

Toolbox 4

ENERGY UNITS, CONVERSIONS, THERMO-PHYSICAL PROPERTIES AND OTHER ENGINEERING DATA

SI UNITS

1. *The System International (SI)*

This came into being in October 1960 and has ever since been recognized officially and adopted by nearly every country, although its actual use varies considerably. It is based on seven principal units, one in each of seven different categories.

Table 4.1: *The SI Seven Principal Units*

| <i>Category</i> | <i>Name</i> | <i>Abbreviation</i> |
|---------------------|-------------|---------------------|
| Length | Meter | m |
| Mass | Kilogram | kg |
| Time | Second | s |
| Electric current | Ampere | A |
| Temperature | Kelvin | K |
| Amount of substance | Mole | mol |
| Luminous intensity | Candela | cd |

From these basic units many other units are derived and named.

2. *Definitions of the Seven Basic SI Units*

meter [m]

Meter is a basic unit of length. It is the distance light travels in a vacuum in $1/299\,792\,458$ th of a second.

kilogram [kg]

Kilogram is a basic unit of mass. It is the mass of an international prototype in the form of a platinum-iridium cylinder kept at Sevres in France. *It is now the only basic unit still defined in terms of a material object, and also the only one with a prefix [kilo] already in place.*

second [s]

Second is a basic unit of time. It is the length of time taken for $9\,192\,631\,770$ periods of vibration of the cesium-133 atom.

ampere [A]

Ampere is a basic unit of electric current. It is that current which produces a specified force between two parallel wires which are 1 meter apart in a vacuum.

kelvin [K]

Kelvin is a basic unit of temperature. It is $1/273.16$ th of the thermodynamic temperature of the triple point of water.

mole [mol]

Mole is a basic unit of substance. It is the amount of substance that contains as many elementary units as there are atoms in 0.012 kg of carbon-12.

candela [cd]

Candela is a basic unit of luminous intensity. It is the intensity of a source of light of a specified frequency which gives a specified amount of power in a given direction.

3. Derived Units of the SI

From the seven basic units of the SI other units are derived for a variety of purposes. Only a few of them are explained here as examples:

farad [F]

Farad is the SI unit of the capacitance of an electrical system, that is, its capacity to store electricity.

hertz [Hz]

Hertz is a SI unit for the frequency of a periodic phenomenon. One hertz indicates that one cycle of the phenomenon occurs every **second**.

joule [J]

Joule is a SI unit of work or energy. One joule is the amount of work done when an applied force of 1 **newton** moves through a distance of 1 **meter** in the direction of the force.

newton [N]

Newton is a SI unit of force. One newton is the force required to give a mass of 1 **kilogram** an acceleration of 1 **meter per second**.

ohm [Ω]

Ohm is a SI unit of resistance of an electrical conductor.

pascal [Pa]

Pascal is a SI unit of pressure. One pascal is the pressure generated by a force of 1 **newton** acting on an area of 1 **square meter**.

volt [V]

Volt is a SI unit of electric potential. One volt is the difference of potential between two points of an electrical conductor when a current of 1 **ampere** flowing between those points dissipates a power of 1 **watt**.

watt [W]

Watt is used to measure power or the rate of doing work. One watt is a power of 1 **joule per second**.

4. The SI allows the sizes of units to be made bigger or smaller by the use of appropriate prefixes:

Table 4.2: Prefixes of Units

| | |
|------------------------|-----------------------------|
| yotta [Y] = 10^{+24} | deci [d] = 0.1 |
| zetta [Z] = 10^{+21} | centi [c] = 0.01 |
| exa [E] = 10^{+18} | milli [m] = 10^{-3} |
| peta [P] = 10^{+15} | micro [μ] = 10^{-6} |
| tera [T] = 10^{+12} | nano [n] = 10^{-9} |
| giga [G] = 10^{+9} | pico [p] = 10^{-12} |
| mega [M] = 10^{+6} | femto [f] = 10^{-15} |
| kilo [k] = 10^{+3} | atto [a] = 10^{-18} |
| hecto [h] = 100 | zepto [z] = 10^{-21} |
| deca [da] = 10 | yocto [y] = 10^{-24} |
| 1 | |

5. SI unites and conversion factors

For other systems of measurement these are as follows:

Table 4.3: Conversion Factors

| Name | SI unit | Conversion factors for most frequently used units of other systems and non-system units |
|---|----------------------|---|
| Acceleration, linear | m/s ² | 1 in/s ² = 0.0254 m/s ² |
| Area | m ² | 1 ft ² = 0.0929 m ² |
| | | 1 in ² = 6.451×10 ⁻⁴ m ² |
| Density | kg/m ³ | 1 ton/m ³ = 1 kg/dm ³ = 1 g/cm ³ = 10 ³ kg/m ³ |
| | | 1 (kgf s ²)/m ⁴ = 9.81 kg/m ³ |
| | | 1 lb/ft ³ = 16.02 kg/m ³ |
| | | 1 lb/in ³ = 27.68×10 ³ kg/m ³ |
| Density of heat flux | W/m ² | 1 kcal/m ² = 1.163 W/m ² |
| Diffusion coefficient | m ² /s | 1 ft ² /s = 0.0929 m ² /s |
| Energy, work, quantity of heat | J | 1 kWh = 3.6×10 ⁶ J |
| | | 1 kcal = 4.1868 kJ = 4.1868×10 ³ J |
| | | 1 lbf ×ft = 1.356 J |
| | | 1 lbf ×in = 0.133 J |
| | | 1 BTU = 1055.1 J |
| Enthalpy, specific | J/kg | 1 kcal/kg = 1 cal/g = 4190 J/kg |
| | | 1 BTU/lb = 2326 J/kg |
| Entropy, specific | J/(kg K) | 1 kcal/(kg K) = 4190 J/(kg K) |
| | | 1 BTU/(lb °F) = 4190 J/(kg K) |
| Force (weight) | N | 1 kgf = 9.81 N |
| | | 1 dyn = 10 ⁻⁵ N |
| | | 1 sn = 10 ³ N |
| | | 1 lbf = 4.45 N |
| Frequency | Hz | 1 s ⁻¹ = 1 Hz |
| | | 1 rps = 1 Hz |
| | | 1 rpm = 1/60 Hz |
| Heat capacity, specific | J/(kg K) | 1 kcal/(kg K) = 4190 J/(kg K) |
| | | 1 BTU/(lb °F) = 4190 J/(kg K) |
| Heat transfer coefficient, individual and overall | W/(m ² K) | 1 kcal/(kg K) 4190 J/(kg K) |
| | | 1 BTU/(ft ² h °F) = 5.6 W/(m ² K) |
| Length | m | 1 μ m (micron) = 10 ⁻⁶ m |
| | | 1 Å = 10 ⁻¹⁰ m |
| | | 1 ft (') = 0.3048 m |
| | | 1 in (") = 0.0254 m |
| Mass | kg | 1 ton (m3tric) = 1000 kg |
| | | 1 lb = 0.454 kg |
| Power | W | 1 (kgf m)/s = 9.81 W |
| | | 1 kcal/h = 1.163 W |
| | | 1 (lbf ft)/s = 1.356 W |
| | | 1 hp = 735.3 W |

