

# Physics of compression chambers and physiological physics of hyperbaric environments

A comprehensive treatise of well known and under-exposed effects

Part 1. The physics of peopled compression chambers

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## Voorwoord

In vrijwel alle standaardwerken over hyperbare geneeskunde, en de fysiologie van duiken en caissonwerk wordt de natuurkunde van de hyperbare omgeving en de medische fysica van de mens onder druk weliswaar behandeld, maar de fysische grondslagen komen er i.h.a. bekaaid van af. Voor mij (als medisch fysicus) was dat nooit zo storend. Wat altijd wel als storend werd ervaren was de constatering dat allerelei zogenaamd algemeen geaccepteerde effecten de revue passeerden zonder dat de schrijver enige moeite deed om uit te leggen wat de (veronderstelde) achterliggende theorie was. Zo zal men bijvoorbeeld het mechanisme van de inerte gas narcose en de principes van de longmechanica onder druk vaak tevergeefs zoeken. Overigins pretendeert dit tractaat geen compleetheit van de behandeling van allerlei fysische effecten en theorieën, het is immers geen compendium of een leerboek. Sommige onderwerpen zoals de theorie van multi-compartiment diffusie en het ontstaan en verdwijnen van de gasballetjes worden niet behandeld. De traktaat-vorm, gekozen vanwege de omvang, impliceert dat niet uitgebreid op probleemstelling, doelstelling en heel elementaire kennis wordt ingegaan. Het traktaat bestaat uit twee delen. *Deel 1* heeft een technisch-fysisch en fysiologisch fysisch karakter, *Deel 2* heeft een fysiologisch en medisch-fysisch karakter.

Opdat de lezer begripmatig niet meteen “in het diepe wordt geworpen” start *Deel 1* met de gaswetten. Dit gebeurt eerst in hun vorm als de “ideale gaswetten”, waarna uitbreiding naar de niet-ideale toestand volgt. Met dit laatste heeft men bijvoorbeeld te maken bij hoge drukken (duikflessen) en bij fundamenteel onderzoek (inerte gasnarcose). Ook wordt de natuurkunde behandeld van het geval waarbij het gas warmte aan zich zelf onttrekt of toevoegt (adiabatische processen, zoals het bevriezen van de 1ste trap van een ademautomaat). Een belangrijke doelstelling is om na te gaan of bij drukveranderingen in compressie kamers adiabatische processen optreden. Een andere belangrijkdoelstelling is om na te gaan of de aanwezigheid van mensen in een drukkamer van invloed zijn op het drukregiem tengevolge van warmte-afgifte. Enig rekenwerk wordt gedaan aan de componenten van normobare en hyperbare warmte afgifte om de vraag te kunnen beantwoorden.

Zij die niet vertrouwd zijn met de basisbegrippen van de gaswetten worden verwezen naar bijv. “Enige natuurkundige kennis in verband met decompressieverschijnselen” (van Grol, 1977). Voor hen die de fysiologie van de mens niet (meer) paraat hebben wordt bijv. “Fysiologie van de mens” (Bernards and Bouwman, 1988) aanbevolen.

Basale concepten en vergelijkingen met hun afleidingen staan i.h.a. in de hoofd-tekst, maar afleidingen die beduidend dieper op de natuurkunde ingaan en gedetailleerde (getalsmatige) discussies zijn weergegeven in tekst-omkaderingen (cursief). De lezer kan deze tekst-kaders overslaan zonder begripmatig het spoor bijster te raken. De lezer late zich niet afschrikken door het Engels: woordkeuze en stijl zijn zeer alledaags.

De auteur bedankt Ir. H.J. van Grol van de Stichting Duik Research voor zijn uitgebreide en waardevolle commentaar en dr. ir. F.H.C. de Jongh voor zijn moeite mij wegwijs te maken op het gebied van de longmechanica.

## Preface

In nearly any textbooks of hyperbaric medicine and physiology of diving, compressed air work and HBO treatment, the physics of the hyperbaric environment and the medical physics of the human body are discussed but their physical fundamentals are often only superficially treated. Some subjects like lung mechanics and the mechanism of inert gas narcosis are hardly or not discussed. This treatise will remove these omissions. For completeness, the basics of the gas laws will comprehensively be considered too.

However, this manuscript does not claim to discuss completely all physical effects. Some subjects, like models of multi-compartment gas diffusion and the process of appearance and disappearance of gas bubbles are not discussed.

This manuscript has been written for physicians, medical investigators, para-medical personnel, personnel working with compression chambers, and interested sport divers. It is assumed that the reader has operative knowledge of mathematics and physics at the advanced level of a secondary education. The knowledge of physiology is supposed to be at the level of 3\* CMAS.

Basic concept and equations with their derivations are presented in the main text (large font) and more sophisticated derivations and detailed discussions are presented in text boxes (smaller font in italics). The reader can skip these text boxes without affecting the understanding of the main text.

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Notes:

- In this manuscript the basic SI (Syst $\bar{I}$ me Internationale) units (or their derivatives) are preferably used. The seven basic units are: m, kg, s, A, K, mole and cd (A en cd not used).
- Figure 1.2 is modified from van Grol (1977).

## Part 1. The physics of peopled compression chambers

### 1.1 The (ideal) gas laws

#### Introduction to gases

A gas is one of the three so-called aggregation states of a substance, solid, fluid and gaseous. A gas is compressible and often a mixture. It occupies all available space uniformly and completely, has a small specific mass, diffuses and mixes rapidly, and is mono- (He), di- (N<sub>2</sub>, O<sub>2</sub>, CO), tri- (CO<sub>2</sub>, O<sub>3</sub>), or poly-atomic (NH<sub>3</sub>, methane etc). In a so-called ideal gas, the particles (molecules or atoms) have no size and do not influence each other since they show no mutual attraction (no cohesion).

#### The gas molecules

Gas molecules move at random with very high speed through each other (Table 1.1.). The mean molecule-molecule distance is in the nm-range. For N<sub>2</sub> this mean distance is 34 nm at 1 bar and 0° C, ca. 9-13 times their molecular diameter. So, the gas volume is empty for ca. 99.9% and therefore the gas molecules infrequently collide with each other. At 300 K and 1 bar the mean free path of H<sub>2</sub> is ca. 66 nm. Collisions with constant temperature (isotherm) are elastic, also with the wall.

**Table 1.1**

Particle	diameter of particle nm	velocity v* (273 K)		molecular mass m	$\frac{1}{2}m \cdot v^2$ (v in km/s)
		m/s	km/h		
He	0.27	1304		4.003	3.403
H <sub>2</sub>		1838		2.016	3.405
O <sub>2</sub>	0.34	461	1740	32.00	3.400
N <sub>2</sub>	0.37	493	1860	28.016	3.405
CO <sub>2</sub>	0.40	393	1480	44.011	3.399
H <sub>2</sub> O	0.27			18.016	

Data from Kronig et al., 1966; PTZ 1993.

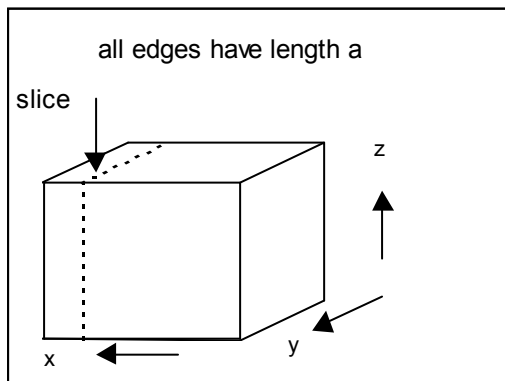
*Box 1 \* Since the velocity v of the individual molecules of a certain kind is not the same, the given velocities are the square root of the mean of the squared velocity of the individual molecules of that kind:  $(\langle v^2 \rangle)^{0.5}$ . This root mean square (RMS) velocity appeared to be a fundamental magnitude to understand the behaviour of a gas (see Box 2 below).*

The right column of Table 1 gives the kinetic energy of the particles. Surprisingly they are the same irrespective the kind of gas. Also for other temperatures this equality holds, be it that the kinetic energy is temperature dependent. Noble gases have mono-atomic particles. For convenience, in this paper the particles of gases will be denoted as molecules.

