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Ambient Air

1.1 Overview

The atmosphere is a mixture of gases and water separating the planet from space. Its maximum thickness is of the order of 8000 km. The mass of dry gas is of the order of 5.1×10^{18} kg, whilst the mass of water is about 1.3×10^{13} kg. Its interface with space is gradual, becoming indistinct at the outer edge. Its composition and density are, however, by no means constant throughout its thickness.

The ***troposphere*** is a dense turbulent layer closest to the earth comprising ~80% by mass of the earth's atmosphere. Its thickness varies from 8 km at the poles to 18 km at the equator. Seasonal variations in thickness can also occur.

An often-used average value is 11 km. It contains ~90% of the planet's atmospheric water content and is home to the world's weather systems. Its mass/energy interaction with the other components of the planet's environments and incoming solar radiation is central to life. We inhabit the very base level of this stratum.

Learning Outcomes

- To appreciate the importance of clean, fresh air to human health
- To be able to differentiate between fresh and respired air in terms of composition
- To be familiar with the basic thermodynamic properties of air
- To be able to evaluate air energy content

1.2 Why Ambient Air Is Important?

Humans cannot survive without air. On the spectrum of human needs, air is special. We are able to choose what to eat and drink, but this is not the case for the air we breathe.

Close to the planetary surface, the air comprises a mixture of oxygen and nitrogen in combination with a much smaller proportion of other elements. In the human body, the oxygen is absorbed by the blood stream in the lungs. Oxygen supports our life and oxidises or '*burns*' food to create energy for metabolic processes and heat for our bodies. This production of energy is termed respiration. Breathing is the means of obtaining the oxygen and

Building Services Engineering: Smart and Sustainable Design for Health and Wellbeing, First Edition.
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the removal of gaseous by-products. The by-products of the process are carbon dioxide and water vapour.

The human body also needs nitrogen, but this is obtained by other means.

It is essential to maintain the necessary quality of atmospheric air in the internal environment, hence the need for impurity or pollution removal and the control of temperature and humidity.

Poor indoor air quality (IAQ) results in poor health. The human health effects of poor air quality are far reaching but principally affect the body's respiratory system and the cardiovascular system. Individual reactions to low-quality air depend on the type of environment a person is exposed to, the degree of exposure, and the individual's health status and genetics.

Poor air quality sources can be divided into three broad categories, i.e. physical, chemical, and biological. In physical terms, the main problem is an inappropriate amount of heat and moisture. Particulates also play a major role, and sometimes noise and static electricity charge/discharge is added to this group. Chemical hazards include a wide range of compounds, e.g. carbon dioxide, carbon monoxide, volatile organic compounds (VOCs), etc. The biological category covers the presence of such hazards as bacteria, viruses, and moulds.

All of these unwanted contaminants can be minimised or even prevented if air quality is monitored and controlled.

To achieve this goal, familiarity with air composition and behaviour is essential.

1.3 Air Composition

The approximate composition of lower atmospheric 'clean' air is shown in Table 1.1. By volume, it largely comprises nitrogen (~78%) and oxygen (~21%) plus other gases present in much smaller volumes.

Oxygen is required by humans for cellular respiration. The human respiratory/pulmonary system comprises a series of dividing tubes and sacs (*alveoli*) supported and moved by bones and muscles. When a pressure slightly below atmospheric pressure is created in the system, then air is inhaled. When a pressure slightly greater than atmospheric pressure is created, air is exhaled. However, the system is never completely emptied and there is always a residual air volume. Gaseous exchange takes place at blood vessels in the alveoli. Oxygen is taken up by the blood and carried to the body's cells. At the same time, carbon dioxide which is a by-product of the respiration process is released from the blood to the alveolar air.

Adults at rest normally take between 12 and 20 breaths per minute. The average person at rest needs about 500 l of air per hour. This has an oxygen content of 130 g.

However, the absorption of oxygen does not have an efficiency of 100% and exhaled breath has an approximate oxygen content of 14–16%.

As detailed in Table 1.1, the carbon dioxide content of atmospheric air is approximately 0.04%. As a result of respiration, the CO_2 content of exhaled breath is closer to 4% by volume. Where intensive metabolic activity takes place (e.g. gymnasiums), the metabolic CO_2

Table 1.1 Approximate composition of "clean" dry air.

Component gas	Chemical symbol	Molar mass (kg/kmol)	Volume (%)	Concentration (ppm)
Nitrogen	N_2	28.01	78.09	780 900
Oxygen	O_2	32	20.94	209 400
Argon	Ar	39.95	0.93	9300
Carbon dioxide	CO_2	44.01	0.04	410
Neon	Ne	20.18	Trace	18.0
Helium	He	4	Trace	5.2
Methane	CH_4	16.04	Trace	1.2
Krypton	Kr	83.8	Trace	0.5
Hydrogen	H_2	2.02	Trace	0.5

Source: Adapted from Williams (2001).

production rate increases substantially and prevailing concentrations in the indoor environment may therefore be expected to rise considerably above the thresholds set for sedentary activities.

Carbon dioxide is also the product of commercial or domestic activities such as combustion for catering as well as other industrial processes which can contribute to local indoor concentrations.

Although Table 1.1 supplies data for dry air, it is not common for air to be entirely bereft of water vapour. Water in the ambient atmosphere is largely the result of contact with oceans, lakes, etc. Atmospheric air contents can range up to 0.03 kg of water vapour per kg of dry air. In a confined space, the relative proportion of water vapour existing is increased by perspiration and the respiration of occupants. Exhaled air is close to being saturated with water vapour and could have a water vapour content of 5–6% by volume at a temperature of 35 °C.

1.4 Gas Mixtures

1.4.1 Mixture Laws

Air is regarded as a *homogenous mixture* of *ideal* gases.

A *homogeneous mixture* comprises matter having a number of different compounds but still retaining uniform properties and composition throughout its bulk. Component compounds are visually indistinguishable but may be separated by physical means. Use of the term *ideal* assumes that the gas atoms are tiny spheres each having a volume that is insignificant relative to their containing boundary. Any collisions between these entities are assumed to be totally elastic and frictionless. Electrostatic forces are considered absent.

Consider a mixture comprising a number of ideal gases.

From a matter conservation perspective, the mixture's total mass (m_{mix}, kg) must be equal to the sum of the masses of its individual components, similarly, for its molar components (n_{mix}, kmol).

Table 1.2 Unit comparison of fundamental mixture laws.

