can be of use to laboratory investigators, meteorologists, design engineers, professors, students, and technicians.

CHAPTER 1

THERMODYNAMIC PROPERTIES OF DRY AND MOIST AIR AND WATER

1.1 INTRODUCTION

The primary source of data regarding thermodynamic properties of moist air for use in air-conditioning and meteorology practice has been the reports formulated by Goff and Gratch[3-6] in the 1940s. Since then other papers have been published, most recently those of Hyland and Wexler,[1,2] who have reexamined all the available thermodynamic data for water and moist air. The first part of this ASHRAE-funded research project reassessed all the fundamental data and prior methods of analysis that led to the development of new tables in the SI system of units for the specific volume, specific enthalpy, and specific entropy of the solid, liquid, and vapor phases of saturated water in the temperature range of –100°C to 200°C. The second part obtained a density series virial equation of state for dry air, which, combined with part one, produced tables of the specific volume, specific enthalpy, and specific entropy of saturated moist air in the range of -100°C to 99°C. The results of the project represent the best achievable thermodynamic property correlations available today. This chapter provides the principal results of the Hyland and Wexler reports, including complete tabulations of thermodynamic properties of moist air. This publication intentionally leaves much of the theory to the referenced sources and provides the user with the fundamental working equations needed for psychrometric computations.

Other psychrometric relationships and moist air properties not directly related to the Hyland and Wexler formulations are also described in this chapter. For more rapid calculation of various moist air properties, perfect gas relationships can be used with only a slight loss of accuracy. The equations are given here in dual units. Furthermore, detailed procedures are outlined in Section 1.8 citing these equations for calculating psychrometric properties either by hand or by computer.

Also included in this chapter are the newly formulated psychrometric charts in SI units. These seven charts, which incorporate the methods of Hyland Wexler[1,2] as well as those of Goff and Gratch,[4,5] are constructed for use at different pressures and temperatures.

To judge the accuracy of available software, tables are included in both SI and I-P units (see Section 1.10) based on the calculated values of the Hyland and Wexler formulations.

Additional references for information on topics cited in this chapter are listed in Sections 1.11, 1.12, and 1.13.

1.2 THE COMPOSITION OF DRY AND MOIST AIR

1.2.1 Dry Air Constituents

Atmospheric air contains a large number of gaseous constituents, as well as water vapor and miscellaneous contaminants (e.g., smoke, pollen, and gaseous pollutants not normally present in free air far removed from the sources of pollution). By definition, dry air exists when all water vapor and contaminants have been removed from atmospheric air. Extensive measurements have shown that the composition of dry air is relatively constant but that small variations in the amounts of individual components do occur with time, geographical location, and altitude. Further information is given by Harrison.[7] In order to determine the thermodynamic properties of dry air, its composition must, of course, be standardized. Table 1, listing the components of dry air and their relative amounts, is an accepted standard and represents the averages for a wide range of conditions. Nitrogen, oxygen, argon, and carbon dioxide obviously are the major components. The amounts of the first three are very stable, while the abundance of carbon dioxide may show considerable local variations relative to its average value due to the condition of vegetation, weather conditions, ocean surface water temperature, pollution, etc. Fortunately, the overall properties of the dry air mixture may generally be determined without concern for carbon dioxide variability, since the average abundance of carbon dioxide is so small.

Moist air, the basic medium in air-conditioning practice, is defined as a binary, or two-component, mixture of dry air and water vapor. Dry air is treated in this chapter as a single entity whose composition is defined in Table 1. The amount of water vapor in moist air is variable, ranging from nearly zero (dry air) to a maximum (typically from 0.0000363 to 0.00907 kg of water vapor per kg of dry air under surface atmospheric conditions) depending upon temperature and pressure.