| | | |
|-----------------------------------|--------------------|--|
| Pressure | Pa | 1 bar = 10^5 Pa |
| | | 1 mbar = 100 Pa |
| | | 1 kgf/cm ² = 1 at = 735 mm Hg = 9.81×10^4 Pa |
| | | 1 atm = 760 mm Hg = 101325 Pa |
| | | 1 kgf/m ² = 9.81 Pa |
| | | 1 mm H ₂ O = 9.81 Pa |
| | | 1 mmHg = 133.3 Pa |
| | | 1 lbf/in ² = (psi) = 6894.76 Pa |
| | | 1 lbf/ft ² = 47.88 Pa |
| Rate of flow, mass | kg/s | 1 lb/s = 0.454 kg/s 1 lb/h = 1.26×10^{-4} kg/s |
| Rate of flow, volumetric | m ³ /s | 1 l/min = 16.67×10^{-3} m ³ /s |
| | | 1 ft ³ /s = 28.3×10^{-3} m ³ /s |
| | | 1 in ³ /s = 16.4×10^{-6} m ³ /s |
| Specific heat of phase transition | J/kg | 1 kcal/kg = 4189 J/kg |
| | | 1 BTU/lb = 2326 J/kg |
| Surface tension | N/m | 1 kgf/m = 9.81 J/m ² = 9.81 N/m |
| Thermal conductivity | W/(m K) | 1 kcal/(m h K) = 1.163 W/(m K) |
| | | 1 BTU/(ft h °F) = 1.73 W/(m K) |
| Time | s | 1 h = 3600 s |
| | | 1 min = 60 s |
| Temperature | K | $t [^{\circ}\text{C}] = (t + 273.15) [\text{K}]$ |
| | | $t [^{\circ}\text{F}] = \left(\frac{5}{9}(t - 32) + 273.15 \right) [\text{K}]$ |
| Velocity, angular | rad/s | 1 rpm = $\frac{\pi}{30}$ rad/s |
| | | 1 rps = 2π rad/s |
| Velocity, linear | m/s | 1 ft/s = 0.3048 m/s |
| Viscosity, dynamic | Pa s | 1 P (poises) = 0.1 Pa s |
| | | 1 cP (centipoises) = $1/9180$ kgf s/m ² = 10^{-3} Pa s |
| Viscosity, kinematic | m ² /s | 1 S (stokes) = 1 cm ² /s = 10^{-4} m ² /s |
| | | 1 ft ² /s = 0.093 m ² /s |
| | | 1 ft ² /h = 25.81 m ² /s |
| Volume | m ³ | 1 l = 10^{-3} m ³ |
| | | 1 ft ³ = 28.3 dm ³ = 0.0283 m ³ |
| | | 1 in ³ = 16.387 cm ³ = 16.39×10^{-6} m ³ |
| Volume, specific | m ³ /kg | 1 m ³ /ton = 10^{-3} m ³ /kg |
| | | 1 l/kg = 1 cm ³ /g = 10^{-3} m ³ /kg |

Note: The values of the conversion factors are given with the sufficient accuracy for engineering calculations

A USEFUL DEFINITION FOR ENERGY ANALYSIS

6. The **ton of oil equivalent (toe)** is a unit for measuring energy. It corresponds to **10 Gcal** or **41.868 GJ** or **11.63 MWh**. It is a rounded amount of energy that would be produced by burning one metric ton of crude oil. Since crude oil of different origin has different chemical properties and therefore gives off varying amounts of heat when burnt, the value is a matter of consensus to a certain extent. **toe** is a particularly useful unit for quantifying energy production or consumption for one country or for the entire world.

7. The most useful and practical definition of **energy** is that it is **a measure of the capacity for doing work**. Energy comes from many sources – sunlight, wind, water, coal, oil, gas, etc., and it has many types: thermal, electrical, chemical, nuclear, etc.

Specific energy is a measure of the amount of energy contained in a single quantity of some substance. It is also known as **calorific value**.

The energy content can be expressed in any unit of energy: BTU, calories, joules, watt-hours, etc. The preferred unit is joules with the appropriate range of prefixes for kilojoules [kJ], megajoules [MJ], etc.

The unit quantity may be either of mass (kg) or of volume (cubic meters). It depends on the nature of the substance. For solids, it is usual to use unit mass, and for gases to use unit volume (together with a statement of pressure and temperature). For liquids, either mass or volume can be used.

The approximate Specific Energy values (NCV¹, LCV²) of some solid fuels are:

| | |
|---|------------------|
| Coal | 23 to 35 MJ/kg |
| Wood | 16 to 21 MJ/kg |
| Peat | 23 MJ/kg |
| Charcoal | 28 to 33 MJ/kg |
| Natural uranium – in light water reactor | 443 000 MJ/kg |
| Enriched uranium (3.5 %) – in light water reactor | 3 456 000 MJ/kg |
| Uranium - in fast breeder reactor | 24 000 000 MJ/kg |

The approximate Specific Energy values (NCV, LCV) of some gas fuels are:

| | |
|-------------|----------------------------|
| Coal gas | 19 to 22 MJ/m ³ |
| Natural gas | 37 MJ/m ³ |
| Acetylene | 56 MJ/m ³ |
| Propane | 93 MJ/m ³ |
| Butane | 110 MJ/m ³ |

All are based on particular pressure and temperature. Gas heating value varies with the geographical location.

Standard metric gas conditions are 101.325 kPa and 15 °C (dry).

Normal metric gas conditions 101.325 kPa and 0 °C (dry).

The approximate specific energy values (LCV) of some liquid fuels are:

| | |
|----------------|------------|
| Gasoline | 42.1 MJ/kg |
| Petroleum | 39.8 MJ/kg |
| Diesel | 41.8 MJ/kg |
| Heavy Fuel Oil | 41.8 MJ/kg |

Higher Heating Value (HHV), Gross Heating Value (GHV), Gross Calorific Value (GCV) and Total Calorific Value (TCV) are different terms for the same value. This can be defined as total heat obtained from combustion of a specified amount of fuel and its stoichiometrically correct amount of air, both being at 15.56 °C (60 °F) when combustion starts, and the combustion products being cooled to 15.56 °C (60 °F) before heat release is measured.

Lower Heating Value (LHV), Net Heating Value (NHV), Low Calorific Value (LCV) is lower than Total Calorific Value for the value of latent heat of vaporization of water formed in combustion.

Some typical values for the ratio of net to gross values are as follows:

| Fuel | Net/Gross Ratio |
|-------------|------------------------|
| Natural gas | 0.90 |
| Fuel oil | 0.94 |
| Coal | 0.98 |

Nuclear energy is totally different in both the method of production and the scale of released energy. As a very rough guide, the fission of a given mass of a suitable material (such as plutonium) produces something of the order of 3 million times the energy obtained from the same mass of an 'ordinary' fuel such as coal.

8. Density is mass of fluid in a unit volume, [kg/m³].

9. Dynamic viscosity is the tangential force per unit area required to move one horizontal plane with respect to the other at unit velocity when maintained at a unit distance apart by the fluid. It appears as a result of cohesion and interaction between molecules.

¹ NCV – Net Calorific Value

² LCV – Low Calorific Value (NCV = LCV)

Different fluids deform at different rates under the same shear forces. Fluid with a high viscosity such as syrup deforms more slowly than fluid with a low viscosity such as water.

Newtonian fluids obey the linear relationship given by the Newton's law of viscosity $\tau = \mu \cdot \frac{dw}{dx}$,

where τ is the shear stress and μ is the coefficient of dynamic viscosity.

Viscosity is resistance of a fluid to flow. This resistance acts against the motion of any solid object through the fluid and also against motion of the fluid itself past stationary obstacles. Viscosity also acts internally on the fluid between slower and faster moving adjacent layers.

All fluids (liquids and gases) exhibit viscosity to some degree. Viscosity may be thought of as fluid friction, just as the friction between two solids resists the motion of one over the other but also makes possible the acceleration of one relative to the other.

The dynamic viscosities of some fluids are presented in Table 4.4. It is very important to know the temperature of the fluid (and pressure).