Parameter	Mass basis	Molar basis
Totals	$m_{\text{mix}} = \sum_{i=1}^{j} m_i$	$n_{\text{mix}} = \sum_{i=1}^{j} n_i$
Fraction	$mf_i = \frac{m_i}{m_{\text{mix}}}$	$y_i = \frac{n_i}{n_{\text{mix}}}$

The contribution of any individual component (i) to the total can be described by either a mass fraction (mf_i) or a volumetric or molar fraction (y_i).

If the gas mixture comprises j components in total, then the above conservation considerations can be stated as given in Table 1.2.

Note that in both mass and molar cases, the fractional sum is equal to unity.

The relationship between the number of kilomoles of the air (n), its mass (m, kg), and molar mass (M, kg/kmol) is given by

$$m = nM \tag{1.1}$$

This relationship is extremely useful as it provides for a conversion from chemical to physical units. It can also be directly applied to a mixture, thus

$$m_{\text{mix}} = n_{\text{mix}} M_{\text{mix}} \tag{1.2}$$

The link between mass (kg) and volume (m^3) is provided by the density (kg/m^3)

$$m = \rho V \tag{1.3}$$

When expressed in flow rate terms, it is commonly described as the *Continuity equation*, thus

$$\dot{m} = \rho \dot{V} \tag{1.4}$$

At any cross section in a confined flow, the volumetric flow rate $\left(\dot{V}, \text{m}^3/\text{s}\right)$ is given by

$$\dot{V} = A\overline{V} \tag{1.5}$$

1.4.2 Dalton's Law

Pressure (P, N/m^2) is associated with the presence of matter and is defined most simply as the force (F, N) acting on a given area (A, m^2), i.e.

$$P = F/A \tag{1.6}$$

A more often used unit is the ***Pascal*** where $1\ \text{N/m}^2 = 1$ Pa; 1 Pa is a small amount of pressure and so multiples with distinctive names are in common use.

For example,

$$1\ \text{bar} = 1 \times 10^5\ \text{Pa}$$

$$1\ \text{atm} = 101\,325\ \text{Pa}$$

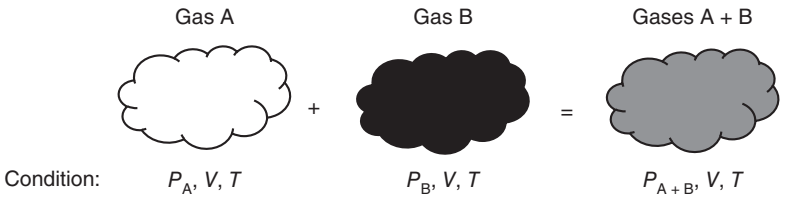

Figure 1.1 Illustration of Dalton's law.

Pressure measurements using a perfect vacuum as a datum or baseline are termed ***absolute pressures*** (P_{abs}).

Measurements using ambient atmospheric pressure (P_{atm}) as a datum or zero are termed ***gauge pressures*** (P_{gauge}).

The contribution that component gases have on the physical behaviour of a mixture can be approximated by assuming that the gases are ideal and using *Dalton's law*.

Dalton's law of partial pressures states that the total pressure (P_{mix}) of a mixture of gases at a given temperature (T_{mix}) and volume (V_{mix}) is equal to the sum of the individual pressures (P_i) of each gas component if existing at the same temperature and volume, i.e.

$$P_{mix} = \sum P_i \quad \text{at } T_{mix}, V_{mix} \tag{1.7}$$

Consider two gases A and B at the same temperature and volume but at different pressures P_A and P_B, respectively. If these gases are now mixed and the mixture exists at the same temperature and volume as its components, then Dalton's law states that the resulting pressure of the mixture will be the sum of P_A and P_B as shown in Figure 1.1

The ratio of any individual pressure of a component gas to the total gas mixture pressure (P_i/P_{mix}) is called the ***pressure fraction***. It can be shown that

$$\frac{P_i}{P_{mix}} = y_i \tag{1.8}$$

i.e. the pressure fraction of any gas component in a mixture of gases is equal to the molar fraction of the component gas in the mixture.

Rearranging Eq. (1.8), the product of molar fraction and mixture pressure ($y_i P_{mix}$) is called the ***partial pressure*** (P_i, Pa).

1.4.3 Gibbs–Dalton Law

The approach to mixture thermodynamic property evaluation is based on an extension to Dalton's law called the ***Gibbs–Dalton law***. This assumes that each component gas has a thermodynamic property (e.g. enthalpy, specific heat capacity, specific gas constant) value equal to the value it would have if occupying the mixture volume alone at the same temperature.

Mass or molar properties of mixtures can be determined by the ***addition*** of component contributions (i).

Let ψ be any mass-*independent* thermodynamic property and $\overline{\psi}$ be its molar-independent counterpart, then mixture property values can be evaluated as shown:

$$\psi_{\text{mix}} = \sum_{i=1}^{j} mf_i \psi_i \tag{1.9}$$

$$\overline{\psi}_{\text{mix}} = \sum_{i=1}^{j} y_i \overline{\psi}_i \tag{1.10}$$

The above relationships are exact for ideal gases and approximate for real gases.

1.4.4 Ideal Gas Behaviour and the Equation of State

An ideal gas is governed by a relationship known as the perfect gas equation of state which relates the state pressure (P, Pa), volume (V, m^3), and temperature (T, K) of a fixed mass (m, kg) of a given gas:

$$\frac{PV}{T} = mR \tag{1.11}$$

For a gas, the specific gas constant (R, J/kg K) can be calculated from knowledge of the molar mass of the gas (M, kg/kmol), thus

$$R = R_o/M \tag{1.12}$$

where R_o is the Universal gas constant having a value of 8.314 kJ/kmol K.

The specific gas constant is a mass-independent quantity, and for a mixture of ideal gases, Eq. (1.9) can be employed:

$$R_{\text{mix}} = \sum_{i=1}^{j} mf_i R_i \tag{1.13}$$

Molar mass is (of course) a molar-independent quantity, and for a mixture of ideal gases, Eq. (1.10) can be employed, thus

$$M_{\text{mix}} = \sum_{i=1}^{j} y_i M_i \tag{1.14}$$

Equation (1.12) can then be modified and used thus

$$R_{\text{mix}} = R_o/M_{\text{mix}} \tag{1.15}$$

A commonly used value for the specific gas constant of dry air is 287 J/kg K.

If the mass and composition of a gas remain constant, the equation of state can be used to determine the behaviour of the air during a process, i.e. what happens to its temperature, volume, and pressure.

This is defined by a simple expression relating the initial (1) and final (2) states:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \tag{1.16}$$

However, a number of change process paths, i.e. from initial to final condition, are possible modifying Eq. (1.16).

