Appendix B

Properties of Air

B.1 Standard Properties

The properties of air are of interest in the context of damper cooling, and for its behaviour internally under pressure, and when forming an emulsion. Table B.1 gives the basic values for standard conditions.

The effective critical point for air (not a pure substance) is:

$$P_C = 3.72\,\text{MPa}$$
$$T_C = -140.7\,°\text{C}\,(132.5\,\text{K})$$

Table B.1 Standard properties of dry air at sea-level, 15°C

Constituents by mass	Nitrogen	(N_2)	0.7553
	Oxygen	(O_2)	0.2314
	Argon	(Ar)	0.0128
	Carbon dioxide	(CO_2)	0.0005
Temperature	T_C	15	°C
	T_K	288.15	K
Pressure (absolute)	P	101325	Pa
Density	ρ	1.2256	kg/m^3
Dynamic viscosity	μ	17.83×10^{-6}	N s/m^2
Kinematic viscosity	ν	14.55×10^{-6}	m^2/s
Molar mass	m_m	28.965	kg/kmol
Specific gas constant	R_A	287.05	J/kg K
Specific heats	c_P	1005	J/kg K
	c_V	718	J/kg K
Ratio of specific heats	γ	1.400	–
Thermal conductivity	k	0.02534	W/m K
Speed of sound	V_S	340.6	m/s
Prandtl number	Pr	0.710	

The Shock Absorber Handbook, Second Edition John C. Dixon
 ISBN: 978-0-470-51020-9

Avogadro's number is 6.0225×10^{26} molecules/kmol, so the mass of an average air molecule is 48.1×10^{-27} kg. At standard temperature and pressure (15°C, 101325 Pa) the molecular density is 25.5×10^{24} molecules/m^3.

B.2 Effect of Temperature

For cooling analysis the properties of air are required from low ambient, e.g. minus 40°C, up to maximum damper temperatures of 130°C.

Air can be treated for most purposes as an ideal gas. The following equations are all of good engineering accuracy over the relevant range.

The relative molecular mass (molecular weight) of dry air is

$$M_{\mathrm{A}} = 28.965$$

with a corresponding molar mass

$$m_{\mathrm{A}} = 28.965\,\mathrm{kg/kmol}$$

The specific gas constant is

$$R_{\mathrm{A}} = 287.05\,\mathrm{J/kg\,K}$$

The absolute (kelvin) temperature T_{K} in terms of the Celsius temperature T_{C} is

$$T_{\mathrm{K}} = 273.15 + T_{\mathrm{C}}$$

and in terms of the Fahrenheit temperature is

$$T_{\mathrm{K}} = 273.15 + (T_{\mathrm{F}} - 32)/1.8$$

At absolute pressure $P(\mathrm{N/m^2} = \mathrm{Pa}$ (pascal)) the density ρ is

$$\rho = \frac{P}{R_{\mathrm{A}} T_{\mathrm{K}}}$$

or, by comparison with a reference condition P_0 and T_{K0}

$$\left(\frac{\rho}{\rho_0}\right) = \left(\frac{P}{P_0}\right)\left(\frac{T_{\mathrm{K0}}}{T_{\mathrm{K}}}\right)$$

The specific thermal capacity at constant pressure c_{P} is given by the empirical expression

$$c_{\mathrm{P}} = 1002.5 + 275 \times 10^{-6}(T_{\mathrm{K}} - 200)^2\ \mathrm{J/kg\ K}$$

which, by comparison with tables, is within 0.1% from 200 to 450 K (−70 to 180°C).

The specific heat at constant volume c_{V} is then

$$c_{\mathrm{V}} = c_{\mathrm{P}} - R_{\mathrm{A}}$$

A direct empirical expression for specific thermal capacity at constant volume is

$$c_V = 717.8 + 0.07075(T_K - 300) + 0.26125 \times 10^{-3}(T_K - 300)^2$$

which is within 0.2% from 0 to 400°C and within 1% from −100 to 500°C.

The ratio of specific thermal capacities γ is

$$\gamma = \frac{c_P}{c_V}$$

The thermal conductivity k is given by

$$k = \frac{0.02646\, T_K^{1.5}}{T_K + 245.4 \times 10^{-12/T_K}}\ \mathrm{W/m\,K}$$

This (unlikely looking) equation has been adapted by the author from an imperial units equation used for the production of reference tables of range 100–1000 K. A simpler expression adequate for cooling calculations is

$$k = 0.02624\left(\frac{T_K}{300}\right)^{0.8646}\ \mathrm{W/m\,K}$$

which is within 1% for −30 to 230°C and within 10% for −100 to 700°C.

The dynamic viscosity μ is given by

$$\mu = \frac{1.458 \times 10^{-6} T_K^{1.5}}{T_K + 110.4}\ \mathrm{Pa\,s}\ (\mathrm{N\,s/m^2})$$

This expression is used for the production of reference tables (100–800 K) so, presumably, is more than sufficiently accurate for engineering purposes.

The kinematic viscosity ν (SI units m^2/s) is, by definition

$$\nu = \frac{\mu}{\rho}$$

The Prandtl number is, by definition,

$$Pr = \frac{c_P \mu}{k}$$

For consistency this may be found by substitution. A direct empirical expression in the case of air is

$$Pr = 0.680 + 4.69 \times 10^{-7}(T_K - 540)^2$$

In practice, for normal air cooling

$$Pr \approx 0.70$$

The volumetric (cubical) thermal expansion coefficient of any permanent gas (at constant pressure) is given by

$$\beta = \frac{1}{T_K}$$

The Grashof number (used for convection cooling) is

$$Gr = \frac{\beta g \rho^2 X^3 (T_S - T_A)}{\mu^2}$$

where X is a length dimension, T_S is the surface temperature and T_A is the ambient air temperature. This can be expressed as

$$Gr = C_{Gr} X^3 (T_S - T_A)$$

with a Grashof coefficient

$$C_{Gr} = \frac{\beta g \rho^2}{\mu^2} = \frac{\beta g}{\nu^2}$$

Using $\beta = 1/T_K$, this becomes

$$C_{Gr} = \frac{g \rho^2}{T_K \mu^2}$$