Table 1: Normal Composition of Clean, Dry, Atmospheric Air Near Sea Level

Constituent Gas and Formula	Content (% by volume)	Content Variable Relative to Its Normal	Molecular Weight on Basis of Carbon-12 Isotope Scale for which C12 (C-12) = 12
Nitrogen (N_2)	78.084	-	28.0134
Oxygen (O_2)	20.9476	-	31.9988
Argon (Ar)	0.934	-	39.943
Carbon dioxide (CO_2)	0.0314	*	44.00995
Neon (Ne)	0.001818	-	20.183
Helium (He)	0.000524	-	4.0026
Krypton (Kr)	0.000114	-	83.80
Xenon (Xe)	0.0000087	-	131.30
Hydrogen (H_2)	0.00005	?	2.01594
Methane (CH_4)	0.00015	*	16.04303
Nitrous oxide (N_2O)	0.00005	-	44.0128
Ozone (O_3)	summer: 0 to 0.000007 winter: 0 to 0.000002	*	47.9982
Sulfur dioxide (SO_2)	0 to 0.0001	*	64.0828
Nitrogen dioxide (NO_2)	0 to 0.000002	*	46.0055
Ammonia (NH_3)	0 to trace	*	17.03061
Carbon monoxide (CO)	0 to trace	*	28.01055
Iodine (12)	0 to 0.000001	*	253.8088
Radon (Rn)	6×10^{-13}	?	†

* The content of the gases marked with an asterisk may undergo significant variations from time to time or from place to place relative to the normal indicated for those gases.

† Radon is radioactive and is known to consist of at least two isotopes, Rn^{220} (half-life 54 seconds) and Rn^{222} (half-life 3.83 days). No value has been assigned to the atomic weight of the mixture of isotopes, which is variable.

1.2.2 The Water Vapor Molecule

A water vapor molecule is formed from two atoms of hydrogen and one oxygen atom, and is represented by the chemical formula H_20. For most so-called nonpolar gases, such as most of the constituents of dry air, the interactive forces between molecules are determined principally by the distance of separation of adjacent pairs. Water vapor molecules possess an asymmetric distribution of the electric charges of the constituent atoms, which leads to a preferred orientation or polarization for two adjacent water molecules. For polar gases, such as water vapor, the intermolecular potential depends not only upon the distance of separation but also upon the mutual orientation. A result of this complication is that interactions between groups of three molecules are nearly as important as interactions between groups of two molecules. Water vapor thus deviates significantly in its behavior from that of a so-called ideal or perfect gas whose molecules have no mutual interactions. A more thorough discussion of the water vapor molecular structure and behavior is contained in Section 5.4 of Chapter 5.

1.2.3 Molecular Weight and Gas Constants

1.2.3.1 Carbon-12 Scale of Atomic and Molecular Weights

On the basis of the Carbon-12 scale, the gram atomic or molecular (whichever is appropriate) weight of a pure substance is defined as the mass in grams of that substance which has the same number of elementary particles (atoms or molecules) as the number of atoms contained in exactly 12 grams of pure Carbon-12 isotope. The pound atomic or molecular weight of a substance has this same definition except that the masses are expressed in pounds. Thus, the two atomic or molecular weights of a given substance are numerically equal but refer to different mass units. In this chapter, both the SI and I-P systems of units will be considered. (See Section 5.3.2 of Chapter 5.) In the SI system, the kilogram is the basic unit of mass; in the Inch-Pound system of units, it is the pound-mass. The mass of a substance equal to its molecular weight is called one mole. (See Section 5.3.2 of Chapter 5 for detailed definition.) Again, both gram moles and pound moles are used, depending upon the unit of mass chosen. Prior to the adoption of the Carbon-12 Scale, the natural oxygen scale was used. The datum for this scale was an atomic weight of exactly 16 for natural oxygen or a molecular weight of 32. On the basis of the new Carbon-12 Scale, the molecular weight of oxygen is 31.9988. Thus, for most practical calculations, the difference between the scales is negligible.

1.2.3.2 Apparent Molecular Weight of Dry Air

Dry air has been defined as a mixture of several gaseous components; as such, the definition for molecular weight given previously does not apply. An apparent molecular weight can be defined as the weighted average molecular weight of all components, using the individual molecular weights and volume percentages given in Table 1. This calculation results in the value of 28.9645 for the apparent molecular weight of dry air on the basis of the Carbon-12 Scale.