The most commonly encountered pathways are as follows:

Adiabatic process: A process characterised by the absence of heat transfer to or from the working fluid.
Isobaric process: A process characterised by the absence of change in the pressure of the working fluid.
Isochoric process: A process characterised by the absence of change in the volume of the working fluid.
Isothermal process: A process characterised by the absence of change in the temperature of the working fluid.
Polytropic process: A process in which pressure, temperature, and volume of the working fluid may all change.

1.5 Air Thermodynamic and Transport Properties

1.5.1 Gas Density

The density of an ideal gas can be estimated by combining Eqs. (1.3, 1.11):

$$\rho = m/V = P/RT \tag{1.17}$$

Water in its vapour form is regarded as a gas.

Thus, ambient air can be regarded as a mixture of gases *plus* water vapour. The presence of water vapour in atmospheric air renders the air *humid*.

For humid air, from Dalton's law, the total mixture air pressure is the sum of the component partial pressures:

$$P_{\text{total}} = P_{\text{da}} + P_{\text{wv}} \tag{1.18}$$

The density of humid air can then be calculated as the sum of the densities of the two gases, dry air and water vapour in proportion with their partial pressures:

$$\rho_{\text{humid air}} = \rho_{\text{da}} + \rho_{\text{wv}} = \frac{P_{\text{da}}}{R_{\text{da}}T} + \frac{P_{\text{wv}}}{R_{\text{wv}}T} \tag{1.19}$$

A commonly used value for the specific gas constant of water vapour (R_{wv}) is 461.5 J/kg K.

For an atmospheric pressure of 1 bar and a specific gas constant of 287 J/kg K, the approximate variation of dry (0% relative humidity or RH) air density (kg/m^3) over a range of −50 to +50 °C is shown in Figure 1.2.

Figure 1.2 also indicates the effect on density of air saturated with moisture (100% RH) over the range 0–50 °C. Saturating air with moisture reduces its density by up to 5%.

1.5.2 Dynamic Viscosity

The dynamic viscosity (μ, kg/ms) describes the resistance to flow in a liquid or a gas. It is sometimes described as its 'internal friction'. Its magnitude depends on molecular motion, cohesion, temperature, and pressure, and it has a significant effect on a range of important fluid flow phenomena.

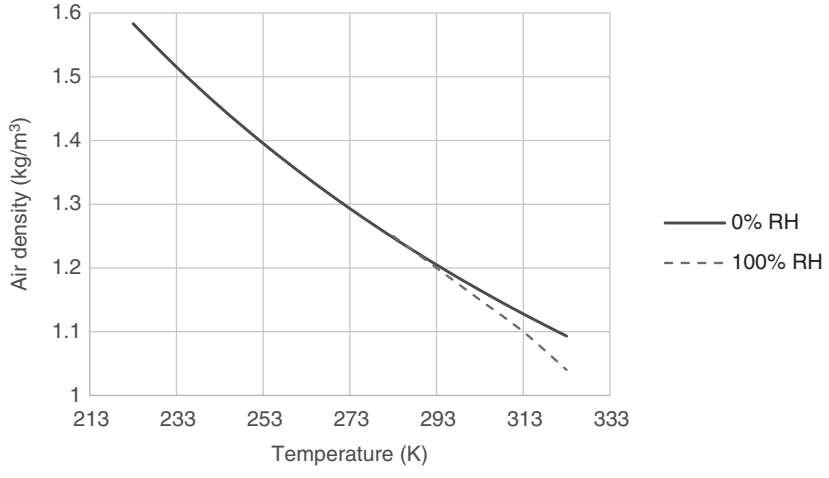

Figure 1.2 Variation of air density with temperature.

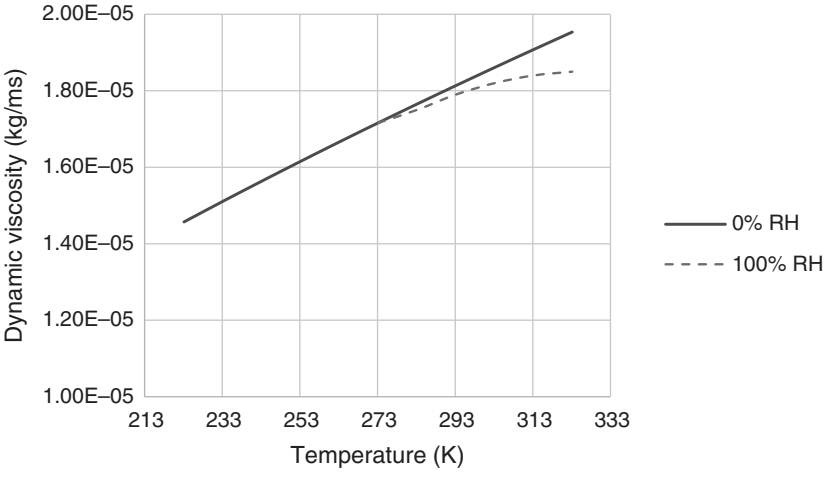

Figure 1.3 Variation of air viscosity with temperature.

The dynamic viscosity of dry air at 1 bar and 20 °C is approximately 1.8×10^{-5} kg/ms.

The effect of temperature (T, K) on air dynamic viscosity (μ, kg/ms) at 1 bar over a range of −50 to +50 °C is shown in Figure 1.3 and can be estimated from

$$\mu = 1.458 \times 10^{-6} \left(\frac{T^{1.5}}{T + 110.4} \right) \tag{1.20}$$

Figure 1.3 also indicates that saturating the air with moisture (100% RH) over the temperature range 0–50 °C reduces its viscosity by up to 5%.

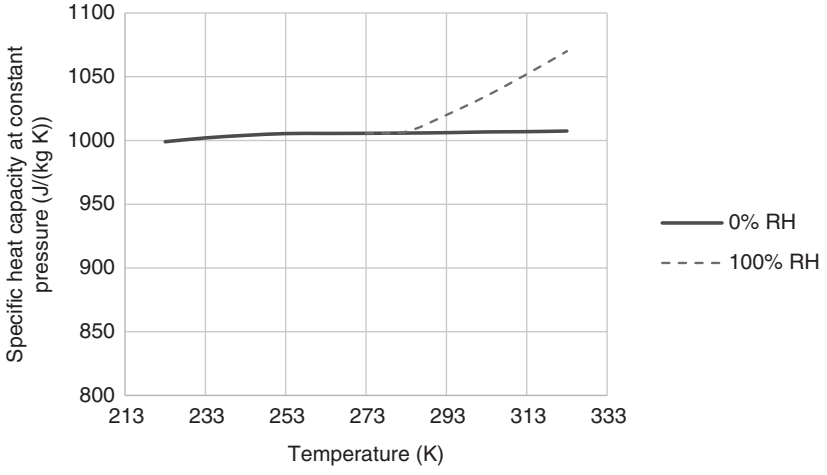

Figure 1.4 Variation of air specific heat capacity with temperature.