### The law of Boyle (and Mariotte); gas pressure explained

In the derivation of Boyle's law it is assumed that the gas molecules make elastic collisions with the wall surrounding the gas. The collisions exert a force on the wall, which is proportional to the number of molecules per unit of volume, their velocity and their mass. Pressure (p) is defined as force (F) per area (A). Doubling the density of the gas (this is doubling the number of molecules in a given volume), the number of collisions doubles, and hence the exerted force and so the pressure. Doubling of the density can be obtained by halving the available volume, and as mentioned before, this results in doubling the pressure. This is the conceptual explanation of Boyle's law. In the physics course at the atheneum, such an explanation will not do. We learned a real derivation, be it simplified. Here, the simplified derivation, as used in the physical education, will be given.

A cubic volume V with sides of length a ( $V=a^3$ ) contains N molecules of a certain type of gas, each with a mass m and velocity v. The upper face of the cube is horizontal and one of the lateral faces is directed to the reader. The molecules collide elastically with the wall and hence return with the same velocity in the opposite direction. We consider the wall at the left side. So, the molecules colliding with this wall move to the left. Each molecule delivers a momentum at the wall, being  $2 \cdot m \cdot v = F \cdot t$ . The factor 2 is due to the fact that there is a momentum when the molecule approaches and also when it leaves, and t) presents the duration of the collision. Many molecules collide in time t). This number of molecules can be calculated. Consider a thin, most left slice of the volume V (the left side of the cube and the slice are in common, see figure).



During  $\Delta t$  the molecules travel over a distance of  $v \cdot \Delta t$ . Consequently, when the slice has a thickness of  $v \cdot \Delta t$  then all the molecules in the slice going to the left will impinge on the wall. The slice volume is  $v \cdot \Delta t \cdot a^2$ . One third of the molecules move upward or downward, one third moves away or approaches and one third moves left or right. So,  $1/6^{\text{th}}$  of the molecules moves to the left. Therefore, the number of molecules is  $1/6$  times  $N$  times slice volume/ $V$ , so  $(1/6)N(v \cdot \Delta t) \cdot a^2 \cdot N/V$ . Substituting  $V$  by  $a^3$ , and calculating the total momentum by multiplying the momentum of a single molecule ( $2 \cdot m \cdot v = F \cdot \Delta t$ ) with the number of molecules involved in time  $\Delta t$ , it is finally found that:

$$F_{\text{total}} \cdot \Delta t = \downarrow \cdot N \cdot m \cdot v^2 \cdot \Delta t / a.$$

Consequently,  $F_{\text{total}} = \downarrow \cdot N \cdot m \cdot v^2 / a$ . Since  $p = F_{\text{total}} / a^2$ ,  $p$  becomes  $p = \downarrow \cdot N \cdot m \cdot v^2 / a^3$ . The product  $N \cdot m$  is the mass of the gas in  $V$ . Substituting  $a^3$  by  $V$  yields:

$$p \cdot V = \downarrow \cdot N \cdot m \cdot v^2 = \text{constant since } N, m \text{ and } v \text{ are constant. This is exactly Boyle's law.}$$

The above derivation may appear solid, but from a physical point of view some problematic points are ignored. First, the velocity is not the same for all gas molecules. Second, the molecules move in all directions, not only left, right, upward etc., but also oblique. A more precise derivation can be found in e.g. Kronig (1966) and Feynman<sup>1</sup> et al. (1963). Here, I will suffice with a concise, slightly simplified version of such a derivation (Box 2).

<sup>1</sup> Feynman, American quantum physicist, obtained the Nobel price in 1965 for the elementary-particle diagrams named after him.

*Box 2 First, a 3 dimensional orthogonal axes-system is defined in which the cube (with sides  $a$ , representing the volume  $V$ ) is placed. Now, the velocity of the molecules is decomposed in the three direction  $x, y$  and  $z$ . The velocity in the  $x$  direction is  $v_x$ . The change of momentum of the molecule impinging at the wall in the  $x$  direction is  $2 \cdot m \cdot v_x$ . The number of collisions of  $n$  molecules (the number of molecules per volume unit is equal to  $N/a^3$ ) at the wall per second at area  $a^2$  is  $n \cdot v_x \cdot a^2$ . At the wall with area  $a^2$  the molecules together perform a force  $F$ :*

$$F = n \cdot v_x \cdot a^2 \cdot 2 \cdot m \cdot v_x = 2 \cdot n \cdot m \cdot v_x^2 \cdot a^2 \quad (1.1)$$

*Actually, this equation is a simplification since  $v_x$  is different for the different molecules. However, first we will calculate the pressure  $p$  from  $F$  and then repair the inaccuracy introduced by the simplification (see Feynman et al., 1963). Since  $p = F/a^2$ ,  $p = 2 \cdot n \cdot m \cdot v_x^2$ . The kinetic energy of a molecule is  $\frac{1}{2} m \cdot v_x^2$  and since this is different for the individual molecules we need the mean kinetic energy  $\frac{1}{2} m \cdot \langle v_x^2 \rangle$  ( $m$  is constant; see Box 1 for  $\langle v_x^2 \rangle$ ) and therefore the square of the mean velocity (mean  $\{v_x\}$ )<sup>2</sup> cannot be used. This also eliminates the factor 2 since negative velocities (reflected molecules) do not contribute to the force. So,  $2v_x^2$  is substituted by  $\langle v_x^2 \rangle$ :  $p = n \cdot m \cdot \langle v_x^2 \rangle$ . The  $x$  direction was arbitrarily chosen. Consequently, the same holds for the  $y$  and  $z$  direction. Therefore,  $\langle v_x^2 \rangle = \langle v_y^2 \rangle = \langle v_z^2 \rangle$ . With some mathematical manipulation it can be shown that  $\langle v_x^2 \rangle = \langle v^2 \rangle / 3$ . This yields:*

$$p = n \cdot m \cdot \langle v^2 \rangle / 3 \quad (1.2)$$

*and since  $n = N/V$ ,  $p \cdot V = \frac{1}{3} \cdot N \cdot m \cdot \langle v^2 \rangle$ .* (1.3)

*As long as  $N$  and  $\langle v^2 \rangle$  are constant  $p \cdot V = \frac{1}{3} \cdot N \cdot m \cdot \langle v^2 \rangle = \text{constant}$ . From (1.3) it also holds that for equal  $p$ ,  $V$  and  $N$  ( $N/V$  is the "concentration") the product  $m \cdot \langle v^2 \rangle$  is constant irrespective the type of gas. This is exactly what was already shown in Table 1.1 (right column)*

**Summarising the derivations, it holds that for a given mass and temperature that:**

$$p_1 \cdot V_1 = p_2 \cdot V_2 = \text{constant} \quad \text{or} \quad p_1 / p_2 = V_2 / V_1, \quad (1.4)$$

the well known law of Boyle (and Mariotte). This law holds rather well for moderate gas densities (pressures < 300 bar, with regular temperatures).

For who is "Boyle" of importance?

- \* for the chamber-operator:
  - to have enough air in the buffers.
- \* for the (para-)medic and diver:
  - not to pressurize or depressurize (rapidly) human gas filled body cavities relative to the ambient pressure.

### Law of Gay-Lussac

Some centuries ago Mariotte and Gay-Lussac proved experimentally that the ratio of pressure and temperature is constant provided that volume and the mass of gas are constant. Later, the same has been established more precisely for the absolute temperature  $T$ , so:

$$p_1 / T_1 = p_2 / T_2 = \text{constant}. \quad (1.5)$$

Nowadays, this relation is called the law of Gay-Lussac. Some hundred years ago, it has been proved experimentally that  $\langle v^2 \rangle = 3RT/(N_A m)$ , with  $R$  a constant (see below) and  $N_A$  Avogadro's number<sup>2</sup>. Statistical thermodynamics shows mathematically that indeed  $\langle v^2 \rangle$  and not  $(\text{mean}\{v\})^2$  is the relevant parameter. Conceptually, the correctness of the law can be understood by realising that  $\frac{1}{2} \cdot m \cdot v^2$  kinetic energy of the molecule. So, for a certain type of molecule an increase in  $T$  gives an increase of  $v^2$  and consequently of  $p$ . When  $p$  and  $n$  are constant it holds that:  $\underline{V_1/T_1 = V_2/T_2 = \text{constant, the law of Charles.}}$

For who is "Gay-Lussac" of importance?