Table 4.4: Dynamic Viscosity of Some Liquids and Gasses

| Liquid | | | | Gas | | | |
|----------|------------------------|--------|------------------------|------------------------|------------------------|-----------------------------|------------------------|
| Gasoline | | Water | | Air (dry) 1.013 bar | | Carbon Dioxide 1.013 bar | |
| t (°C) | μ [Pa s] | t (°C) | μ [Pa s] | t (°C) | μ [Pa s] | t (°C) | μ [Pa s] |
| 20 | 0.529×10^{-3} | 0 | 1.780×10^{-3} | 0 | 0.017×10^{-3} | 0 | 0.014×10^{-3} |
| 40 | 0.411×10^{-3} | 20 | 1.004×10^{-3} | 100 | 0.022×10^{-3} | 100 | 0.018×10^{-3} |
| 60 | 0.328×10^{-3} | 40 | 0.653×10^{-3} | 200 | 0.026×10^{-3} | 200 | 0.023×10^{-3} |
| 100 | 0.225×10^{-3} | 60 | 0.470×10^{-3} | 300 | 0.030×10^{-3} | 300 | 0.026×10^{-3} |
| | | 80 | 0.355×10^{-3} | 400 | 0.033×10^{-3} | 400 | 0.030×10^{-3} |
| | | 100 | 0.283×10^{-3} | 500 | 0.036×10^{-3} | 500 | 0.033×10^{-3} |

10. **Kinematic viscosity** is the ratio of absolute viscosity to density. For either dynamic or kinematic viscosity to be meaningful a reference temperature must be quoted.

11. **Thermal conductivity** is a measurement of the ability of a material to conduct heat. It is defined using the Fourier's law of conduction which relates the rate of heat transfer by conduction to the temperature gradient:

$$q = -k \cdot A \cdot \frac{dT}{dx} \quad (4.1)$$

where k is the thermal conductivity. Using the Fourier's law, we can define the thermal conductivity as the rate of heat transfer through a unit thickness of material per unit area and per unit temperature difference. A good conductor of heat has a high value of thermal conductivity.

The temperature variations of the thermal conductivities of some materials are presented in Table 5.

Table 4.5: Thermal Conductivity of Some Materials – k [W/(m K)]

| t (°C) | Solid | | Liquid | | Gas | |
|--------|--------|----------|----------|--------|------------------------|----------------------|
| | Copper | Aluminum | Gasoline | Water | Air (dry) 1.013 bar | Steam (saturated) |
| -100 | 407 | - | | | | |
| 0 | 386 | 221 | | | 0.0244 | 0.01760 |
| 100 | 379 | - | 0.1005 | 0.0680 | 0.0321 | 0.02372 |
| 200 | 373 | 229 | | 0.0670 | 0.0393 | 0.03547 |
| 300 | - | 222 | | 0.0558 | 0.0460 | 0.06270 |
| 500 | - | - | | | 0.0574 | |
| 700 | - | - | | | 0.0671 | |

12. *Specific heat* is the amount of heat that is required to raise the temperature of the unit mass of a substance by one degree. In a constant pressure process

$$q = m \cdot c_p \cdot \Delta T \quad (4.2)$$

c_p is specific heat at constant pressure.

Values of c_p [kJ/(kg K)] for various materials (at 20 °C) are shown in Table 4.6.

Table 4.6: Specific Heat at Constant Pressure of Some Materials

| SOLID | c_p kJ/(kg K) | LIQUID | c_p kJ/(kg K) | GAS | c_p kJ/(kg K) |
|-----------------|--------------------|---------------|--------------------|----------------|--------------------|
| Aluminum (pure) | 0.903 | Water | 4.18 | Air | 1.010 |
| Copper (pure) | 0.385 | Ethyl Alcohol | 2.29 | Nitrogen | 1.047 |
| Gold | 0.129 | Gasoline | 2.06 | Sulfur Dioxide | 0.633 |
| Silicon | 1.382 | Oil | 1.85 | Carbon Dioxide | 0.837 |

13. *Coefficient of thermal expansion* is defined as the change in the density of a substance as a function of temperature at constant pressure. It is expressed as follows:

$$\beta = -\frac{1}{\rho} \cdot \left(\frac{\Delta \rho}{\Delta T} \right)_p \quad (4.3)$$

For ideal gases $\left(\frac{p}{\rho} = R \cdot T \right)$ there is $\beta = \frac{1}{T}$.

14. *Thermal diffusivity* is measure of heat propagation through a medium and may be defined by the ratio of heat conducted through a material to the heat stored in the material. The thermal diffusivity is defined as:

$$a = \frac{k}{\rho \cdot c_p} \quad (4.4)$$

The larger the thermal diffusivity is the faster the propagation of heat into the material. If the thermal diffusivity is small, it means that a large part of heat is absorbed by the material and only a small portion is conducted through it. Some typical values of thermal diffusivity are given in Table 4.7 (0 °C, 1.013 bar).

Table 4.7: Thermal Diffusivity of Some Materials

| SOLID | a m^2/s | LIQUID | a m^2/s | GAS | a m^2/s |
|-------------|--------------------------|---------------|------------------------|----------------|-------------------------|
| Aluminum | 93.166×10^{-6} | Water | 0.131×10^{-6} | Air | 18.777×10^{-6} |
| Copper | 114.085×10^{-6} | Ethyl Alcohol | 0.100×10^{-6} | Nitrogen | 18.703×10^{-6} |
| Gold | 12.479×10^{-6} | Gasoline | 0.075×10^{-6} | Sulfur Dioxide | 4.711×10^{-6} |
| Polystyrene | 0.611×10^{-6} | Oil | 0.154×10^{-6} | Carbon Dioxide | 9.097×10^{-6} |

PHYSICAL PROPERTIES

15. Physical Properties of Selected Gases

Table 4.8: Physical Properties of Selected Gases (1.0 bar; 0 °C)

| Material | Density | Molar Mass | Gas Const. | Boiling Point | c_p | c_p/c_v | $10^6 \times \mu^*$ | K | Pr |
|-----------------------------------|-------------------|------------|------------|---------------|----------|-----------|---------------------|---------|------|
| | kg/m ³ | g/mol | J/(kg K) | °C | J/(kg K) | - | Pa s | W/(m K) | - |
| Air (dry)* | 1.293 | 28.95 | 287 | -195 | 1010 | 1.4 | 17.3 | 0.0245 | 0.71 |
| Argon [Ar] | 1.782 | 39.94 | 208.5 | -185.8 | 532 | 1.65 | 20.9 | 0.0173 | 0.64 |
| Carbon Dioxide [CO ₂] | 1.976 | 44.01 | 189 | - | 837 | 1.3 | 13.7 | 0.0137 | 0.84 |
| Carbon Monoxide [CO] | 1.25 | 28.01 | 297 | - | 1047 | 1.4 | 16.6 | 0.0226 | 0.77 |
| Helium [He] | 0.178 | 4.002 | 2079 | -268.9 | 5274 | 1.66 | 18.8 | 0.144 | 0.69 |
| Hydrogen [H ₂] | 0.0898 | 2.016 | 4125 | -252.9 | 14266 | 1.407 | 8.42 | 0.163 | 0.74 |
| Nitrogen [N ₂] | 1.251 | 28.02 | 296.7 | -195.8 | 1047 | 1.4 | 17 | 0.0228 | 0.78 |
| Oxygen [O ₂] | 1.429 | 32 | 259.9 | -182.9 | 913 | 1.4 | 20.3 | 0.024 | 0.77 |

* Normal composition of clean, dry atmospheric air near the sea level,

Nitrogen (N₂) = 78.084 %, Oxygen (O₂) = 20.948 %, Argon (Ar) = 0.934 %, Carbon Dioxide (CO₂) = 0.031 %

Neon (Ne), Helium (He), Krypton (Kr), Hydrogen (H₂), Xenon (Xe), Methane (CH₄), Nitrogen Oxide (N₂O), Ozone (O₃),

Sulfur Dioxide (SO₂), Ammonia (NH₃), Carbon Monoxide (CO), and Iodine (I₂) = traces of each gas for a total of 0.003 %

Formulae for the calculation of average constant-pressure specific heat – c_p [kJ/kg] of various gases in the range from 0 to 2000 °C are presented in Table 4.9.