1.5.3 Specific Heat Capacity

Heat capacity is a property that describes the heat storage capabilities of a single phase (solid, liquid, or gas) substance. Note that this property is often quoted on a mass independent basis and is then termed the *specific heat capacity* (C: J/kg K). The heat capacity will determine the amount of energy required to change the temperature of 1 kg of substance by 1 °C.

As a result of being virtually incompressible, a single heat capacity parameter is usually sufficient for solids and liquids.

Gases are of course easily compressed, and hence, it is useful to further divide this property into two parameters depending on the prevailing conditions:

- Specific heat capacity *at constant volume* C_v
- Specific heat capacity *at constant pressure* C_p

For a given gas, these properties are related to specific gas constant (R):

$$R = C_p - C_v \tag{1.21}$$

The effect of temperature (T, K) on dry air thermal specific heat capacity at constant pressure at 1 bar over a range of −50 to +50 °C is shown in Figure 1.4.

A commonly used value of specific heat capacity at constant pressure for dry, atmospheric air is 1005 J/kg K.

The specific heat capacity of water vapour has a typical value of 1865 J/kg K over the range 0–50 °C, and the effect of moisture content (100% RH) can also be seen in Figure 1.4.

Like its constant pressure relation, the specific heat capacity at constant volume for air (C_v, J/kg K) varies little over the same temperature range. A commonly used value of specific heat capacity at constant volume for dry, atmospheric air is 718 J/kg K.

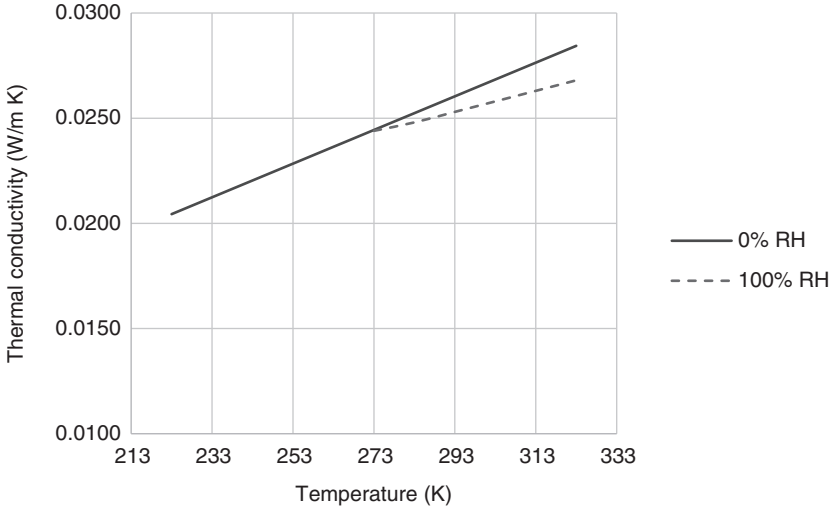

Figure 1.5 Variation of air thermal conductivity with temperature.

1.5.4 Thermal Conductivity

The thermal conductivity (k, W/m K) is a measure of the resistance to the flow of heat. Conduction of heat takes place as a result of energy transfer between adjacent atoms or molecules. The motion of the atoms or molecules is, in this case, regarded as vibrational, as opposed to translational, in nature. For liquids and gases in large-scale motion, heat transfer can be enhanced by other phenomena.

The thermal conductivity will determine the required thermal power $\left(\dot{Q}, \mathrm{W}\right)$necessary to induce a 1 °C temperature reduction per unit linear length or thickness of material.

A typical value of thermal conductivity for dry, atmospheric air is 0.025 W/m K.

The effect of temperature (T, K) on dry air thermal conductivity at 1 bar over a range of −50 to +50 °C is shown in Figure 1.5.

For dry air (0% RH), the relationship can be approximated by

$$k = 8 \times 10^{-5} T + 0.0023 \tag{1.22}$$

Figure 1.5 also indicates that saturating the air with moisture (100% RH) over the temperature range 0–50 °C reduces its thermal conductivity.

Many building materials rely on encapsulated or integral air pockets for their insulating properties; hence, the resulting practical value will depend on the combination of solid and gaseous thermal conductivities.

1.5.5 Heat Transfer Coefficient

Heat transport in a fluid or between a fluid and a solid depends on heat conduction, energy storage, and fluid mixing motion. If the motion is instigated by a fan or blower, the heat transfer mechanism is termed ***forced convection***.

If the motion is instigated as a result of a simple temperature difference, the heat transfer mechanism is termed natural, buoyancy-driven, or ***free convection***.

In both cases, the resulting rate of heat transferred is a function of a parameter known as the heat transfer coefficient (h_c, W/m^2 K). Its value is dependent on system geometry, fluid transport properties, and flow modes, i.e. laminar/turbulent.

For a gas like air, free convection heat transfer coefficients are typically of the order of 5–25 W/m^2 K. For forced convection in air, this value could be increased by 10 times.

These values are quite small, however, compared with a light liquid, like water, where free convection heat transfer coefficients can be up to 1000 W/m^2 K and forced convection values up to 20 000 W/m^2 K. Water phase change (i.e. evaporating/condensing) values are even greater ranging up to 100 000 W/m^2 K.

1.5.6 Combinations of Properties

The properties described above are often used in *dimensionless* ratio combination to describe thermophysical and fluid behaviour. These ratios provide a means of expressing this behaviour in a useful empirical fashion.

The most common dimensionless groups are as follows:

1. Discharge coefficient $= \frac{\text{Actual flow rate}}{\text{Theoretical flow rate}}$

$$C_d = \frac{\dot{V}_{\text{act}}}{\dot{V}_{\text{theo}}} \tag{1.23}$$

The discharge coefficient is associated with flow openings, orifices, and nozzles. A value of zero indicates no flow and a value of unity indicates a theoretical maximum flow. Typical values for C_d are dependent of the prevailing flow regime through an opening. For a simple orifice, values between 0.5 and 0.7 are in common use.