\* for the operator,

since the temperature in the tank is different during descent, stay and ascent.

\* for the operator and the (para-)medic,

since human subjects are heat generators.

These items will be discussed in §1.2.3.

## Law of Boyle Gay-Lussac

We have seen that  $p \cdot V = \frac{1}{3} \cdot N_A \cdot m \cdot \langle v^2 \rangle = \text{constant}$ . Now, for  $N$  we take  $N_A$ . Further it holds that the squared RMS velocity is  $\langle v^2 \rangle = 3RT/(N_A m)$  with  $N_A$  the number of Avogadro. After substitution of  $\langle v^2 \rangle$  it follows that  $p \cdot V = RT$ . For  $n$  moles holds the **universal, ideal gas law**:

$$pV = n \cdot R \cdot T, \quad (1.6)$$

with  $n$  the number of kmoles of the gas and  $R$  the molar gas constant (= 8315 J/kmol·K). It contains four variables:  $p$ ,  $V$ ,  $n$  and  $T$ . When applied in calculations, only one dependent variable, being it  $p$ ,  $V$ ,  $n$  or  $T$  can be solved if the other (three independent) variables are known, either by process and/or model assumptions or by other equations.

In practise of diving or applying a compression chamber, often two variables remain constant and the other two other variables change reciprocally or linearly with each other. A trivial example is the case that a compression chamber or a diving bottle is (slowly) pressurized or depressurized by changing  $n$ . The variables  $V$  and  $T$  remain ideally the same and  $p$  increases linear with  $n$ . For pressurizing and depressurizing body cavities, the variables  $n$  and  $T$  are constant and  $p$  and  $V$  change reciprocally (their product is constant). Also this is a very well known application of the ideal gas law. Less trivial but still realistic is that during a dive with a substantial change of water temperature the temperature of a body cavity also changes. Than only  $n$  is constant.

## Law of Avogadro

Equal volumes of ideal gasses at equal pressure and equal temperature comprise an equal number of molecules. This directly follows from equation 1.6. With constant  $T$  and  $p$ , it also means that  $V_1/n_1 = V_2/n_2 = \text{constant}$ .

## Law of Dalton

<sup>2</sup> A gas volume of 22.712 litre at 0 °C (/273.15 K) and 1 bar (/10<sup>5</sup> Pa) comprises 6.0225·10<sup>23</sup> molecules. This is the number of Avogadro ( $N_A$ ).  $N$  molecules are equivalent to  $N/(N_A)$  mole =  $n$  mole. The mass of  $n$  mole is  $n \cdot M_w$  (gram). It is noted that the above description is not the formal definition of  $N_A$ .

The pressure of a mixtures of gasses is the sum of the pressure of the individual gasses (defined as the partial pressures) since the kinetic energy ( $\frac{1}{2} \cdot m \cdot \langle v^2 \rangle$ ) of all types of molecules, irrespective their type, is the same (Table 1.1). So:

$$p_{\text{total}} = p_1 + p_2 + p_3 \dots \quad (1.7)$$

### Refinement of the Law of Boyle Gay-Lussac: the van der Waals correction

For high gas densities the gas molecules do not behave ideal. Therefore “Boyle” needs correction with the Van der Waals<sup>3</sup> constants (Table 1.2). A correction “a” factor is needed for the interaction between the gas molecules (attraction coefficient), and a correction factor “b” for the volume occupied by the gas molecules. Under certain conditions a Van de Waals correction makes sense. For instance, a dive tank of 10 litre at 200 bar and 290 K comprises 82.94 mole of air, as directly found by applying the universal ideal gas law. However, according to Van der Waals 85.25 mol, so 2.8% more (assumed that  $a_{\text{air}}=37.4 \times 10^{-3}$ ). The same bottle, but now at 300 bar comprises 7.8% less. At 200 bar the interaction effect dominates the molecule-volume-effect, but at 300 bar the situation is reversed. The p-V diagram of Fig. 1.1 also illustrates the rather complex behaviour of the correction. Since "Boyle" is independent of the type of molecules, the straight line of Boyle (log-log diagram) holds for both air and helium. The Van der Waals curve of He shows already strong deviations from Boyle's law, since the interaction effect is weak compared to the molecule-volume-effect. The p-V curve approaches the straight Boyle line from above, but the air-curve first crosses the Boyle line and then approaches the line from below. For low pressures the Boyle line is the asymptote for the Van der Waals curves. This rather surprising behaviour of the Van der Waals equation (1.8 in Box 3) is due to the fact that it is a cubic equation in  $n$  (the number of kmoles in the volume  $V$ ), which had to be solved in the above numerical examples. The equation is also a cubic equation in  $V$ .

Summarising, it appears that at pressures (and temperatures) common in diving the Van der Waals correction doesn't play a role, but for extreme deep dives with He mixtures there is an effect of some 5% for the pressure. However, for dive bottles, especially filled with a 300 bar He mixture the effect is already 35% and for experiments with e.g. He-mixtures applied to biological material at some 3000 bar the effect is very considerable (see Fig. 1.1).

**Table 1.2**

Molecule	Van der Waals constants	
	$a$ $10^3 \text{J} \cdot \text{m}^3 / \text{kmol}^2$	$b$ $10^{-3} \text{m}^3 / \text{kmol}$
He	3,5	22
H <sub>2</sub>	25	26
O <sub>2</sub>	140	31
N <sub>2</sub>	140	39
CO <sub>2</sub>	360	44
H <sub>2</sub> O	550	30.5

Data from PTZ (1993).

<sup>3</sup>Van der Waals, professor at the University of Amsterdam, obtained in 1910 the Noble price for his work on the non-ideal behaviour of gases and liquids (the so-called state equations).

Box 3 According to van der Waals:

$$(p + an^2/V_m^2)(V_m - nb) = nRT, \quad (1.8a)$$

with  $V_m$  the total volume, “ $b$ ” a correction factor for the volume occupied by the gas molecules, and “ $a$ ” a correction factor for the interaction between the gas molecules (attraction coefficient). They increase and reduce pressure, respectively. Table 1.2 gives for some gases the numerical values of the two constants. When  $a$  and  $b$  are zero, than the van der Waals equation degenerates to Boyle's law. To calculate  $p$ , (1.8a) can be rewritten:

$$p = nRT/(V_m - nb) - an^2/V_m^2, \quad (1.8b)$$

The  $p/V$  relation of van der Waals for gases is always monotonic increasing to the left to be physical realisable. For very precise calculations, like the complicated modelling of inert gas narcosis of gas mixtures at pressures above 50 bar (see Part 1, §2.2.3), this correction is even not precise enough. Then, the theory of Kamerlingh Onnes<sup>4</sup>, taking also into account the (first and higher order) interactions between the types of molecules in a mixture (virial coefficients), is applied.