Table 4.9: Average Specific Heat at Constant Pressure of some Gases

| Gas | Average Specific Heat at Constant Pressure: | Maximum Error |
|---------------------------------------|--|---------------|
| | $c_{p,0}^t$ [kJ/(kgK)] (t[°C]) (Range 0 to 2000 °C) | |
| Hydrogen (H ₂) | $= -1.08329E - 13 \cdot t^4 + 3.42031E - 10 \cdot t^3 - 3.56131E - 08 \cdot t^2 + 2.00328E - 04 \cdot t + 1.43810E + 01$ | 0.06 |
| Nitrogen (clean) (N ₂) | $= 2.07571E - 14 \cdot t^4 - 1.06900E - 10 \cdot t^3 + 1.73326E - 07 \cdot t^2 - 8.57115E - 06 \cdot t + 1.03937E + 00$ | 0.09 |
| Oxygen (O ₂) | $= 1.23574E - 14 \cdot t^4 - 4.43486E - 11 \cdot t^3 + 1.50961E - 08 \cdot t^2 + 1.44682E - 04 \cdot t + 9.07389E - 01$ | 0.12 |
| Carbon Monoxide (CO) | $= 2.51706E - 14 \cdot t^4 - 1.20740E - 10 \cdot t^3 + 1.76241E - 07 \cdot t^2 + 1.24096E - 05 \cdot t + 1.03823E + 00$ | 0.11 |
| Carbon Dioxide (CO ₂) | $= -1.56925E - 14 \cdot t^4 + 1.04359E - 10 \cdot t^3 - 2.98914E - 07 \cdot t^2 + 5.16236E - 04 \cdot t + 8.20310E - 01$ | 0.06 |
| Water Vapor (H ₂ O) | $= 2.35461E - 14 \cdot t^4 - 1.42139E - 10 \cdot t^3 + 2.67351E - 07 \cdot t^2 + 1.35306E - 04 \cdot t + 1.85773E + 00$ | 0.04 |
| Sulfur Dioxide (SO ₂) | $= -8.04281E - 15 \cdot t^4 + 6.53115E - 11 \cdot t^3 - 2.01319E - 07 \cdot t^2 + 3.21094E - 04 \cdot t + 6.06803E - 01$ | 0.12 |
| Air | $= 1.99627E - 14 \cdot t^4 - 9.68901E - 11 \cdot t^3 + 1.42841E - 07 \cdot t^2 + 2.18551E - 05 \cdot t + 1.00361E + 00$ | 0.09 |
| Nitrogen (form Air) (N ₂) | $= 1.48364E - 14 \cdot t^4 - 7.97576E - 11 \cdot t^3 + 1.31381E - 07 \cdot t^2 + 1.42726E - 05 \cdot t + 1.02694E + 00$ | 0.14 |

16. Physical Properties of Selected Liquids

Table 4.10: Physical Properties of Selected Liquids

| Liquid | t [°C] | ρ [kg/m ³] | c_p [kJ/(kg K)] | k [W/(m K)] | $\mu \times 10^3$ [Pa s] | $\beta \times 10^5$ [1/K] | a [m ² /s] |
|-------------------|--------|-----------------------------|-------------------|-------------|--------------------------|---------------------------|-----------------------|
| Acetone | 20 | 791 | 2.16 | 0.170 | 0.331 | 143 | |
| | 50 | 756 | 2.25 | 0.163 | - | - | |
| Gasoline | 20 | 751 | 2.06 | 0.1165 | 0.529 | 125 | |
| | 40 | 735 | 2.15 | - | 0.411 | - | |
| | 60 | 717 | 2.24 | - | 0.328 | - | |
| | 100 | 681 | 2.46 | 0.1005 | 0.225 | - | |
| Benzene | 20 | 879 | 1.738 | 0.154 | 0.65 | 124 | |
| Ethyl Alcohol | 0 | 806 | 2.29 | 0.185 | 1.78 | | |
| | 20 | 789 | 2.45 | 0.183 | 1.19 | | |
| | 50 | - | 2.81 | 0.178 | 0.695 | | |
| Ethylene Glycol | 20 | 1113 | 2.382 | 0.258 | 19.90 | | |
| | 40 | 1099 | 2.474 | - | 9.13 | | |
| | 60 | 1085 | 2.562 | - | 4.95 | | |
| | 80 | 1070 | 2.650 | - | 3.02 | | |
| | 100 | 1056 | 2.742 | 0.269 | 1.99 | | |
| Glycerin | 20 | 1260 | 2.35 | - | 1480 | 53 | |
| | 50 | 1244 | 2.50 | 0.283 | 180 | - | |
| | 100 | 1200 | 2.79 | 0.289 | 13 | - | |
| | 200 | 1090 | 3.34 | - | 0.22 | - | |
| Methyl Alcohol | 0 | 810 | 2.43 | 0.241 | 0.818 | | |
| | 20 | 792 | 2.47 | 0.212 | 0.585 | | |
| | 50 | 765 | 2.56 | - | 0.400 | | |
| Petroleum | 20 | 819 | 2.00 | - | 1.49 | 100 | |
| | 50 | 801 | 2.14 | 0.1114 | 0.956 | - | |
| | 100 | 766 | 2.38 | 0.1042 | 0.545 | - | |
| | 200 | 785 | 2.89 | 0.0891 | 0.262 | - | |
| Oil (lubricant) | 25 | 920 | 1.850 | 0.130 | 190 | | |
| | 50 | 905 | 1.943 | 0.128 | 42.9 | | |
| | 75 | 896 | 2.041 | 0.125 | 15.6 | | |
| | 100 | 880 | 2.136 | 0.123 | 5.72 | | |
| Oil (transformer) | 25 | 860 | 1.918 | 0.123 | 24.20 | | |
| | 50 | 845 | 2.043 | 0.122 | 9.90 | | |
| | 75 | 835 | 2.169 | 0.120 | 4.77 | | |
| | 100 | 820 | 2.294 | 0.117 | 3.02 | | |

17. Thermodynamic and Transport Properties of Water and Steam

a. Some of thermodynamic properties of water are:

| | |
|--------------------|---|
| H ₂ O = | Chemical formula |
| M = | 18.016 [kg/kmol] (Molecular Mass) |
| t _c = | 374.15 [°C] (Critical Temperature) |
| T _c = | 647.286 [K] (Absolute Critical Temperature) |
| p _c = | 220.89 [bar] (Critical Pressure) |
| ρ_c = | 317.0 [kg/m ³] (Critical Density) |
| t _m = | 0.01 [°C] (Melting Temperature at 1.01325 bar) |
| r _m = | 332.432 [kJ/kg] (Heat of Melting at 1.01325 bar) |
| t _b = | 100.0 [°C] (Boiling Temperature at 1.01325 bar) |
| r _b = | 2257.0 [kJ/kg] (Heat of Evaporation at 1.01325 bar) |
| R = | 462.507 [J/(kg K)] (Gas Constant) |