2. Pressure coefficient $= \frac{\text{Static pressure}}{\text{Dynamic pressure}}$

$$\mathbb{C}_p = \frac{P - P_o}{0.5\rho\overline{V}^2} \tag{1.24}$$

The pressure coefficient is defined as the difference between the mean local pressure (P) on a surface and that of the free stream (P_o) as fraction of the dynamic (or velocity-associated) pressure (Pa).

3. Nusselt number $= \frac{\text{Convective resistance}}{\text{Conductive resisance}}$

$$Nu = \frac{h_c l}{k} \tag{1.25}$$

The Nusselt number figures in both free and forced convection correlation equations.

The parameter l is some representative length (m) of the system geometry.

For example, in a circular pipe or duct, this representative length would typically be its diameter.

4. Reynolds number $= \frac{\text{Inertia forces}}{\text{Viscous forces}}$

$$Re = \frac{\rho\overline{V}l}{\mu} \tag{1.26}$$

This parameter is ubiquitous in the study of fluid flow where its absolute value is used as a test to determine whether a flow is laminar (steady and undisturbed) or turbulent (unstable, perhaps with vortices).

The Reynolds number is also associated with forced convection correlation equations.

5. Grashof number $= \frac{\text{Buoyancy forces}}{\text{Viscous forces}}$

$$Gr = \frac{\rho^2 g \beta \Delta T l^3}{\mu^2} \tag{1.27}$$

The Grashof number is associated with free convection correlation equations, where ΔT is the temperature difference between a heated/cooled surface (T_s, K) and the fluid free stream (T_f, K) and β is the coefficient of cubical expansion (K^{-1}) given by

$$\beta = \frac{1}{\left(T_s + T_f\right)/2} \tag{1.28}$$

6. Prandtl number $= \frac{\text{Viscous transfer}}{\text{Heat transfer}}$

$$Pr = \frac{\mu C_p}{k} \tag{1.29}$$

The Prandtl number figures in both free and forced convection correlation equations. A typical value of Prandtl number for atmospheric air is 0.7.

7. Friction factor $= \frac{\text{Local (wall) shear stress}}{\text{Dynamic pressure}}$

$$f = \frac{\Delta P_w}{0.5 \rho \overline{V}^2} \tag{1.30}$$

This parameter is commonly used to estimate the frictional pressure losses associated with flow in conduits, in general, such as ducts and pipes. Values vary with flow regime (laminar/turbulent), flow rate, and conduit material.

Use of the above groups is not limited to air. They are in common usage for other fluids including water, steam, and refrigerants.

1.6 Important Energy Concepts

1.6.1 First Law of Thermodynamics

Laying aside considerations of mass–energy conversion, the principle of energy conservation as laid down in the First Law of Thermodynamics states that energy conversion from one form to another is permitted, but the sum of all energy forms remains constant.

In *flow* terms, the first law is commonly described by the following equation relating the initial (1) and final (2) energy states of a flowing fluid:

$$\dot{Q} - \dot{W} = \dot{m} \left[\left(h_2 - h_1\right) + \frac{\left(\overline{V}_2^2 - \overline{V}_1^2\right)}{2000} + g \frac{\left(z_2 - z_1\right)}{1000} \right] \tag{1.31}$$

Qualitatively:

$$\text{Heat flow} - \text{Rate of thermodynamic work} = \text{Mass flow} \times (\text{specific enthalpy change} + \text{kinetic energy change} + \text{potential energy change})$$

Since the equation utilises the mass flow rate, each term has the units of energy flow (Joules per second or Watts).

This equation is applicable to fluid flow in general and can be used with water, steam, and refrigerants as well as gases and can be employed in a reduced form depending on application.

The term ***specific enthalpy*** (h, kJ/kg) describes a bundle of energy forms including pressure-based and thermal (temperature and phase change-related) energy. The use of the term "specific" denotes the fact that the property is evaluated per unit mass of substance.

Applying Eqs. (1.9, 1.10) for a mixture of gases:

$$h_{\text{mix}} = \sum_{i=1}^{j} mf_i h_i \quad \text{and} \quad \overline{h}_{\text{mix}} = \sum_{i=1}^{j} y_i \overline{h}_i \tag{1.32}$$

Property changes in a mixture are evaluated by summing the individual component changes. For example,

$$\Delta h_{\text{mix}} = \sum_{i=1}^{j} \Delta h_i = \sum_{i=1}^{j} mf_i \Delta h_i = \sum_{i=1}^{j} y_i \Delta \overline{h}_i \tag{1.33}$$

A process realising no change in the enthalpy of the working fluid is termed *Isenthalpic*.

1.6.2 Thermal Energy

Knowledge of thermal energy content is important in both estimating building loads and the plant necessary to satisfy them.

In the absence of thermodynamic work and any changes in kinetic and potential energy, the rate of heat input/extract $(\dot{Q}, \text{kW})$ necessary to heat/cool a flow $(\dot{m}, \text{kg/s})$ of fluid is given by modifying Eq. (1.31), thus

$$\dot{Q} = \dot{m}\left(h_2 - h_1\right) \tag{1.34}$$

To produce positive design values in all cases, the following convention is adopted for calculation purposes:

Heat added to a fluid flow is positive, i.e. $+\dot{Q}$.
Heat extracted from a flow is negative, i.e. $(-)\,\dot{Q}$.

For *ideal gases*, enthalpy is proportional to specific heat capacity at constant pressure; thus, for a gas mixture, heat flow can be evaluated by

$$\dot{Q}_{\text{gas}} = \dot{m}_{\text{gas}} C_p \Delta T \tag{1.35}$$

where ΔT is the difference in gas temperature between final (2) and initial (1) states and C_p (kJ/kg K) is the specific heat capacity at constant pressure for the gas mixture.

The water component of air requires further consideration as, in maintaining the internal environment, evaporation, condensation, and perhaps the freezing of water will be of significance.

For the *water* component of the air, the enthalpy change associated with phase change (or *latent heat)* will be important. It may be regarded as the amount of energy required

for the complete conversion of 1 kg of substance from one phase to another. In thermodynamics, the temperature at which phase change occurs is termed the (energy) *saturation temperature*.

For a phase change-associated mass flow of water, the amount of heat flow is given by

$$\dot{Q}_{pc} = \dot{m}_{water} h_{pc} \tag{1.36}$$

where h_{pc} (kJ/kg) is the specific latent heat value.

Again, values of latent heat vary with pressure and temperature. Typical values of the latent heat of vaporisation/condensation and the melting/freezing of water at ambient temperatures are in the area of 2450 kJ/kg (20 °C) and 335 kJ/kg (0 °C), respectively.

More accurate tables of values and charts are available in many design handbooks that account for both sensible and latent heat components in enthalpy terms.