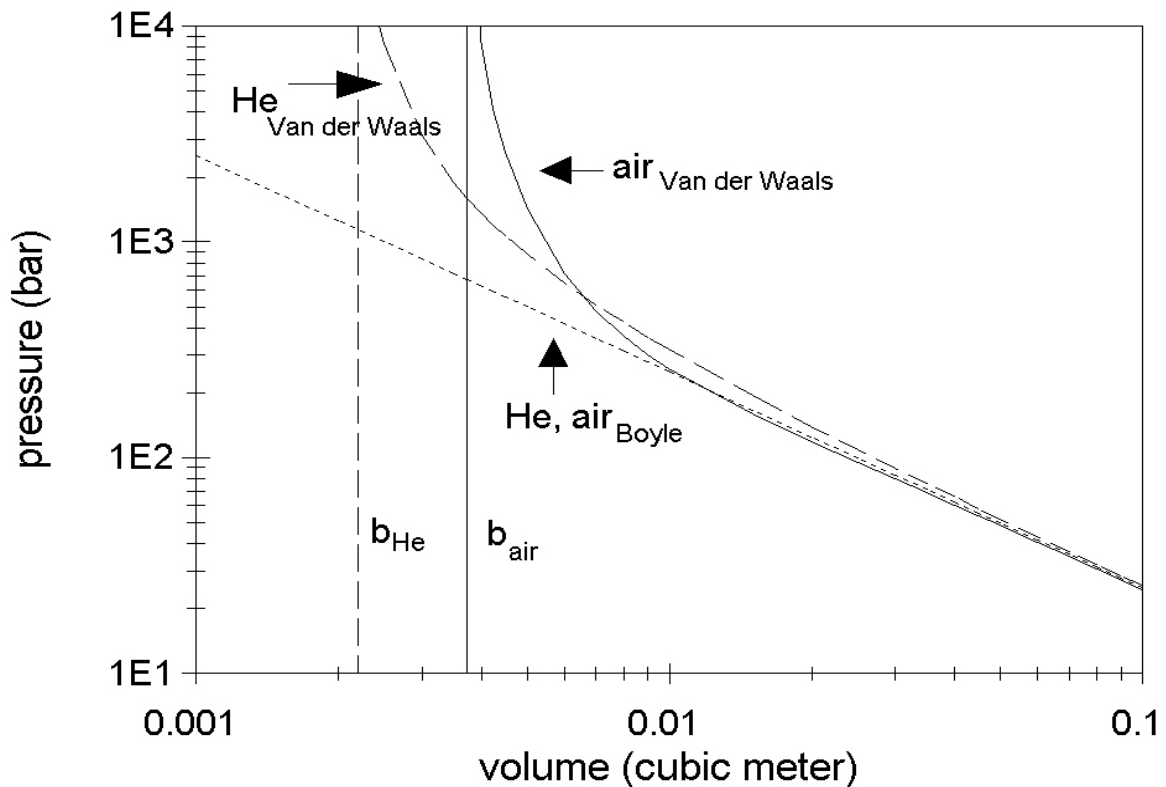


Fig. 1.1 Comparison of  $p/V$  relation according to the Law of Boyle and according to the Van der Waals equation for air and He. For low densities of air (low pressures),  $p$  of Boyle is slightly larger, but for high densities  $p$  of Van der Waals is larger due to the volume of the molecules ( $nb$ ). This is indicated by the vertical asymptote. The curves are calculated for  $n = 0.1$  kmole and  $T = 300$  K.

<sup>4</sup> Kamerlingh Onnes, professor at the University of Leiden obtained in 1913 the Noble price for his work on low temperatures of gases and liquids.

## 1.2 Temperature effects

### 1.2.1 The relevance of temperature effects

Fig. 1.2 gives an example of pressurizing a chamber ( $V_b$ ) with a buffer-vessel ( $V_a$ ). The question is whether the resulting pressure (to be calculated by the reader) after opening of the valve is indeed in accordance with Boyle's law. The answer is definitely **not**. The reason is that during pressurizing of the right compartment and depressurizing of the left compartment the temperature of the gas is not constant. A well-known phenomenon is the increase of temperature during the filling procedure of a diving bottle. A very rigorous one, which caused the drowning of divers, is the freezing of the first pressure reduction valve during "ice diving". Also in the practise of compression chambers, temperature effects are obvious. During pressurizing of the chamber the temperature rises and during depressurizing the temperature drops, often that strong that fog is produced.

In addition to these physical effects, temperature effects based on the human physiology also can play a role in compression chambers as well as in the human body. Humans or other homeothermic creatures produce heat. The pure physical temperature effects will be discussed in § 1.2.2 and some temperature effects related to the human body, the various components of body heat loss, are discussed in Part 2.

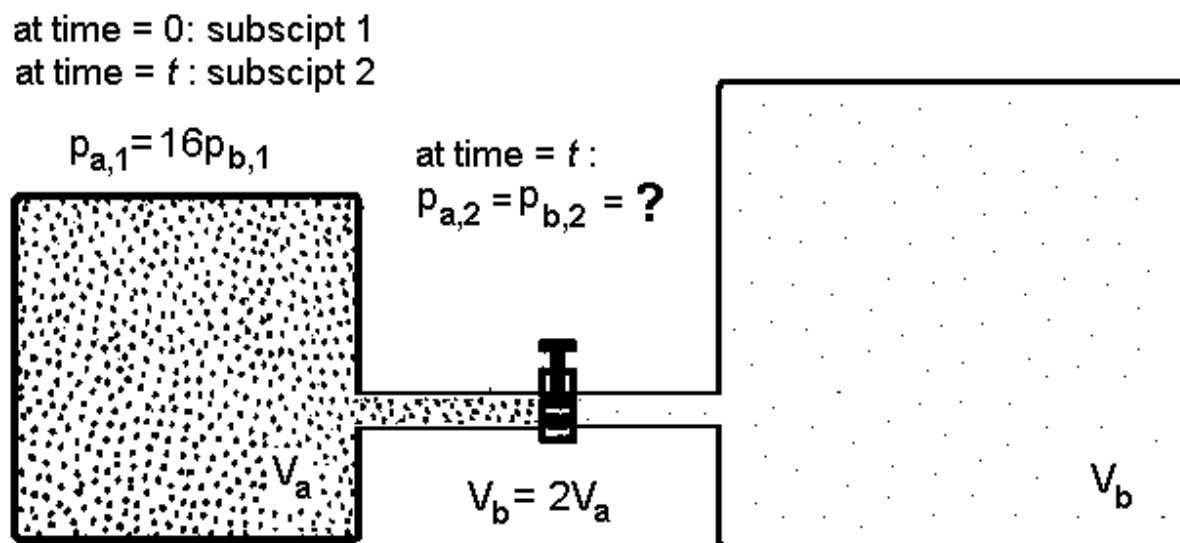


Fig. 1.2 Calculate the pressure with Boyle's law after equilibration of the pressure in both compartments at time  $t$ . The valve is opened at zero time.

### 1.2.2 Adiabatic compression and expansion

Boyle's law being  $p \cdot V = \text{constant}$  only holds when  $T$  is constant, so-called isothermic compression or expansion. It is well known from daily life that a bicycle pump becomes warm when a tire is inflated. This is due to heat transfer from the heated, compressed air. When the heat produced by compression is not given off to the environment but "absorbed" by the gas it self, or when the energy needed for expansion is not provided by the environment but provided by the expanding gas itself, than Boyle's law doesn't hold. Under the above conditions, a compressing gas heats and an expanding gas cools down. These processes are called adiabatic compression and expansion. The deviation from Boyle's law can be very substantial, as will be explained conceptually on the basis of the example of Fig. 1.2.

From the above it becomes clear that the actual behaviour of the temperatures in the volumes  $V_a$  and  $V_b$  of Fig.1.2 and also in the pipe left and right of the valve is not a trivial problem. When the valve has a very narrow opening, the process of equilibration takes so much time (tens of minutes) that the whole process is isothermic. This is due to heat transfer between the system and the environment. When the equilibration is very fast (about a second; pipe and valve diameter large) the process is practically adiabatic and the changes of temperature can rather well be calculated. When the situation is in between the temperature of the various gas volumes change. But during the process, there is also heat (positive and negative) transfer between at the one hand the walls of the volumes, the pipe and the valve and at the other hand the gas volumes. Moreover, there is also heat exchange with the environment. This complicates the temperature behaviour. Therefore, the temperature decrease in  $V_a$  and the temperature increase in  $V_b$  are hard to calculate. The temperature in the left side of the pipe decreases (valve diameter is of the order of pipe diameter), the valve itself severely cools down and may block by freezing. The flow in the pipe, left and right of the valve is strongly turbulent and the same holds close to the inlet of  $V_b$ . Therefore, the temperature of the both parts of the pipe is even harder to calculate than in  $V_a$  and  $V_b$ . Such calculations can only be performed with numerical, complicated mathematical models.