- Enthalpies and entropies of boiling water and saturated steam versus temperature and pressure (0.01 < p < 20 bar; 7 < t < 212 °C)

a. Saturated steam and boiling water temperature versus pressure³

$$\begin{aligned}
 t = & 5.518190E - 05 \cdot 10^{-5} \cdot [\ln(p)]^6 + 1.285144 \cdot 10^{-3} \cdot [\ln(p)]^5 + \\
 & 1.786280 \cdot 10^{-2} \cdot [\ln(p)]^4 + 2.118802 \times 10^{-1} \cdot [\ln(p)]^3 + \\
 & 2.397684 \cdot [\ln(p)]^2 + 2.794824 \cdot 10^{+1} \cdot [\ln(p)] + 9.963430 \cdot 10^{+1}
 \end{aligned} \quad (4.5)$$

Error is in the range ± 0.07 %

b. Saturated steam and boiling water pressure versus temperature

$$\begin{aligned}
 p = \exp[& -7.789316 \cdot 10^{-15} \cdot t^6 + 7.363934 \cdot 10^{-12} \cdot t^5 - 3.381446 \cdot 10^{-9} \cdot t^4 + \\
 & 1.096061 \cdot 10^{-6} \cdot t^3 - 2.974345 \cdot 10^{-4} \cdot t^2 + 7.261845 \cdot 10^{-2} \cdot t - 5.098158]
 \end{aligned} \quad (4.6)$$

Error is in the range of ± 0.05 %

c. Enthalpy of boiling water versus temperature

$$\begin{aligned}
 h' = & 8.33022 \cdot 10^{-9} \cdot t^4 + 7.06612 \cdot 10^{-7} \cdot t^3 - 7.23854 \cdot 10^{-5} \cdot t^2 \\
 & + 4.17927 \cdot t + 3.59463 \cdot 10^{-1}
 \end{aligned} \quad (4.7)$$

d. Enthalpy of saturated steam versus temperature

$$\begin{aligned}
 h'' = & -3.32313 \cdot 10^{-8} \cdot t^4 + 1.51237 \cdot 10^{-6} \cdot t^3 - 1.03177 \cdot 10^{-3} \cdot t^2 \\
 & + 1.87334 \cdot t + 2500.44
 \end{aligned} \quad (4.8)$$

e. Entropy of boiling water versus pressure

$$\begin{aligned}
 s' = & 9.73390 \times 10^{-5} \cdot (\ln(p))^4 + 1.45398 \cdot 10^{-4} \cdot (\ln(p))^3 + 1.67802 \cdot 10^{-3} \cdot (\ln(p))^2 \\
 & + 3.15672 \times 10^{-2} \cdot \ln(p) + 1.30250
 \end{aligned} \quad (4.9)$$

f. Entropy of saturated steam versus pressure

$$\begin{aligned}
 s'' = & -5.38843 \times 10^{-4} \cdot (\ln(p))^3 + 7.60363 \cdot 10^{-4} \cdot (\ln(p))^2 - 3.36497 \cdot 10^{-1} \cdot \ln(p) + 7.36130
 \end{aligned} \quad (4.10)$$

- **Water properties** (temperatures from 0 to 300 °C)
(From 0 to 100 °C at 1.013 bar and for higher temperatures for boiling pressure)

g. Density ρ [kg/m³]

$$\begin{aligned}
 \rho = & -6.44703 \cdot 10^{-13} \cdot t^6 + 5.56465 \cdot 10^{-10} \cdot t^5 - 2.08168 \cdot 10^{-7} \cdot t^4 + 4.28877 \cdot 10^{-5} \cdot t^3 \\
 & - 7.26539 \cdot 10^{-3} \cdot t^2 + 4.10381 \cdot 10^{-2} \cdot t + 9.99945 \cdot 10^2
 \end{aligned} \quad (4.11)$$

³ ln - natural logarithm

h. Specific heat at constant pressure c_p [J/(kg K)]

$$c_p = 4.00424 \times 10^{-11} \cdot t^6 - 3.17259 \cdot 10^{-8} \cdot t^5 + 9.76851 \cdot 10^{-6} \cdot t^4 - 1.42353 \cdot 10^{-3} \cdot t^3 + 1.09452 \cdot 10^{-1} \cdot t^2 - 3.70637 \cdot 10^{-0} \cdot t + 4.21629 \cdot 10^3 \quad (4.12)$$

i. Thermal conductivity λ [W/(m K)]

$$\lambda \cdot 10^2 = 3.65944 \cdot 10^{-11} \cdot t^6 - 1.87737 \cdot 10^{-11} \cdot t^5 - 7.40918 \cdot 10^{-9} \cdot t^4 + 6.72554 \cdot 10^{-6} \cdot t^3 - 2.10253 \cdot 10^{-3} \cdot t^2 + 2.85413 \cdot 10^{-1} \cdot t + 5.49688 \cdot 10^1 \quad (4.13)$$

j. Thermal diffusivity a [m²/s]

$$a = \frac{\lambda}{c_p \cdot \rho} \quad (4.14)$$

k. Dynamic viscosity μ [Pa s]

$$\mu \cdot 10^6 = \text{Exp}(-2.91877 \cdot 10^{-12} \cdot t^5 + 2.72328 \cdot 10^{-9} \cdot t^4 - 1.03401 \cdot 10^{-6} \cdot t^3 + 2.18237 \cdot 10^{-2} \cdot t^2 - 3.22128 \cdot 10^{-2} \cdot t + 7.48230) \quad (4.15)$$

l. Kinematic viscosity ν [m²/s]

$$\nu = \frac{\mu}{\rho} \quad (4.16)$$

m. Coefficient of volume expansion β [1/K]

$$\beta \cdot 10^4 = -1.28773 \cdot 10^{-13} \cdot t^6 + 1.70218 \cdot 10^{-10} \cdot t^5 - 7.46034 \cdot 10^{-8} \cdot t^4 + 1.58931 \cdot 10^{-5} \cdot t^3 - 1.82013 \cdot 10^{-3} \cdot t^2 + 1.63711 \cdot 10^{-1} \cdot t - 6.84475 \cdot 10^{-1} \quad (4.17)$$

Some important properties for heat transfer calculations are presented in Table 4.8. It is obvious that they depend on temperature much more than on pressure. Because of that, for almost all industrial calculations, the influence of pressure can be ignored.

Table 4.11: Water Density, Specific Heat, Thermal Conductivity and Dynamic Viscosity versus Temperature and Pressure

| p [bar] | ρ [kg/m ³] | | | c_p [J/(kg × K)] | | | λ [W/(m × K)] | | | $\mu \times 10^6$ [Pa × s] | | |
|---------|-----------------------------|--------|--------|--------------------|-------|-------|-----------------------|-------|-------|----------------------------|-------|-------|
| | 0.981 | 98.07 | 196.1 | 0.981 | 98.07 | 196.1 | 0.981 | 98.07 | 196.1 | 0.981 | 98.07 | 196.1 |
| t [°C] | | | | | | | | | | | | |
| 0 | 999.8 | 1004.8 | 1009.6 | 4216 | 4195 | 4178 | 0.551 | 0.555 | 0.558 | 1785 | 1776 | 1756 |
| 10 | 999.7 | 1004.2 | 1008.7 | 4191 | 4178 | 4158 | 0.576 | 0.579 | 0.584 | 1305 | 1295 | 1295 |
| 20 | 998.2 | 1002.5 | 1006.7 | 4183 | 4162 | 4141 | 0.599 | 0.604 | 0.608 | 1001 | 1001 | 1001 |
| 30 | 995.6 | 999.9 | 1004 | 4174 | 4158 | 4132 | 0.618 | 0.622 | 0.628 | 802 | 803 | 803 |
| 40 | 992.2 | 996.4 | 1000.5 | 4174 | 4153 | 4128 | 0.634 | 0.638 | 0.644 | 653 | 655 | 657 |
| 50 | 988.0 | 992.4 | 996.4 | 4174 | 4153 | 4128 | 0.648 | 0.652 | 0.657 | 549 | 551 | 554 |
| 60 | 983.3 | 987.6 | 991.8 | 4178 | 4153 | 4128 | 0.659 | 0.664 | 0.669 | 470 | 472 | 475 |
| 70 | 977.8 | 982.2 | 986.5 | 4178 | 4158 | 4132 | 0.668 | 0.672 | 0.678 | 406 | 408 | 411 |