1.6.3 Rate of Thermodynamic Work

This term $\left(\dot{W}\right)$ in Eq. (1.31) accounts for mechanical or electrical energy transfers that take place in devices such as fans, compressors, and pumps or even simple electrical heaters.

In general, thermodynamic terms, the work (J) associated with a fluid changing its state through a process (1) to (2) is given by

$$W = \int_1^2 PdV \tag{1.37}$$

The calculation of the work integral will depend on the actual process pathway undergone by the fluid.

1.6.4 Nonthermal Energy

A reduced and modified First Law of Thermodynamics is commonly used for ductwork design, the specification of air movement devices and conduits in general.

Nonthermal energy is normally considered to have three forms:

- Pressure energy associated with the presence of matter on a microscopic scale
- Kinetic energy associated with velocity on a large scale
- Potential or gravitational energy associated with position (relative to a datum)

Hence, for any given set of conditions:

Pressure energy + Kinetic energy + Potential energy = Constant

Using the SI unit of energy (Joule) as a basis, this can be written as

$$PV + \frac{1}{2}m\overline{V}^2 + mgz = \text{Constant} \tag{1.38}$$

This equation can be expressed in some other different ways. In the field of fluid mechanics when applied to inviscid, incompressible conditions, it is commonly known as the *Bernoulli equation*.

Here, each term is expressed using *head* (m) as its unit:

Pressure head + Kinetic head + Potential head = Constant

i.e.

$$\frac{P}{\rho g} + \frac{\overline{V}^2}{2g} + z = \text{Constant} \tag{1.39}$$

(The use of the term '*head*' alludes to the height of a column of fluid exerting a pressure on its base.) The constant is termed the *total head*.

In indoor climate studies, the potential term is often ignored and the energy relationship is expressed in *pressure* (Pa) terms, i.e.

$$\text{Static pressure} + \text{Velocity pressure} = \text{Constant}$$

i.e.

$$P + \rho\frac{\overline{V}^2}{2} = \text{Constant} \tag{1.40}$$

The constant here is termed the *stagnation or total pressure*.

Taking atmospheric air to have a density of 1.2 kg/m^3, the velocity pressure term is commonly expressed as

$$\text{Velocity pressure} = 0.6\overline{V}^2 \tag{1.41}$$

1.6.5 Non-flow Conditions

The First Law of Thermodynamics caters for *non-flow* conditions with the following expression:

$$Q - W = m\left(u_2 - u_1\right) \tag{1.42}$$

where u (kJ/kg) is the ***specific internal energy*** which is a term that accounts for the sum of sensible, latent, chemical bond, and nuclear bond energy.

Being applicable to a non-flow condition, the units of each term in Eq. (1.42) are expressed in Joules.

For ideal *gases*, internal energy is proportional to specific heat capacity at constant volume; thus, for dry air, the heat content can be evaluated by

$$Q = m_{\text{gas}} C_v \Delta T \tag{1.43}$$

Note that there is a relationship between specific enthalpy and specific internal energy:

$$h = u + PV \tag{1.44}$$

1.6.6 Entropy

Enthalpy is concerned with the *quantity* of energy, and the First Law of Thermodynamics states that the quantity of energy is conserved in a process.

Entropy (S, kJ/K) is a property that is concerned with energy *quality* or *usefulness*. This is the business of the Second Law of Thermodynamics. Entropy is a nonconservative property, and, in general, engineering processes result in an increase in *global* entropy or a reduction in energy usefulness. Entropy increases as a result of the presence of *irreversibilities,* i.e. nonrecoverable energy transfers like, for example, friction.

Thus, a gas compression over a given pressure range will result in a temperature higher than that suggested by simple gas law theory.

To compare the ideal constant entropy case (termed *reversible adiabatic* or *isentropic*) with a real process, the term *isentropic efficiency* (η_{isen}) is often employed.

For example, if the ideal or isentropic final temperature in a compression process is designated ($T_{2,\text{ isen}}$), then the isentropic efficiency for the process would be defined as

$$\eta_{\text{isen}} = \frac{T_{2,\text{isen}} - T_1}{T_{2,\text{actual}} - T_1} \tag{1.45}$$

This can also be described in enthalpy terms:

$$\eta_{\text{isen}} = \frac{h_{2,\text{isen}} - h_1}{h_{2,\text{actual}} - h_1} \tag{1.46}$$

Again, this approach can also be applied to other fluids such as steam and refrigerants.

1.7 Worked Examples

Worked Example 1.1 A Mole to Mass Conversion

A sample of air contains 0.8 kmol of nitrogen (N_2).

If the molar mass of nitrogen is 28 kg/kmol, determine the mass (kg) of the nitrogen.

Solution

Given: $n_{N_2} = 0.8$ kmol, $M_{N_2} = 28$ kg/kmol

Find: m_{N_2}

$$m_{\text{mix}} = n_{\text{mix}} M_{\text{mix}}$$
$$= 0.8 \times 28$$
$$= 22.4 \text{ kg}$$

Worked Example 1.2 The Molar Mass of Air

Ignoring minor components, it has been determined that the composition of air can be approximated as follows in Table E1.2:

Using the above, determine its mixture molar mass (kg/kmol).

Solution

Given: $M_{N_2} = 28$ kg/kmol, $M_{O_2} = 32$ kg/kmol, $y_{N_2} = 0.79$, $y_{O_2} = 0.21$

Find: M_{air}

$$M_{\text{mix}} = \sum_{i=1}^{j} y_i M_i$$
$$= \left(y_{N_2} \times M_{N_2}\right) + \left(y_{O_2} \times M_{O_2}\right)$$
$$= (0.79 \times 28) + (0.21 \times 32)$$
$$= 28.84 \text{ kg/kmol}$$

Table E1.2 Data for Worked Example 1.2.

Component gas	% by volume	Molar mass (kg/kmol)
Nitrogen (N_2)	79	28
Oxygen (O_2)	21	32

Worked Example 1.3 Calculation of Partial Pressure

Consider atmospheric air at a pressure of 101 325 Pa to consist of 79% nitrogen (N_2) and 21% oxygen (O_2) by volume.

Determine the partial pressures (Pa) for each gas in the mixture.

