1
Water – Substance of Life

1.1
Water as a Natural Resource

Water plays a key role in the formation and evolution of our planet and the life it supports. Water is present, in different aggregate states, throughout all parts of the Earth. In solid and liquid forms, water covers approximately 71% of the Earth's surface, while the large amount of gaseous, liquid, and solid water in the atmosphere governs both the global climate and the local weather. Global climatic balance and heat transfer are determined mainly by the large oceanic circulations of warm and cold water. Water has a high degree of transparency for visible light, one of the key factors that enabled the formation and evolution of life in the primeval oceans. The atmospheric layer of water vapor reflects heat emitted from the surface of the Earth and thus prevents the freezing of the planet. Liquid water forms the landscapes on continents, and its presence or absence determines the degree of biological activity and suitability for agriculture.

Every form of life on Earth requires water vapor in the respiratory air. Water is an essential component of each organism, and needs to be present in sufficient amounts at all times. Humans, for example, may survive without the intake of proteins, carbohydrates, and fiber for several weeks. Without water, however, survival is possible for only a few days. Humans require a daily amount of 2–3 l of water in order to maintain biological functions. Water has thus always been a central element in human consciousness and culture. In the ancient philosophies, for example, water is one of the four basic elements, and it is a symbol of purity and life in every religion.

Apart from its immediate nutritional function, humans make use of the different properties of water in many ways, for example,

- for the generation of energy,
- for the transportation of people and goods,
- as a building material,
- in industrial manufacturing processes,
- for relaxing and recreation,
- for the removal of waste,

Industrial Moisture and Humidity Measurement: A Practical Guide, First Edition.
Roland Wernecke and Jan Wernecke.

- as a cleaning agent, and
- for the interim or final storage of many different materials.

1.2
Physical and Chemical Properties of Water

1.2.1
The Water Molecule

Water is a molecule consisting of two hydrogen atoms and one oxygen atom (Figure 1.1).

The difference in electronegativity between oxygen and hydrogen, and the arrangement of atomic orbitals, results in an angle of 104.5° and thus the formation of an electric dipole. The negative charge of the molecular dipole is located at the free pair of valence electrons of oxygen, while the hydrogen ions form the positively charged pole. Different symmetric and asymmetric oscillation modes (Figure 1.2) can

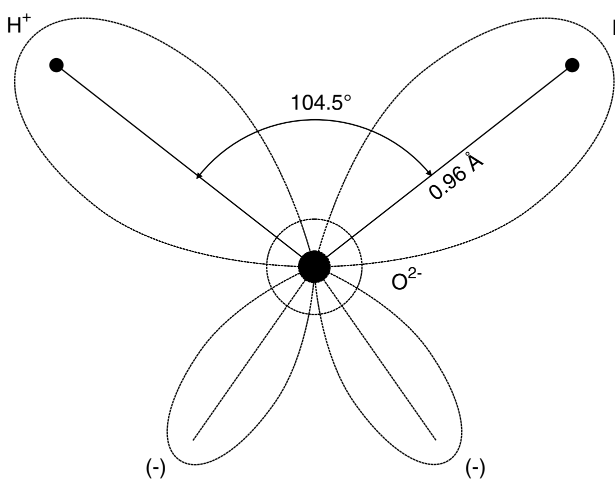

Figure 1.1 Binding angles in a water molecule.

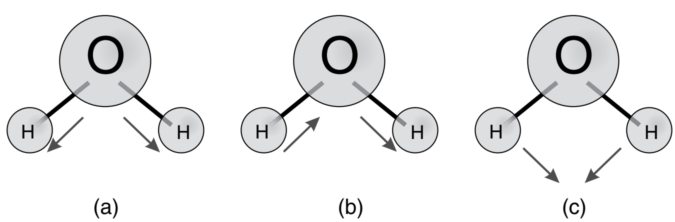

Figure 1.2 Vibration states of a water molecule.

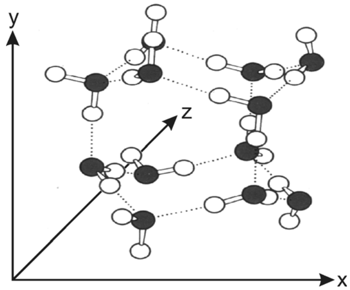

Figure 1.3 Clustering of water molecules.

be excited and result in a variation of the dipole moment. The dipole character of water molecules is the reason for the formation of the strong intermolecular hydrogen bonds that cause clustering (Figure 1.3).

This results in a density that is significantly lower than that of chemically similar substances. The diameter of H_2O molecules of 0.28 nm also differs from that of other components of air, such as

- H_2: 0.23–0.29 nm,
- N_2: 0.32–0.36 nm,
- O_2: 0.29–0.35 nm, and
- CO_2: 0.33 nm,

which makes the physical and chemical properties of water so unique. More than 40 anomalies of water, in terms of chemical, thermodynamic, electrical, or optical properties, to name but a few, have been observed in various experiments. Details can be found in the specialist literature.