| | | | | | | | | | | | | |
|-----|-------|-------|-------|------|------|-------|-------|-------|-------|-----|-----|-----|
| 80 | 971.8 | 976.3 | 980.6 | 4195 | 4166 | 4141 | 0.674 | 0.679 | 0.685 | 355 | 357 | 360 |
| 90 | 965.3 | 969.8 | 974.2 | 4208 | 4174 | 4149 | 0.68 | 0.685 | 0.691 | 315 | 317 | 320 |
| 100 | | 963 | 967.4 | | 4187 | 4158 | | 0.69 | 0.695 | | 285 | 287 |
| 150 | | 922.1 | 927.3 | | 4275 | 4237 | | 0.693 | 0.699 | | 188 | 190 |
| 200 | | 870.7 | 877.6 | | 4455 | 4396 | | 0.672 | 0.679 | | 138 | 140 |
| 250 | | 805.9 | 816.1 | | 4781 | 4681 | | 0.624 | 0.636 | | 112 | 115 |
| 300 | | 715.4 | 734.6 | | 5661 | 5275 | | 0.542 | 0.558 | | 91 | 94 |
| 350 | | | 600.6 | | | 8206 | | | 0.452 | | | 75 |
| 360 | | | 547 | | | 12560 | | | 0.412 | | | 69 |

• Saturated steam properties ($0 < t < 210$ °C or $0.006 \text{ bar} < p < 19.08 \text{ bar}$)

n. Density of saturated steam

$$\rho'' = 0.000144118 \cdot p^3 - 0.00557908 \cdot p^2 + 0.554983 \cdot p + 0.0203297 \quad (4.18)$$

o. Specific heat at constant pressure of saturated steam

$$c_p'' = 0.0000995693 \cdot t^3 + 0.00461955 \cdot t^2 + 0.784614 \cdot t + 1864.59 \quad (4.19)$$

p. Thermal conductivity of saturated steam

$$\lambda'' \times 10^2 = 0.000000643939 \cdot t^3 - 0.000261738 \cdot t^2 + 0.0474611 \cdot t - 0.404835 \quad (4.20)$$

q. Dynamic viscosity of saturated steam

$$\mu'' \times 10^6 = 0.00000762281 \cdot t^2 + 0.0375325 \cdot t + 8.1587 \quad (4.21)$$

• Superheated steam properties ($250 < t < 550$ °C or $19.61 \text{ bar} < p < 58.84 \text{ bar}$)

Table 4.12: Superheated Steam

| p[bar] | ρ [kg/m ³] | | | c_p [J/(kg × K)] | | | $\lambda \times 10^2$ [W/(m × K)] | | | $\mu \times 10^{-6}$ [Pa × s] | | |
|--------|-----------------------------|-------|-------|--------------------|-------|-------|-----------------------------------|-------|-------|-------------------------------|-------|-------|
| | 19.61 | 39.23 | 58.84 | 19.61 | 39.23 | 58.84 | 19.61 | 39.23 | 58.84 | 19.61 | 39.23 | 58.84 |
| t [°C] | | | | | | | | | | | | |
| 220 | 9.588 | | | 2935 | | | 3.73 | | | 16.8 | | |
| 230 | 9.285 | | | 2784 | | | 3.83 | | | 17.4 | | |
| 240 | 9.025 | | | 2633 | | | 3.93 | | | 17.7 | | |
| 250 | 8.787 | 19.62 | | 2554 | 3647 | | 4.03 | 4.53 | | 18.1 | 18.3 | |
| 280 | | | 29.37 | | | 4438 | | | 5.32 | | | 19.8 |
| 290 | | | 28.08 | | | 4.028 | | | 5.05 | | | 20.2 |
| 300 | 7.806 | 16.61 | 26.95 | 2311 | 2788 | 3621 | 4.56 | 4.79 | 5.10 | 20.1 | 20.3 | 20.5 |
| 350 | 7.082 | 14.71 | 23.13 | 2219 | 2478 | 2834 | 5.12 | 5.31 | 5.57 | 22.2 | 22.3 | 22.5 |
| 400 | 6.485 | 13.35 | 20.64 | 2198 | 2365 | 2554 | 5.70 | 5.87 | 6.08 | 24.3 | 24.4 | 24.6 |
| 450 | 5.999 | 12.25 | 18.77 | 2202 | 2319 | 2445 | 6.29 | 6.44 | 6.63 | 26.5 | 26.7 | 26.8 |
| 500 | 5.587 | 11.34 | 17.29 | 2206 | 2294 | 2386 | 6.93 | 7.06 | 7.22 | 28.7 | 28.8 | 28.9 |
| 550 | | | 16.06 | | | 2353 | | | 7.84 | | | 31.2 |

18. Physical Properties of Selected Solid Materials

Table 4.13: Properties of Selected Solids at 25 °C

| Substance | ρ kg/m ³ | c_p [kJ/(kg K)] |
|--------------------|-----------------------------|----------------------|
| Asphalt | 2120 | 1.67 |
| Brick (common) | 1800 | 0.84 |
| Carbon (diamond) | 3250 | 0.51 |
| Carbon (graphite) | 2000–2500 | 0.61 |
| Coal | 1200–1500 | 1.26 |
| Concrete | 2200 | 0.88 |
| Glass (plate) | 2500 | 0.80 |
| Glass (wool) | 200 | 0.66 |
| Granite | 2750 | 0.89 |
| Ice (0 °C) | 917 | 2.04 |
| Paper | 700 | 1.20 |
| Plexiglas | 1180 | 1.44 |
| Polystyrene | 920 | 2.30 |
| Polyvinyl chloride | 1380 | 0.96 |
| Rubber (soft) | 1100 | 1.67 |
| Salt (rock) | 2100–2500 | 0.92 |
| Sand (dry) | 1500 | 0.80 |
| Silicon | 2330 | 0.70 |
| Snow (firm) | 560 | 2.10 |
| Wood (hard, oak) | 720 | 1.26 |
| Wood (soft, pine) | 510 | 1.38 |
| Wool | 100 | 1.72 |

Table 4.14: Properties of Selected Metals at 25 °C

| Metals | ρ kg/m ³ | c_p [kJ/(kg K)] |
|---------------------|-----------------------------|----------------------|
| Aluminum | 2700 | 0.90 |
| Copper (commercial) | 8300 | 0.42 |
| Brass (60-40) | 8400 | 0.38 |
| Gold | 19300 | 0.13 |
| Iron (cast) | 7272 | 0.42 |
| Iron (Steel 304 St) | 7820 | 0.46 |
| Lead | 11340 | 0.13 |
| Magnesium (2 % Mn) | 1778 | 1.00 |
| Nickel (10 % Cr) | 8666 | 0.44 |
| Silver (99.9 Ag) | 10524 | 0.24 |
| Sodium | 971 | 1.21 |
| Tin | 7304 | 0.22 |
| Tungsten | 19300 | 0.13 |
| Zinc | 7144 | 0.39 |