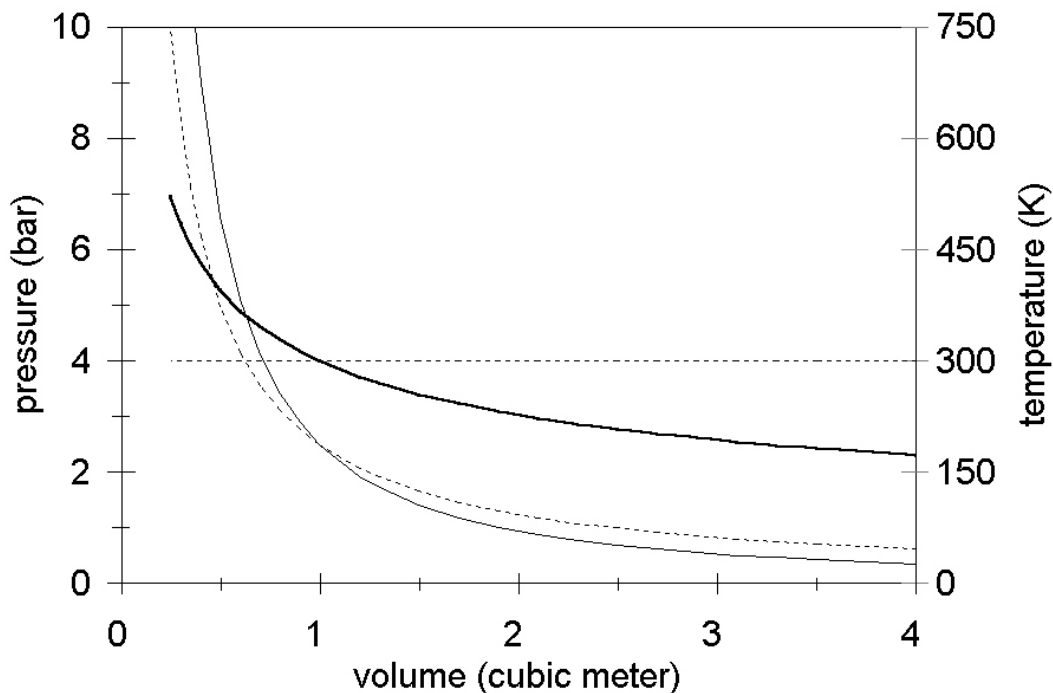


Fig.1.3 Isothermic and adiabatic p-V relation. The dashed curve gives the p-V relation according to Boyle and the dashed straight line the temperature belonging to it, the solid curve the adiabatic p-V relation and the thick solid curve the adiabatic temperature.  $n = 0.1$  kmole.

The above example shows that moderately fast (de)pressurizing is in reality a complicated process. Some quantitative insight in the theory of adiabatic processes is worthwhile. At the end of this paragraph some numerical applications are discussed.

For ideal gases under pure adiabatic conditions the p-V relation is:

$$p \cdot V^\gamma = \text{constant}, \quad (1.9)$$

with a numerical value greater than 1 and depending on the type of gas. Theoretically, it can be proved that (depends on the number of atoms in the gas molecule. For a mono-atomic gases, e.g. the noble gases,  $\gamma$  is 5/3. For a diatomic gases, for instance air,  $\gamma$  is 7/5 (= 1.4). As follows from (1.0), reducing a volume by a factor  $k$  gives a pressure increase much higher than  $k$  (being  $k^{1.4}$ ). Conceptually, one can say that a factor  $k$  is due to the volume decrease according to Boyle and that the remaining factor,  $k^{0.4}$ , is caused by the temperature increase.

*Box 4 The exponent  $\gamma$  is the so-called  $c_p/c_v$  ratio, the ratio of heat capacity of the gas with constant  $p$  ( $c_p$ ) and the heat capacity of the gas with constant  $V$  ( $c_v$ ). The derivation can be found in various textbooks (e.g. Feynman et al., 1965). The derivation from the point of physics is not an easy one. Here, a conceptual explanation is given.*

*The process of compression always has an energetic cost. This external energy is added to the intrinsic energy of the gas, which is actually the kinetic energy of the molecules. When the external energy is supplied instantaneously, it is added to the internal energy of the system. We have seen that the kinetic energy ( $\frac{1}{2}m \cdot \langle v^2 \rangle$ ) of the molecules is proportional with the temperature.*

*Consequently, addition of the external energy will increase  $\langle v^2 \rangle$  and so the temperature. This increase can be calculated as follows. Suppose that volume  $V$  with pressure  $p$  is compressed to  $V'$  yielding a new pressure  $p'$ . Applying (1.9) means that:*

$$p \cdot V^{\gamma} = p' \cdot (V')^{\gamma} \quad (1.10)$$

*Before compression and after compression equation (1.6) also holds. So,  $pV = nRT$  and  $p'V' = nRT'$  ( $T'$  is the new temperature). Rewriting both equalities to  $p = nRT/V$  and  $p' = nRT'/V'$  and substituting these both expressions of the pressure in (1.10) yields:*

$$nRT \cdot V^{(\gamma-1)} = nRT' \cdot (V')^{(\gamma-1)}$$

*and rewriting yields:*

$$T' = T \left( \frac{V}{V'} \right)^{(\gamma-1)}, \text{ or} \quad (1.11a)$$

$$\Delta T = T' - T = T \left( \left( \frac{V}{V'} \right)^{(\gamma-1)} - 1 \right) \quad (1.11b)$$

*This relation also holds for volume expansion.*

An isothermal  $p$ - $V$  curve according to Boyle and an adiabatic  $p$ - $V$  curve are depicted in Fig. 1.3. Numerically, the resulting temperature effect can be substantial.

Suppose, everything ideal, that a gas volume at 300 K (27 °C) is instantaneously reduced in volume by a factor 2.5 and that there is no heat transport. According to (1.11b) this yields  $\Delta T = 300 \times (2.5^{0.4} - 1) = 133$  K. Consequently, a much higher factor of pressure increase is obtained (being  $2.5^{1.4} = 3.6$ ) rather than the factor of 2.5 according to Boyle's law. Actually, a compression-factor of 1.92 (=  $2.5^{1/1.4}$ ) is required to obtain  $p_2 = 2.5$  bar. Then, the temperature increase becomes  $300 \times (1.92^{0.4} - 1) = 90$  K.

The process of pressurizing in the AMC-chamber is very different from reducing a volume by a factor 2.5. The chamber is pressurized, by increasing the number of air molecules with a factor of 2.5. However, this is equivalent (equation 1.6) with reducing the volume by a factor of 2.5. The difference is, that pressurized the AMC tank from 1 bar to 2.5 bar takes ten minutes. In the AMC-tank without climate control an increase of about 25 °C is found. This is a value found by extrapolation of the temperature-time curve before the climate control starts to reduce the adiabatic temperature increase. This 25 °C is much less than the calculated increase of 90 °C. This effect is due to the heat transport (air streams, fan) to the chamber wall within the 10-min duration of pressurizing. Another important factor is the low temperature of the gas entering the tank. This gas is cooled some tens of degrees by its adiabatic expansion in the buffer vessel and the connecting pipes. In practise, it appears that the processes are seldom purely adiabatic or isothermic. There exist a physical theory to calculate the pressure and

thermal effects in a process of mixed behaviour, but this is beyond the scope of this treatise.

The question remains what happens with all these "adiabatic energy", at least with that part related to the temperature difference of  $90 - 25 = 65 \text{ }^\circ\text{C}$  in  $75 \text{ m}^3$ . A small calculation, without discussing its details, gives the answer. The mass of this volume of air at 2.5 bar is about 220 kg (supposed air temperature is 290 K). A temperature increase of  $65 \text{ }^\circ\text{C}$  of this mass of air requires about 14.6 MJ. A chamber wall of  $70 \text{ m}^2$  and 15 mm thick iron has a mass of about 12,500 kg. To heat this mass  $1 \text{ }^\circ\text{C}$ , about 1350 kJ is required ( $c_{\text{iron}} = 0.1075 \text{ kJ}_\text{K}^{-1}\text{kg}^{-1}$ ). The wall temperature increases  $11 \text{ }^\circ\text{C}$  when the 14.6 MJ is stored in the wall. Since the process takes some 10 minutes, part of the heat energy is lost to the outer air by convection. When this is about half, the wall temperature increases with about  $6 \text{ }^\circ\text{C}$  and this seems quite reasonable.

The equation  $p \cdot V^{\gamma} = \text{constant}$  works also the other way around. Suppose that the pressure  $p$  is increased instantaneously to  $k \cdot p$  by a factor of  $k$ . Then, according to Boyle, the volume  $V$  reduces with a factor  $k$ , but now, the reduction is only a factor  $k^{1/1.4}$ . Again, in the pressure increase a "Boyle factor"  $k^{1/1.4}$  and a "temperature factor"  $k^{0.4/1.4}$  are comprised. Of course, these two factors together have to yield  $k$  ( $= k^{1/1.4} \cdot k^{0.4/1.4}$ ). Now, with  $k = 2.5$  and  $T = 300 \text{ K}$  (AMC chamber) the temperature increase is again  $90 \text{ K}$  ( $2.5^{0.4/1.4} \times 300$ ).