1.2.2
Physical Properties

In the terrestrial atmosphere, water can be present in the solid, liquid, and gaseous states. All three phases are colorless and possess a high optical transparency in the visible and ultraviolet range. Infrared and microwave radiation, in contrast, is absorbed by water molecules due to the positions of the molecular energy orbitals. Water molecules are electrically neutral, but possess a dipole moment due to the inhomogeneous charge distribution.

The formation of clusters during freezing is the reason for the anomalous density change of water, compared to other molecules with similar structure. Due to clustering, water expands in volume during the phase transition from liquid to solid, which is associated with a reduction in density (Figure 1.4). This process continues as temperatures further decrease, as long as crystallization occurs. The crystal structure of water molecules in ice is a monocrystalline hexagonal lattice. Water has the highest density (e.g., smallest volume) at a temperature of around

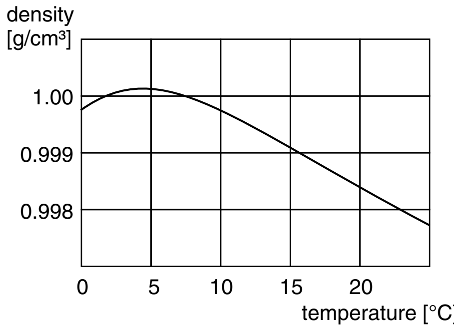

Figure 1.4 Density of water as a function of pressure.

$T \approx 4\,°C$. A further increase in temperature results in a decrease in density, similar to any other liquid. This anomaly of density has direct implications on the landscape, and on natural processes: Lakes freeze from top to bottom, which allows fish to survive during winter. Water that penetrates into rock crevices and freezes during the night can cause significant frost wedging due to the volume expansion.

A further anomaly of water is the temperature at which melting and freezing occurs. According to the chemical properties of compounds of hydrogen and other elements from group VI of the periodic table, the phase transition temperatures should be as shown in Figure 1.5.

The reason for this significant deviation is the strong hydrogen bonds between the molecules, which need to be overcome by using an increased amount of energy. As a consequence, the melting and evaporation temperatures of water at standard pressure are shifted to $T_{\mathrm{melt}} = 0\,°C$ and $T_{\mathrm{evapo}} = 100\,°C$, respectively. The strong

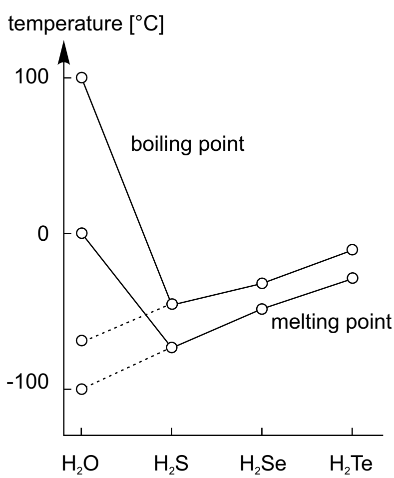

Figure 1.5 Melting and boiling temperatures of hydrogen compounds in the oxygen group of the periodic table and the expected values for H_2O.

hydrogen bonds also cause a strong surface tension at interfaces, which results in a high viscosity and a good wetting behavior on polarized surfaces.

Water possesses a high heat capacity, which dampens the low temperature change upon heating or cooling. Thus, the transition between the aggregate states is associated with a significant release or absorption of thermal energy.

1.2.3 Chemical Properties

Water is formed during the combustion or, more precisely, the oxidation of hydrogen according to

$$2H_2 + O_2 \rightarrow 2H_2O \tag{1.1}$$

The oxidation is an exothermic process, where hydrogen is oxidized and oxygen is reduced. Water can be used as a solvent for a wide range of chemicals, because

- it is soluble in many substances and forms free ions by dissociation,
- it can be easily absorbed due to the low molar mass of the molecule,
- the dipole of the molecules allows for the formation of stable bonds, and
- the hydrogen bonds cause an interlinking with other polar molecules.

Salts, bases, and acids can be dissolved and diluted in water and are used for many chemical reaction processes. Dissolved oxygen is an important factor for life and biological activity. In the atmosphere, the ratio of oxygen to nitrogen is roughly 1 : 4. This ratio is 1 : 1.8 in water, that is, a much higher oxygen content, which is essential for the respiration processes of underwater life forms.

Metals are only corroded by liquid water and in environments with a relative humidity of $U > 70\%$rh. Dissociation of water molecules yields unbound hydroxide ions, OH^-, which are highly reactive. In the atmosphere, OH^- ions react with many substances and pollutants and thus act as a cleaning agent. An example of this process is the natural decomposition of ozone by a reaction with water according to

$$O_3{}^{2-} + H_2O \rightleftharpoons 2OH^- + O_2 \tag{1.2}$$

Man-made atmospheric substances, for example, industrial sulfur compounds, are also, to a certain extent, decomposed and bound by water. This generates condensation nuclei, which causes cloud formation. The particles are then washed out of the atmosphere by precipitation, and into the ground. Investigations into the distribution of these substances yield information on the amount and the location of atmospheric pollution.