Table 4.15: Thermal Expansion Coefficients and Thermal Conductivity of Solids

| Material | Thermal Expansion Coefficient ($\times 10^{-6}/^{\circ}\text{C}$) | Thermal Conductivity ($\text{W/m}\cdot\text{K}$) |
|-----------------------------|---|--|
| Aluminum | 23.0 | 237 |
| Aluminum Alloy | 23.0 | – |
| Brass | 19.1 – 21.2 | – |
| Brass; Noval | 21.1 | – |
| Brass; Red (80% Cu, 20% Zn) | 19.1 | – |
| Brick | 5.00 – 7.00 | – |
| Bronze; Regular | 18.0 – 21.0 | – |
| Bronze; Manganese | 20.0 | – |
| Concrete | 7.00 – 14.0 | – |
| Copper | 16.6 – 17.6 | 410 |
| Copper Alloy | 17.0 | – |
| Glass | 5.00 – 11.0 | – |
| Gold | – | 317 |
| Iron | – | 80.2 |
| Iron (Cast) | 9.90 – 12.0 | – |
| Iron (Wrought) | 12.0 | – |
| Lead | – | 35.3 |
| Magnesium | 25.2 | 156 |
| Magnesium Alloy | 26.1 – 28.8 | – |
| Monel (67% Ni, 30% Cu) | 14.0 | – |
| Nickel | 13.0 | 90.7 |
| Nylon; Polyamide | 75.0 – 100 | – |
| Platinum | – | 71.6 |
| Rubber | 130 – 200 | – |
| Silicon | – | 148 |
| Silver | – | 429 |
| Solder; Tin-Lead | – | 30.0 – 49.8 |
| Steel | 10.0 – 18.0 | – |
| Tin | – | 66.6 |
| Titanium | – | 21.9 |
| Titanium Alloy | 8.00 – 10.0 | – |
| Tungsten | 4.30 | 174 |
| Zinc | 30.2 | 116 |

Table 4.16: Density, Melting and Boiling Points of Solids

| Material | Density [$\times 1000 \text{ kg/m}^3$] | Melting Point [$^{\circ}\text{C}$] | Boiling Point [$^{\circ}\text{C}$] |
|--------------------------------|--|--------------------------------------|--------------------------------------|
| Aluminum | 2.71 | 660.3 | 2519 |
| Aluminum Alloy | 2.64 – 2.8 | 565.0 – 660.0 | – |
| Brass | 8.4 – 8.75 | 930.0 | – |
| Brass; Noval | 8.4 | – | – |
| Brass; Red (80% Cu, 20% Zn) | 8.75 | 1000 | – |
| Brick (Compression) | 1.8 – 2.4 | – | – |
| Bronze; Regular | 7.8 – 8.8 | 1050 | – |
| Bronze; Manganese | 8.3 | – | – |
| Carbon | 2.25 | 4492 | 3642 |
| Ceramic | 2 – 3 | 3870 | – |
| Concrete | 2.3 – 2.4 | – | – |
| Copper | 8.94 | 1085 | 2562 |
| Copper Alloy | 8.23 | 925.0 | – |
| Cork | 0.15 – 0.2 | – | – |
| Glass | 2.4 – 2.8 | – | – |
| Gold | 19.32 | 1064 | 2856 |
| Iron (Cast) | 7.87 | 1538 | 2861 |
| Iron (Wrought) | 7 – 7.4 | – | – |
| Magnesium [Mg] | 7.4 – 7.8 | – | – |
| Magnesium Alloy | 11.3 | 327.5 | 1749 |
| Monel (67% Ni, 30% Cu) | 1.74 | 650.0 | 1090 |
| Nickel [Ni] | 1.77 | 1246 | 2061 |
| Nylon; Polyamide | 8.84 | 1330 | – |
| Platinum | 8.89 | 1455 | 2913 |
| Rubber | 1.1 | – | – |
| Silver | 21.4 | 1768 | 3825 |
| Solder; Tin-Lead | 0.96 – 1.3 | – | – |
| Steel | 2.33 | 1382 | – |
| Stone; Granite (Compression) | 10.49 | 961.8 | 2162 |
| Stone; Limestone (Compression) | 8.17 – 11.34 | 215.0 | – |
| Stone; Marble (Compression) | 7.85 | 1425 | – |
| Tin | 2.6 | – | – |
| Titanium | 2 – 2.9 | – | – |
| Titanium Alloy | 2.6 – 2.9 | – | – |
| Wood; Ash (Bending) | 2.6 | – | – |
| Wood; Douglas Fir (Bending) | 7.3 | 231.9 | 2602 |
| Wood; Oak (Bending) | 4.54 | 1668 | 3287 |
| Wood; Southern Pine (Bending) | 4.51 | – | – |
| Zinc | 19.3 | 3422 | 5555 |

19. Software IV – 4: Thermodynamic Properties of Water and Steam

Water and steam are probably the most frequently used fluids in industry. This is the reason why they are accorded such special attention in this Toolbox. This paragraph provides all of the relevant constants and equations used for the creation of software which enables the computation of the thermodynamic properties of water and steam.

Software can be used for solving the following ten problems that appear in practice:

1. Given T [$^{\circ}\text{C}$] and v [m^3/kg]
2. Given T [$^{\circ}\text{C}$] and P [bar]
3. Given T [$^{\circ}\text{C}$] and h [kJ/kg]
4. Given T [$^{\circ}\text{C}$] and s [kJ/(kg K)]
5. Given v [m^3/kg] and P [bar]
6. Given v [m^3/kg] and h [kJ/kg]
7. Given v [m^3/kg] and s [kJ/(kg K)]
8. Given P [bar] and h [kJ/kg]
9. Given P [bar] and s [kJ/(kg K)]
10. Given s [kJ/(kg K)] and h [kJ/kg]

The software calculates the saturated parameters of water for the first of given values if this value is lower than the critical one.

Constants:

$$\begin{aligned} T_c &= 647.286 \text{ K} \\ P_c &= 22.089 \text{ MPa} \\ \rho_c &= 317.0 \text{ kg/m}^3 \\ T_o &= 273.16 \text{ [K]} \end{aligned}$$

$$\begin{aligned} R &= 461.518 \text{ [J/(kg K)]} \\ T_p &= 338.15 \\ u_o &= 2375020.7 \text{ [J/kg]} \\ s_o &= 6696.5776 \text{ [J/(kg K)]} \end{aligned}$$

$$\begin{aligned} E &= 0.0048 \\ a &= 0.01 \\ T_a &= 1000 \\ \tau_c &= 1.544912141 \\ a &= 0.01 \end{aligned}$$

(a) Pressure – Specific Volume – Temperature Equation - $P = P(v, T)$

$$P = \rho \cdot R \cdot T \cdot \left[1 + \rho \cdot Q + \rho^2 \cdot \left(\frac{\partial Q}{\partial \rho} \right)_T \right] \quad (4.22)$$