As mentioned before, adiabatic effects play a role in diving practise. The adiabatic effect of filling diving bottles is well known. Due to the temperature increase the bottles are mostly filled to 210-220 bar. For He, this effect with filling is stronger than with air (or Nitrox) since ( $\gamma_{\text{He}} = 5/3$ ).

A frozen first valve in ice diving is a potential risk. In the last decades, manufacturers have improved substantially the design of regulators to minimise the risk. However, a small increase of the secondary pressure has a strong reducing effect, since the strength of the adiabatic effect is dependent on the pressure ratio (secondary pressure versus bottle pressure). With He-mixture diving, the stronger adiabatic effect is counteracted by the smaller pressure ratio. Whether heating of the primary valve with expired air (counter current principle) and some increase of the secondary pressure have ever been applied, is not known to the author.

Conclusion Adiabatic, or say "semi-adiabatic" processes play some role in the physics of compression chambers. Of more importance is their role in diving practise and they are a serious hazard during diving in water with a temperature close to the freezing point.

### 1.2.3 The influence of subjects on the gas regime of compression chambers

The type of energy produced by a human body all depends on chemical processes. With a constant mass (no grow or loss of body weight) and in rest nearly all chemical energy is transformed to heat. Also the small amount of mechanical energy (heart and part of ventilatory energy) is mainly transformed to heat. This heat is transferred to the environment and there are various components of this heat transfer. This holds for warm as well as cold-blooded animals, but for the latter the amount of heat loss per unit of mass is much lower.

A subject (normobar) in rest produces about 80 Watt. With an ambient temperature of  $29 \text{ }^\circ\text{C}$  (the critical temperature, Davson and Eggleton, Ch. 33, 1962) this rest metabolism is minimal. The heat transfer of the human body to in-door ambient air will (thermal closed system) increase the ambient temperature. The question arises whether this process is dependent on the ambient pressure of a compression chamber. To answer this question it is necessary to know the components of the body heat loss and their pressure dependency. The contributing components of heat transfer from a subject in rest to the environment are:

$C_{\text{res}}$ , the heat transfer caused by expiration of heated inspired air,

$E_{\text{res}}$ , the heat transfer caused by evaporated water in expired air (in excess of that in inspired air),

- $R_{\text{skin}}$ , the heat transfer caused by radiation,
- $C_{\text{skin}}$ , the heat transfer by caused convection via the (partly clothed) skin,
- $E_{\text{skin}}$ , the heat transfer caused by evaporation via skin (perspiration), without sweating.

Due to the heat output of the body, the temperature in a compression chamber will rise. However, this only holds when the temperature is not controlled (nowadays most multiplace clinical and commercial chambers are controlled) and when the heat leakage to the environment of the chamber is much lower than the heat output of the body. In other words, the chamber behaves as a closed system. In mono-place chambers, like military transport chambers, human heat production is more important due to the relative small volume of such chambers. A related problem is the heat stress of labourers performing heavy labour in caissons and other gas-filled hyperbaric environments (tunnelling constructions) which will be treated in part 2.

To perform some calculations the specification of a human heat-model and the specifications of the compression chamber will be discussed. For the latter two chambers, the AMC chamber and the monoplace chamber (DR-65) of the Stichting Duik Research (SDR) has been chosen.

#### Specifications of the standard human heat-model

- 40 years, male.
- Body weight  $W=75$  kg, length  $H=175$  cm, body area<sup>5</sup>  $A=1.90$  m<sup>2</sup>.
- In rest, in sitting (AMC chamber) and lying (SDR chamber) position.
- No sweat production (subject is in rest) and thin clothing.
- MRV (minute respiratory volume of inspiration) is 5.6 l/min in rest, in sitting position and independent from p.
- $FI_{N_2}/FE_{N_2} = 1.06$  (N<sub>2</sub> fraction in inspired air/N<sub>2</sub> fraction in expired gas, see Part 2, Table 2.1. With this ratio  $MRV_{\text{expiration}}/MRV_{\text{inspiration}}$  is calculated);
- Temperature of expired air is 310 K, independent from p and practically independent of the ambient air temperature.
- Temperature of the skin and clothed skin in the AMC chamber  $T_{\text{skin,AMC}}$  is 303 K (=30 °C) and in the monoplace chamber  $T_{\text{skin,mono}} = 298$  K.
- $\Phi_m = 88.2$  W in sitting position.  $\Phi_m$  is total metabolic power<sup>6</sup>.

The heat contribution to the environment is expressed in Joules per second (/ Watts, a unit of power). This implies that in all equations the ultimate unit of time is second (unless stated differently).

#### Conditions and characteristics of the AMC chamber:

- effective area for radiation of the inside of the chamber wall  $A_{\text{wall}} = 70$  m<sup>2</sup>, net volume  $V = 75$  m<sup>3</sup>;
- emission coefficient of the (whit) chamber wall  $\epsilon_{\text{e-wall}} = 0.9$ ,
- temperature of the air in the chamber  $T_{\text{air}} = 298$  K (= 25 °C),
- temperature of the chamber wall  $T_{\text{wall}} = 296$  K,
- velocity of air stream in the chamber  $v_{\text{air}} = 0.15$  m/s (arbitrary estimate).

#### Conditions and characteristics SDR monoplace chamber:

- effective area for radiation of the inside of the chamber wall  $A_{\text{wall}} = 3.8$  m<sup>2</sup>, net volume  $V = 0.640$  m<sup>3</sup>,

<sup>5</sup> According to Dubois and Dubois (1915),  $A=0.007184xW^{0.425}xH^{0.725}$  with A in m<sup>2</sup>, H in cm and W in kg.

<sup>6</sup>  $\Phi_m$  is age (and sex) dependent. For males in rest (lying)  $\Phi_m/m^2$  decreases from 43.7/m<sup>2</sup> at 25 years to 40.7/m<sup>2</sup> at 60 years (Davson and Eggleton, Ch. 23, 1962). The lying standard male of 40 years old has a  $\Phi_m/m^2$  of 42.2 W/m<sup>2</sup>. With  $A=1.9$  m<sup>2</sup> this yields  $\Phi_m = 80.2$  (sitting 10% more).

- $T_{\text{air}} = 295 \text{ K} (= 22 \text{ }^\circ\text{C})$ ,
- $T_{\text{wall}} = 290 \text{ K}$ ,
- other parameters as the AMC chamber.

Below, a calculation is given of the various components of heat loss of the model-subject. The calculation is made for a pressure of  $p$  is 1.0 and 2.5 bar (the pressure of HBO treatment in the AMC).

### a. Convective heat loss $C_{\text{res}}$ by expiration of gas heated by the body

For simplicity the expired gas is considered to have the composition of air to prevent in the calculations all kinds of corrections for its small content of  $\text{H}_2\text{O}$  and  $\text{CO}_2$ . These corrections have a marginal effect on the result.  $C_{\text{res}}$  is proportional to:

- the mass  $m$  of gas (air) expired per second,
- the temperature difference  $\Delta T$  between inspired and expired gas (air) and,
- the specific heat coefficient  $c_p$  (the amount of energy to increase the temperature of 1 kg gas with  $1 \text{ }^\circ\text{C}$  under constant pressure, see §1.2.2) of the expired gas (air).

So, basically  $C_{\text{res}}$  is:

$$C_{\text{res}} = m \cdot c_p \cdot \Delta T. \quad (1.12a)$$

As calculated in Box 5, at 1 bar in the AMC chamber  $C_{\text{res}}$  obtains the small value of 1.17 W. Since the mass of the expired gas is linearly proportional with its density,  $C_{\text{res}}$  will be proportional with the ambient pressure. So, at 2.5 bar  $C_{\text{res}}$  is 2.5 times higher, yielding 2.93 W. This contrast the much larger heat loss of 47 W calculated for a sport diver at 50 m. (See the box for the calculation.) This is due to the higher pressure (and so gas density) and the fact that a diver is certainly not in rest. Consequently his MRV is much larger.