Water is an amphoteric substance, which means that it can act as both an acid (hydronium, H_3O^+) and a base (OH^-); the equation of the dynamic dissociation equilibrium is

$$H_3O^+ \rightleftharpoons H_2O \rightleftharpoons OH^- \tag{1.3}$$

A consequence of the amphoteric character of water is that is acts as a buffer for acids and bases; that is, pH-value fluctuations due to the application of small amounts of acid or bases are balanced out. This property of water is again a basic requirement for the formation of more complex life, as we know it, because it enables the continuous reactions of enzymes throughout many different metabolic processes.

1.3
Significance of Water for Energy Conversion

Many of the physical, chemical, mechanical, and thermodynamic properties of water can be used for the conversion, transport, and storage of energy. Some techniques have been in use by humans for thousands of years, while others have only very recently been developed.

Water molecules are inert compounds with a low redox potential that can be used for the conversion and storage of energy, for example, thermal energy. However, water can also be dissociated into hydrogen gas by electrolysis, which is a highly combustible fuel in itself. Hydrogen is used in engines, jet propulsion, and can be used for the conversion of electrical energy in fuel cells. The by-product of the reaction is simply water, which does not pollute the environment. The dynamic equilibrium of dissociation can be expressed as

$$2H_2 + O_2 \underset{\text{electrolysis}}{\overset{\text{combustion}}{\rightleftharpoons}} 2H_2O + \text{energy} \tag{1.4}$$

The combustion of hydrogen, also called bright-gas reaction, is highly significant for the generation of clean energy. Water is dissociated into hydrogen and oxygen by solar cells. The gases can be transported through pipes over long distances. The reverse reaction of hydrogen to water in combustion engines, power plants, or fuel cells is associated with a release of energy, that is,

$$2H_2 \rightarrow 4H^+ + 4e^- \tag{1.5a}$$

$$O_2 + 4e^- \rightarrow 2O^{2-} \tag{1.5b}$$

$$4H^+ + 2O^{2-} \rightarrow 2H_2O + \text{energy} \tag{1.5c}$$

Life forms use water and the energy of this process for metabolic activities, for example, for photosynthesis and chemosynthesis. In power plants, steam, with a high temperature and at a high pressure, is guided through the blades of a turbine. The resultant rotation is converted into electrical energy in a generator. The cooled and depressurized water vapor is further cooled, liquefied, and fed back into the heating circuit. The physical principle of this energy conversion process is governed by the thermodynamic state transitions and phase transitions of water. This is a very general principle in energy conversion, and is also the fundamental operating principle of nuclear plants and of wind turbines, for example.

Hydropower plants make use of accumulated water that possesses a high potential energy. Turbines that generate electrical energy are driven by the conversion of the potential energy into kinetic energy by flowing water through sloped pipes and channels. In this way, large amounts of electrical energy can be generated at lakes and rivers, but the environmental impact of massive installations such as dams should always be considered first. Hydropower plants also play an ever-increasing role in the storage of energy. The fluctuating energy of renewable energy sources (e.g., wind, sun) needs to be stored during phases of excess generation, until it is needed. This energy can then be used to pump the water to a higher level, thus increasing the potential energy of the water. At times when the consumption of energy is higher than that generated, the water can be directed through turbines to generate additional electrical energy.

Tidal and wave power plants convert the kinetic energy of water due to the tides into electrical energy.

These are only a few examples of how electrical energy can be generated either directly from or by the involvement of water. Many more principles and methods can be found in the specialist literature on this topic.

1.4 General Terminology

For clarity and in order to avoid ambiguity, the terminology used in this book to identify the different states of water is described briefly in the following.

The naming of physical and chemical states (such as triple point, redox potential, etc.) is unambiguous and generally accepted by consensus. The aggregate states of water and thus associated terms (e.g., dew point, water vapor pressure) are described and defined by the laws of thermodynamics. It should be noted that, occasionally, identical terms are used in the context of technical applications (e.g., in energy conversion or for drying) with a different definition.

The term *humidity* describes the states and interactions of gaseous water in other gases. A general definition does not exist.

The term *moisture* describes the states and interactions of liquid or gaseous water in either solids or liquids, regardless of the specific type of physical or chemical bonding. As in the case of humidity, no general definition exists.

Other humidity- or moisture-related terms that can be found occasionally (e.g., trace humidity, high temperature humidity) are used for particular states of water and measurement ranges for specific manufacturing processes.

The term *water steam* is frequently used for energy conversion processes. This term is used to describe water as an aerosol, possibly at elevated temperatures. Such a mixture of small water droplets and a gas has a high significance as an energy source (e.g., hot steam, supersaturated steam). In gas humidity measurement, however, the term *water vapor* is used, which implies the description of water as a real gas, for example, as a van der Waals gas.

Further Reading

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