Solution

Given: $y_{N_2} = 0.79,\ \ y_{O_2} = 0.21,\ P_{mix} = 101\,325$ Pa

Find: $P_{N_2},\ \ P_{O_2}$

From Dalton's law, the volumetric or molar fractions are equal to the pressure fractions, hence

$$\frac{P_{N_2}}{P_{mix}} = y_{N_2}$$

$$\frac{P_{N_2}}{101\,325} = 0.79$$

$$P_{N_2} = 80\,046.75 \text{ Pa}$$

Since

$$P_{mix} = \sum P_i \quad \text{at } T_{mix}, V_{mix}$$

$$P_{mix} = P_{N_2} + P_{O_2}$$

$$101\,325 = 80\,046.75 + P_{O_2}$$

$$P_{O_2} = 21\,278.25 \text{ Pa}$$

Worked Example 1.4 Density of Dry Air

An office of dimensions 20 m × 10 m × 3 m is kept at a temperature of 18 °C and absolute pressure of 100 kPa. See Figure E1.4. Determine:

(a) The mass of air in the room
(b) The density of air

Take the specific gas constant for air as 287 J/kg K.

Solution

Given: $P = 100 \times 10^3$ Pa, $V = 20 \times 10 \times 3 = 600\,\text{m}^3$, $T = 18 + 273 = 291$ K, $R_{air} = 287$ J/kg K

Find: m, ρ

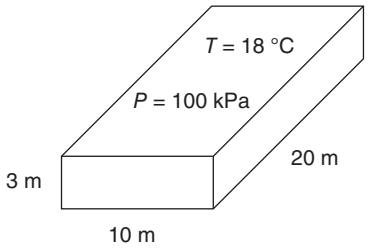

Figure E1.4 Office dimensions for Worked Example 1.4.

(a) Using the equation of state:

$$\frac{PV}{T} = mR$$

$$\frac{100\,000 \times 600}{291} = m \times 287$$

$$m = 718\ \text{kg}$$

(b) By definition, density is the ratio of mass to volume:

$$\rho = \frac{m}{V} = \frac{718}{600} = 1.197\ \text{kg/m}^3$$

Worked Example 1.5 Density of Moist Air

A sample of moist air has a total pressure of 100 000 Pa and a temperature of 27 °C.

Determine the density (kg/m^3) of the dry portion of the air and, assuming a water vapour partial pressure of 3.6 kPa, the effect of humidity on the value of the mixture density.

Take $R_{da} = 287$ J/kg K and $R_{wv} = 461.5$ J/kg K.

Solution

Given: $P_{total} = 100\,000$ Pa, $T = 27 + 273 = 300$ K, $R_{da} = 287$ J/kg K, $R_{wv} = 461.5$ J/kg K, $P_{wv} = 3.6 \times 10^3$ Pa

Find: ρ_{da}, $\rho_{moist\ air}$

$$P_{da} = P_{total} - P_{wv}$$

$$= 100\,000 - 3600$$

$$= 96\,400\ \text{Pa}$$

Rearranging the Ideal gas law:

$$\frac{m}{V} = \rho = \frac{P_{da}}{R_{da}T} = \frac{96\,400}{287 \times 300} = 1.12\ \text{kg/m}^3$$

Using Eq. (1.19):

$$\rho_{moist\ air} = \frac{P_{da}}{R_{da}T} + \frac{P_{wv}}{R_{wv}T}$$

$$= \left(\frac{96\,400}{287 \times 300}\right) + \left(\frac{3600}{461.5 \times 300}\right)$$

$$= 1.12 + 0.026 = 1.146\ \text{kg/m}^3$$

Worked Example 1.6 Thermophysical Properties of Air
Estimate the dynamic viscosity (kg/ms) and thermal conductivity (W/m K) for a sample of dry air at 22 °C.

Solution
Given: $T = 22 + 273 = 295$ K
Find: μ, k

$$\mu = 1.458 \times 10^{-6} \left(\frac{T^{1.5}}{T + 110.4} \right)$$
$$= 1.458 \times 10^{-6} \left(\frac{295^{1.5}}{295 + 110.4} \right)$$
$$= 1.82 \times 10^{-5} \text{ kg/ms}$$

$$k = 8 \times 10^{-5} T + 0.0026$$
$$= 8 \times 10^{-5} (295) + 0.0026$$
$$= 0.0262 \text{ W/m K}$$

Worked Example 1.7 A Heated Air Supply
A workspace of dimensions (10 m × 6 m × 5 m) is to be kept at 20 °C when the outside air temperature is 0 °C. See Figure E1.7.

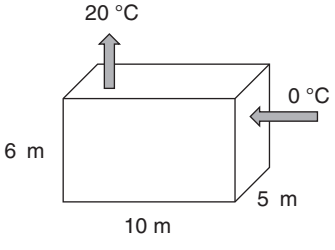

Figure E1.7 Work space dimensions for Worked Example 1.7.

If the air supply to the space is changed once *every hour*, determine:

(a) The mass flow rate (kg/s) of air to room.
(b) The heat required (kW) to maintain the room at its desired temperature.

Assume the density of air to be 1.2 kg/m^3 and $C_p = 1.0$ kJ/kg K.

Solution
Given: $V = 10 \times 6 \times 5 = 300$ m^3, $\Delta T = 20 - 0 = 20$ K, $\rho = 1.2$ kg/m^3, $C_p = 1.0$ kJ/kg K, 1 air change per hour, i.e. (1/3600) air changes per second
Find: $\dot{m}, \dot{Q}$

(a) Volume flow rate of air through the room (m^3/s) = Room volume × number of times air is replaced per second

$$\dot{V} = V \times (1/3600)$$
$$= 300 \times 0.000\,27$$

$= 0.083\ \text{m}^3/\text{s}$

$\dot{m} = \rho \dot{V}$

$= 1.2 \times 0.083$

$= 0.1\ \text{kg/s}$

(b) The hear (kW) required to maintain the room at 20 °C

$+\dot{Q} = \dot{m} C_p \Delta T$

$= 0.1 \times 1.0 \times 20$

$= 2.0\ \text{kW}$

Worked Example 1.8 An Extract System

How much heat will be carried away by an extractor fan rated at $2\ \text{m}^3/\text{min}$ from a sports hall kept at constant pressure of 1×10^5 Pa and a temperature of 20 °C while the temperature of air outside is 0 °C?

For air assume: $C_p = 1.005\ \text{kJ/kg K}$ and $R = 287\ \text{J/kg K}$.

Solution

Given: $\dot{V} = 2\ \text{m}^3/\text{min} = 2/60\ \text{m}^3/\text{sec}$, $\Delta T = 20 - 0 = 20\ \text{K}$, $P = 1 \times 10^5\ \text{Pa}$, $C_p = 1.005\ \text{kJ/kg K}$, $R = 287\ \text{J/kg K}$

Find: $\dot{Q}$

Calculate the density of air through the fan using the equation of state

$$\frac{m}{V} = \rho = \frac{P_{\text{air}}}{RT} = \frac{100\,000}{287 \times 293} = 1.189\ \text{kg/m}^3$$

$\dot{m} = \rho \dot{V}$

$= 1.189 \times (2/60)$

$= 0.0396\ \text{kg/s}$

Heat extracted by fan will be equal to heat added by heating external air to inside temperature.