*Box 5 Starting from  $\text{MRV}_{\text{exp}}$ , the mass  $m$  can be calculated by using the density of air  $\rho$  (in  $\text{kg}/\text{m}^3$ ), the ambient pressure (in bar), and a temperature correction  $(273/T)$ . Moreover, seconds in stead of minutes are used. For the AMC chamber, the equation becomes:*

$$C_{\text{res}} = \{\text{MRV}_{\text{exp}} \cdot \rho_0 \cdot (273/T) \cdot p/60\} \cdot c_{p,\text{air}} \cdot \Delta T, \text{ with:} \quad (1.12b)$$

- $\text{MRV}_{\text{exp}} = (\text{FI}_{\text{N}_2}/\text{FE}_{\text{N}_2})\text{MRV} = 1.06 \times 5.6 \text{ l/min}$  at  $p=1 \text{ bar}$ ;
- $\rho_0 = 1.29 \text{ kg}/\text{m}^3$ , the specific density of air at 273.15 K and 1 bar;
- $T = 310 \text{ K}$ , the temperature  $T$  of the expired gas is;
- $p = 1 \text{ bar}$ , the ambient pressure;
- 60, the conversion factor from minute to second;
- $c_{p,\text{air}} = 1.00 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$  of (at  $0 \text{ }^\circ\text{C}$ );
- $\Delta T = 12 \text{ K}$  (ambient temperature in AMC chamber is 298 K).

*After filling out all parameters, the equation of  $C_{\text{res}}$  yields 1.17 W.*

*$\Delta T$  in the monoplace chamber is 3 K less, so  $C_{\text{res}} = 0.75 \times 1.17 \text{ W} = 0.88 \text{ W}$ .*

*In the literature (ASHRAE, 1989, cited by Parsons 1994) a completely different, empirical approach is described:  $C_{\text{res}} = 0.0014 \Phi_m (307 - T_{\text{ambient}})$  with  $\Phi_m$  the total metabolic power. This equation is not surprising since  $\Phi_m$  is tightly coupled to MRV. Sitting,  $C_{\text{res}}$  is assumed to be 10% more and so  $C_{\text{res}}$  according to ASHRAE (1989) yields 1.23 W, a value nearly the same as found with (1.12b).*

*The question arises whether this component of heat loss is also very low for a diver performing a deep dive. A diver at 50 m with a supposed MRV of 17 liter (volume calculated for 298 K, the same temperature as used for the subject in the AMC chamber) and  $\Delta T$  of 22 K (the water temperature is such that  $T_{\text{inspiration}}$  is 288 K and  $T_{\text{expiration}}$  is 310 K) has a  $C_{\text{res}}$  of  $6 \times (17/5.6) \times (22/10) \times 1.17 = 47 \text{ W}$ . This is a substantial loss of heat.*

**Conclusion** For low p's and low MRV's is  $C_{res}$  small, but for high p's and MRV's it may be substantially since  $C_{res}$  increases linearly with p and MRV. Apart from the ambient temperature, chamber characteristics are irrelevant.

### b. Heat loss by alveoli-evaporated water in expired air ( $E_{res}$ )

This loss is given by  $E_{res}$  = mass m of water vapour times specific evaporation heat  $\Delta H$  of water:

$$E_{res} = m_{H_2O} \cdot \Delta H_{H_2O}. \quad (1.13a)$$

The calculation is rather similar as the previous one. It yields 9.4 W (see Box 6). The amount of evaporated water is independent of the ambient pressure, since the  $p_{H_2O}$  in the alveoli is always<sup>7</sup>

*Box 6 Starting from MRV (in m<sup>3</sup>), correcting for ( $FI_{N_2}/FE_{N_2}$ ), considering the fraction of water vapour ( $FE_{H_2O} = 0.0618$  and  $FI_{H_2O} = 0.003$ , see Part 2, Table 2.1), correcting for temperature we first calculate the volume of water vapour in m<sup>3</sup>/min at 273 K. Considering seconds, the volume per time unit (m<sup>3</sup>/s) is calculated. Next, this volume is converted to the number of kmoles by dividing by 22.4 m<sup>3</sup> (1 kmole at standard conditions has a volume of 22.4 m<sup>3</sup>). Then the mass in kg/s is calculated by multiplying with the molecular weight of water ( $M_{W_{H_2O}}$ ). Finally this mass is multiplied by specific evaporation heat  $\Delta H_{H_2O}$  (kJ/kg). Then, the equation becomes:*

$$E_{res} = \{[MRV \cdot (FI_{N_2}/FE_{N_2}) \cdot (FE_{H_2O} - FI_{H_2O}) \cdot (273/T)/60]/22.4\} M_{W_{H_2O}} \cdot \Delta H_{H_2O} \quad (1.13b)$$

*With  $\Delta H_{H_2O}$  is 2260 kJ/kg (PTZ, 1993),  $E_{res}$  becomes 9.4 W.  $E_{res}$  is invariant with ambient pressure and the chamber.*

*An empirical approach is  $E_{res} = 0.0173 \Phi_m (5.87 - p_{H_2O, ambient}/1000)$  (modified after ASHRAE, 1989). With  $p_{H_2O, ambient} = 304$  Pa for the standard subject a  $E_{res}$  of 8.26 W is found, a value slightly less than found with (1.13b), the direct approach.*

*The approach resulting in equation 1.13b cannot give insight into pressure dependency since the calculation starts with determining the fraction of MRV occupied by H<sub>2</sub>O-vapour is. The pressure independence becomes obvious when one realises that the alveolar  $p_{H_2O}$  is always 6.3 kPa.*

**Conclusion**  $E_{res}$  is independent of p and the chamber used.

### c. Heat loss by radiation

The peak wavelength of the radiated light by the human body is about 10  $\mu$ m. (This wavelength can be calculated from the temperature of the skin with the translation law of Wien<sup>8</sup>). This wavelength means that mainly infrared light is emitted.

The law of Stefan-Boltzmann<sup>9</sup> says that a black emitting body radiating in an infinite space with 0 K as background temperature emits  $\sigma \cdot A_{body} T_{body}^4$  Watt. The constant  $\sigma$  is the constant of Stefan-Boltzmann, being  $5.7 \times 10^{-8}$  W/(K<sup>4</sup>·m<sup>2</sup>). Extending the law for grey bodies (law of Kirchhoff) and non-zero Kelvin background the equation for the radiation loss  $R_{body}$  becomes:

<sup>7</sup> This holds also on Mount Everest and even at an altitude of some 14 km, where the ambient pressure is 6.3 kPa. This means that inspiration of pure oxygen doesn't result in any oxygen intake.

<sup>8</sup> Wien, a German radiation physicist obtained the Nobel price in 1911.

<sup>9</sup> Boltzmann, Famous 19-century Austrian physicist, known for e.g. the constant, statistics and law of Boltzmann.

$$R_{\text{body}} = \epsilon_{\text{body}} \cdot \sigma \cdot A_{\text{body}} T_{\text{body}}^4, \text{ with} \quad (1.15a)$$

$\epsilon_{\text{body}}$  the emittance coefficient, which is smaller than 1, and generally larger than 0.8. A mean value for the thin-clothed human body is 0.95 (Bernards and Bouman, 1988). The derivation of (1.15a), which can be found in e.g. Kronig (1966), is outside the scope of this treatise. Now, the problem arises that the background doesn't have a temperature of 0 K but a temperature of  $T_{\text{wall}}$ . Then,  $R_{\text{body}}$  appears to be equal to:

$$R_{\text{body}} = \epsilon_{\text{body}} \cdot \sigma \cdot A_{\text{body}} (T_{\text{body}}^4 - T_{\text{wall}}^4). \quad (1.15b)$$

Actually, the body is surrounded at a finite distance by a chamber wall with its own area. Whereas the body radiates in all directions to the chamber wall, each small part of the inside of the chamber wall basically radiates to the rest of the area of the chamber wall. This makes the equation to calculate  $R_{\text{body}}$  more complicated:

$$R_{\text{body}} = C \cdot \sigma \cdot A_{\text{body}} (T_{\text{body}}^4 - T_{\text{wall}}^4) \quad (1.15c)$$

The parameter  $C$  comprises the surface of the body and the wall, and the emittance factor of the body and the wall. In literature, often an equation is found with a temperature difference and a third power of the two temperatures. This is an approximation, being:

$$R_{\text{body}} \approx C \cdot \sigma \cdot A_{\text{body}} (T_{\text{body}} - T_{\text{wall}})^3/2, \quad (1.15c)$$

with  $T = T_{\text{body}} - T_{\text{wall}}$ . The absorption coefficient for infrared light (per meter) is very low, so  $R$  is independent of the gas density and consequently pressure independent. Box gives the details of the calculation.