Where

$$Q = \left(-\tau_c \right) \sum_{j=1}^7 \left(-\tau_{a,j} \right)^{j-2} \cdot \left[\sum_{i=1}^8 A_{i,j} \cdot \left(-\rho_{a,j} \right)^{i-1} + e^{-E \times \rho} \cdot \sum_{i=9}^{10} A_{i,j} \cdot \rho^{i-9} \right] \quad (4.23)$$

$$\left(\frac{\partial Q}{\partial \rho} \right)_T = \left(-\tau_c \right) \sum_{j=1}^7 \left(-\tau_{a,j} \right)^{j-2} \cdot \left[\sum_{i=2}^8 A_{i,j} \cdot (i-1) \cdot \left(-\rho_{a,j} \right)^{i-2} - e^{-E \times \rho} \cdot \left(-\tau_c \right) \cdot A_{9,j} - (1 - E \times \rho) \cdot A_{10,j} \right] \quad (4.24)$$

and

$$\tau = \frac{T_a}{T}; \quad \tau_{a,1} = \tau_c; \quad \tau_{a,j} = 2.5 \quad \text{for } j = 2, 3, \dots, 7$$

$$\rho_{a,1} = 634; \quad \rho_{a,j} = 1000 \quad \text{for } j = 2, 3, \dots, 7$$

$$\begin{aligned} A(1, 1) &= 0.029492937 \\ A(4, 1) &= -3.6093828\text{E-}10 \\ A(7, 1) &= 1.5518535\text{E-}19 \\ A(10, 1) &= -0.0004160586 \end{aligned}$$

$$\begin{aligned} A(2, 1) &= -0.00013213917 \\ A(5, 1) &= 3.4218431\text{E-}13 \\ A(8, 1) &= 5.9728487\text{E-}24 \end{aligned}$$

$$\begin{aligned} A(3, 1) &= 0.00000027464632 \\ A(6, 1) &= -2.4450042\text{E-}16 \\ A(9, 1) &= -0.41030848 \end{aligned}$$

| | | |
|---------------------------|-----------------------------|-----------------------------|
| A(1, 2) = -0.005198586 | A(2, 2) = 0.0000077779182 | A(3, 2) = -0.00000033301902 |
| A(4, 2) = -1.6254622E-11 | A(5, 2) = -1.7731074E-13 | A(6, 2) = 1.2748742E-16 |
| A(7, 2) = 1.3746153E-19 | A(8, 2) = 1.5597836E-22 | A(9, 2) = 0.3373118 |
| A(10, 2) = -0.00020988866 | | |
| A(1, 3) = 0.0068335354 | A(2, 3) = -0.000026149751 | A(3, 3) = 0.00000065326396 |
| A(4, 3) = -2.6181978E-11 | A(5, 3) = 0 | A(6, 3) = 0 |
| A(7, 3) = 0 | A(8, 3) = 0 | A(9, 3) = -0.13746618 |
| A(10, 3) = -0.00073396848 | | |
| A(1, 4) = -0.0001564104 | A(2, 4) = -0.00000072546108 | A(3, 4) = -9.2734289E-09 |
| A(4, 4) = 4.312584E-12 | A(5, 4) = 0 | A(6, 4) = 0 |
| A(7, 4) = 0 | A(8, 4) = 0 | A(9, 4) = 0.0067874983 |
| A(10, 4) = 0.000010401717 | | |
| A(1, 5) = -0.0063972405 | A(2, 5) = 0.000026409282 | A(3, 5) = -0.00000047740374 |
| A(4, 5) = 5.632313E-11 | A(5, 5) = 0 | A(6, 5) = 0 |
| A(7, 5) = 0 | A(8, 5) = 0 | A(9, 5) = 0.13687317 |
| A(10, 5) = 0.0006458188 | | |
| A(1, 6) = -0.0039661401 | A(2, 6) = 0.000015453061 | A(3, 6) = -0.0000002914247 |
| A(4, 6) = 2.9568796E-11 | A(5, 6) = 0 | A(6, 6) = 0 |
| A(7, 6) = 0 | A(8, 6) = 0 | A(9, 6) = 0.07984797 |
| A(10, 6) = 0.0003991757 | | |
| A(1, 7) = -0.00069048554 | A(2, 7) = 0.0000027407416 | A(3, 7) = -0.00000005102807 |
| A(4, 7) = 3.9636085E-12 | A(5, 7) = 0 | A(6, 7) = 0 |
| A(7, 7) = 0 | A(8, 7) = 0 | A(9, 7) = 0.013041253 |
| A(10, 7) = 0.000071531353 | | |

(b) Ideal as isochoric specific heat equation – $c_v^0 = c_v^0(T)$

$$c_v^0 = \sum_{i=1}^6 G(i) \cdot T^{i-2} \quad (4.25)$$

where:

$$\begin{aligned} G(1) &= 46000 \\ G(2) &= 1011.249 \\ G(3) &= 0.83893 \\ G(4) &= -0.000219989 \\ G(5) &= 0.000000246619 \\ G(6) &= -0.00000000097047 \end{aligned}$$

(c) Saturation Pressure Equation – $p_{\text{sat}} = p_{\text{sat}}(T_{\text{sat}})$

$$\ln\left(\frac{p_{\text{sat}}}{P_c}\right) = \left(\frac{T_c}{T_{\text{sat}}} - 1\right) \cdot \sum_{i=1}^8 F(i) \cdot \left[\frac{T_c}{T_{\text{sat}}} - T_p\right]^{i-1} \quad (4.26)$$

where:

$$\begin{aligned} F(1) &= -7.419242 \\ F(2) &= 0.29721 \\ F(3) &= -0.1155286 \\ F(4) &= 0.008685635 \\ F(5) &= 0.001094098 \end{aligned}$$

$$\begin{aligned} F(6) &= -0.00439993 \\ F(7) &= 0.002520658 \\ F(8) &= -0.0005218684 \end{aligned}$$

(d) Saturated Liquid Density Equation – $\rho_f = \rho_f(T_{sat})$

$$\rho_f = \rho_c \cdot \left[1 + \sum_{i=1}^8 D(i) \cdot \left(1 - \frac{T}{T_c} \right)^{i/3} \right] \quad (4.27)$$

where:

$$\begin{aligned} D(1) &= 3.6711257 \\ D(2) &= -28.512396 \\ D(3) &= 222.6524 \\ D(4) &= -882.43852 \\ D(5) &= 2000.2765 \\ D(6) &= -2612.2557 \\ D(7) &= 1829.7674 \\ D(8) &= -533.5052 \end{aligned}$$

(e) The specific internal energy of a simple compressible substance is generally expressible as:

$$u = u_0 + \int_{T_0}^T c_v^0(T) \cdot dT + \int_0^{\rho} \frac{1}{\rho^2} \left[P - T \left(\frac{\partial P}{\partial T} \right)_{\rho} \right] \cdot d\rho \quad (4.28)$$

The first integration is at zero density and the second is at constant temperature. $T_0 = 200$ [K] is chosen reference temperature. The constant u_0 is simply a term used to set the datum for u as desired.

The enthalpy of such a substance is:

$$h = u + P \cdot v \quad (4.29)$$

Datum for water is set to be:

$$u_0 = 2375020.7 \text{ [J/kg]}$$

The entropy is determined as:

$$s = s_0 + \int_{T_0}^T \frac{c_v^0(T)}{T} \cdot dT - R \cdot \ln(\rho) + \int_0^{\rho} \frac{1}{\rho^2} \left[\rho \cdot R - \left(\frac{\partial P}{\partial T} \right)_{\rho} \right] \cdot d\rho \quad (4.30)$$

Here, s_0 is a constant that can be chosen to set the datum for s as desired. For water, it is set as:

$$s_0 = 6696.5776 \text{ [J/(kg K)]}$$

The enthalpy of vaporization is calculated from the Clapeyron equation:

$$h_{fg} = T \cdot \left(v_g - v_f \right) \cdot \frac{dP_{sat}}{dT_{sat}} \quad (4.31)$$

The specific enthalpy of boiling liquid is:

$$h_f = h_v - h_{fg} \quad (4.32)$$

The entropy of vaporization is given by:

$$s_{fg} = \frac{h_{fg}}{T} \quad (4.33)$$

and the specific entropy of boiling liquid is:

$$s_f = s_v - s_{fg} \quad (4.34)$$

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