$(+)\ \dot{Q} = \dot{m} C_p \Delta T$

$= 0.0396 \times 1005 \times 20$

$= 796\ \text{W}$

Worked Example 1.9 Latent Heat Condensation

A flow of moist air has a total mass flow rate of 0.25 kg/s.

The water vapour component comprises 1.5% by mass of the flow.

Assuming the water component is cooled to its saturation temperature, determine the rate of heat transfer (kW) required for the complete condensation of the water vapour.

Take the phase change enthalpy associated with the water condensation to be 2480 kJ/kg.

Solution

Given: $\dot{m}_{\text{total}} = 0.25\ \text{kg/s}$, $h_{\text{pc(cond)}} = 2480\ \text{kJ/kg}$

Find: $\dot{Q}_{\text{cond}}$

$$\dot{m}_{\text{wv}} = 0.015 \times \dot{m}_{\text{total}}$$
$$= 0.015 \times 0.25$$
$$= 3.75 \times 10^{-3}\ \text{kg/s}$$

$$\dot{Q}_{\text{cond}} = \dot{m}_{\text{wv}} h_{\text{pc(cond)}}$$
$$= 3.75 \times 10^{-3} \times 2480$$
$$= 9.3\ \text{kW}$$

Worked Example 1.10 Nonthermal Energy

A flow of air has a velocity of 3.5 m/s.

Express its nonthermal energy content as a kinetic head (m) and as a velocity pressure (Pa).

When flowing over a building, a pressure of 100 005 Pa resulted on the exterior surface. Using the data supplied, determine the pressure coefficient on the surface.

Data

Ambient air density: 1.2 kg/m^3, Ambient atmospheric pressure: 100 000 Pa.

Solution

Given: $\overline{V} = 3.5$ m/s, $P = 100\,005$ Pa, $\rho = 1.2$ kg/m^3, $P_o = 100\,000$ Pa

Find: Kinetic head (m), velocity pressure (Pa)

Kinetic head:

$$\frac{\overline{V}^2}{2g} = \frac{3.5^2}{19.62} = 0.624\ \text{m}$$

$$\text{Velocity pressure} = \rho\frac{\overline{V}^2}{2} = 1.2 \times \frac{3.5^2}{2} = 7.35\ \text{Pa}$$

$$\mathbb{C}_p = \frac{P - P_o}{0.5\rho\overline{V}^2}$$
$$= \frac{100\,005 - 100\,000}{0.5 \times 1.2 \times 3.5^2} = 5/7.35$$
$$= +0.68$$

1.8 Tutorial Problems

1.1 A sample of oxygen (O_2) has a mass of 20 kg.
If the molar mass of oxygen is 32 kg/kmol, determine the number of moles of oxygen.
[Answer: 625 mol]

1.2 Ignoring minor components, it has been determined that the composition of air can be approximated as follows in Table P1.2.
Using the above, determine its mixture specific gas constant (J/kg K).

Table P1.2 Data for tutorial Problem 1.2.

Component gas	% by mass	Specific gas constant (J/kg K)
Nitrogen (N_2)	75.5	296.8
Oxygen (O_2)	23.2	259.8
Argon (Ar)	1.3	208.1

[Answer: 287.06 J/kg K]

1.3 Carbon dioxide comprises 0.04% of atmospheric air by volume.
If air pressure is taken as 101 325 Pa, determine the partial pressure contribution of the carbon dioxide.
[Answer: 4053 Pa]

1.4 Estimate the dynamic viscosity (kg/ms) and thermal conductivity (W/m K) for a sample of dry air at 25 °C.
[Answers: 1.84×10^{-5} kg/ms, 0.0264 W/m K]

1.5 Use the Gibbs–Dalton law and the approximate data supplied in Table P1.5 to estimate the enthalpy (kJ/kg) of air at 27 °C.
If the tabulated value for air is 300.19 kJ/kg, determine the % error associated with the approximation.

Table P1.5 Data for tutorial Problem 1.5.

Component gas	Mass fraction (%)	Enthalpy (kJ/kg) at 27 °C
Nitrogen (N_2)	75.5	311.5
Oxygen (O_2)	23.3	273

[Answers: 298.79 kJ/kg, 0.47%]

1.6 A room is kept at a temperature of 10 °C and absolute pressure of 100 kPa. Determine:

- The density of the air if water vapour is ignored.
- The density allowing for humidity assuming the partial pressure of water vapour at this temperature to be 1200 Pa.

Assume $R_{da} = 287$ J/kg K, $R_{wv} = 461.5$ J/kg K.
[Answers: 1.231 kg/m^3, 1.226 kg/m^3]

1.7 An occupied space of dimensions $4\,\text{m} \times 4\,\text{m} \times 3\,\text{m}$ is to be kept at 20 °C when the outside air temperature is 10 °C. The air in the space is changed once every hour. Determine:
(a) The mass flow rate (kg/s) of air assuming ambient pressure to be 90 kPa.
(b) The heat required (kW) to maintain the gym at 20 °C.
Assume $C_{p,\,\text{air}} = 1.005\,\text{kJ/kg K}$, $R_{\text{air}} = 287\,\text{J/kg K}$.
[Answers: 0.0143 kg/s, 143 W]

1.8 A swimming pool ventilation system heats 60 l/s of air. The pool air is kept at constant pressure (100 kPa) and a temperature of 25 °C while the temperature of supplied external air is −5 °C.
Determine the output (kW) of the ventilation heater.
[Answer: 2.115 kW]

1.9 A flow of moist air has been cooled until its water vapour is on the point of condensation. It is then passed over a heat exchanger with a capacity to extract latent heat at a rate of 5 kW. The total air flow rate is 0.1 kg/s.
If the latent heat of condensation for the water is 2470 kJ/kg, determine the maximum mass flow rate of water vapour (kg/s) in the air that can be completely condensed by the heat exchanger.
Express this as a percentage of the total incoming air flow.
[Answers: 2×10^{-3} kg/s, 2%]

1.10 A flow of air has a velocity pressure of 3.75 Pa.
Determine its velocity (m/s).
For air assume: $\rho = 1.2\,\text{kg/m}^3$.
[Answer: 2.5 m/s]