*Box 7 The parameter  $C$  is defined as  $1/C = 1/\epsilon_{\text{body}} + (A_{\text{body}}/A_{\text{wall}})(1/\epsilon_{\text{wall}} - 1)$  (PTZ, 1993). The AMC tank has an effective area of  $70 \text{ m}^2$ , the effective area of the sitting body  $A_{\text{s-skin}}$  is  $1.33 \text{ m}^2$ , (70% of  $A_{\text{skin}}$ , see Parsons 1994) and  $\epsilon_{\text{wall}} = 0.9$ .  $C$  appears to be  $5.4 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-1}$ . With  $T_{\text{skin}} = 303 \text{ K}$  and  $T_{\text{wall}} = 296 \text{ K}$  the radiant power is  $40.7 \text{ W/m}^2$ .*

*In a similar way the radiant power of the chamber wall in the direction of the subject can be calculated. It amounts to  $10.1 \text{ W/m}^2$ . Since the absorption coefficient of the subject is about 0.65 (Bernards and Bouman, 1988), the net dissipation is  $40.7 - 6.6 = 36.1 \text{ W/m}^2$ . For the sitting standard subject this finally yields  $R_{\text{skin}} = 45.4 \text{ W}$ .*

*When  $A_{\text{wall}} \gg A_{\text{skin}}$ , in the definition of  $C$ , the second term at the right can be ignored. In our case, this holds since this reduces  $C$  with about 0.1 % only.*

*Foggy air, which occurs during ascent, reduces  $R$  since it reduces the effective area of the tank, but this is a small effect. More relevant is the strong increase of radiation due to the larger  $T$  during ascent.*

The calculation yields a  $R_{\text{skin}}$  of  $45 \text{ W}$  ( $36 \text{ W/m}^2$ ). The radiation of a body, an electro-magnetic wave phenomenon (as light actually is), is independent from the surrounding medium (as long as there is no interaction between the emitted waves and the surrounding media close to the interface between both media). In other words, the radiation is independent of pressure.

ASHRAE (1989) applies the equation  $R'_{\text{skin}} = 4.7 \text{ Wm}^{-2}\text{K}^{-1}$  for most typical indoor conditions. This results for our example in a value of  $33 \text{ W/m}^2$ . The discrepancy with the present calculation is due to the fact that for a large  $T$  with a large body temperature the linear approximation of ASHRAE holds less well.

A similar calculation on the basis of (1,15) for the SDR monoplace tank with  $T_{\text{skin}} = 298 \text{ K}$ ,  $T_{\text{wall}} = 290 \text{ K}$ ,  $C=0.920$  and  $A_{\text{l-body}}$  (lying subject) is  $1.14 \text{ m}^2$  ( $0.6 \times 1.9 \text{ m}^2$ ) yields a radiant power of  $42.6 \text{ W/m}^2$ . Since the absorption correction is  $23.5 \text{ W/m}^2$ . This finally yields  $R_{\text{skin}}$

=22 W.

**Conclusion** About ¼ to ½ of the dissipated power by the subject is due to radiation, depending on the tank volume. This loss is independent of pressure.

#### d. Heat loss by laminar convection

A difference in temperature always results in heat transport from a medium with a high temperature to a medium with a low temperature. Under most conditions, the human body transfers heat to the surrounding air. The underlying mechanism is that the air molecules colliding with the skin (the “wall”) obtain a larger momentum at the cost of the velocity of the Brownian motion of the skin molecules. And so, the air molecules increase their velocity, and consequently the boundary layer of air covering the skin obtains a higher temperature. This heated layer has a lower specific density than the cooler air at a larger distance. This difference causes a laminar ascend of the boundary layer. This is the process of heat loss by convection. Heat transfer by convection is hard to calculate and various approaches can be found in literature (Bernards and Bouman, 1988; Parsons, 1995; PTZ 1993). With laminar convection the problem is easier, although still complicated.

A laminar current has a Rayleigh<sup>10</sup> number (Ra) between  $10^4$  and  $10^8$ . The convection currents in the chamber ( $v_{\text{air}} < 0.15$  m/s) appear to be laminar since Ra is about  $1.0 \times 10^6$ . Also in the AMC chamber where air velocities are low (despite an operating fan and air refreshment). Under the above conditions the refrigeration-law of Newton applies:

$$C_{\text{skin}} = \alpha \cdot A \cdot \Delta T, \quad (1.15)$$

with  $\alpha$  the heat convection coefficient, A the area of the body and  $\Delta T$  the difference in temperature between skin and ambient air ( $\Delta T = T_{\text{skin,AMC}} - T_{\text{air}} = 303 - 298 = 5$  K). For a seated subject  $C_{\text{skin}}$  is estimated at 14.6 W.

*More precisely, the calculation is as follows. The parameter  $\alpha$  is  $1.35 (\Delta T/H)^{1/4}$  at 1 bar and 20 °C (according to McAdams, PTZ), with H the effective height of the subject.*

*For a human body, the effective body area A and effective height H for convection are dependent on the position of the body:*

*lying):  $A_{\text{l-body}} = 1.235 \text{ m}^2$ , (65% of naked skin),  $H_{\text{l}} = 0.3$  m;*

*sitting):  $A_{\text{s-body}} = 1.33$  (70%),  $H_{\text{s}}$  is actually comprised of more values. Therefore,  $\alpha$  in sitting position is estimated from the values in lying and standing position.*

*standing):  $A_{\text{st-body}} = 1.39 \text{ m}^2$  (73%),  $H_{\text{st}} = 1.60$  m.*

*With  $\Delta T = 5$  K,  $\alpha$  and  $C_{\text{skin}}$  could be calculated:*

*lying body):  $\alpha = 2.72$  and so  $C_{\text{skin}}$  is 16.8 W.*

*standing position):  $\alpha = 1.79$  and so  $C_{\text{skin}}$  is 12.5 W*

*For the seated position  $\alpha$  is estimated at 2.2  $C_{\text{skin}}$  is estimated at 14.6 W. Foggy air (fast decompression) augments  $C_{\text{skin}}$ .*

*The parameter  $\alpha$  comprises a factor 1.35. This factor is dependent on the pressure p. ISO 7933, cited by Parsons (1994) claims that  $\alpha$  is proportional to  $p^{0.25}$ . Then, at 2.5 bar,  $\alpha$  becomes  $1.35 \times 2.5^{0.25} \times 1.63$  (since  $2.2/1.35 = 1.63$ ). This yields  $\alpha = 2.8$ , and so  $C_{\text{skin}} = 18.4$  W.*

*For the small chamber  $\Delta T = 3$  K, yielding an  $\alpha$  in lying position of 2.4 and 3.0 at 1 and 2.5 bar respectively. Finally this yields a  $C_{\text{skin}}$  of 14.8 and 18.6 W.*

*Air velocities  $v > 1$  m/s give a substantial increase in  $C_{\text{skin}}$ : the factor of proportionality is  $(v \cdot p)^{0.6}$  (Parsons, 1994). From this factor the wind-chill temperature factor can be calculated.*

<sup>10</sup> Rayleigh, English physicist, amongst others he discovered argon, for which he obtained the Nobel price in 1904. The Rayleigh number is the product of the Grashof number Gr and the Prandtl number Pr. For the definition of these numbers the reader is referred to e.g. PTZ (1993).

Heat transfer by laminar convection is pressure dependent:  $C_{p\text{ bar}} = p^{1/4} C_{1\text{ bar}}$ . This can be conceptually clarified as follows. With a higher pressure, there is a higher density and so more collisions with the wall. This effect proportionally speeds up the heat transfer. But a higher density means that in the gas there are also more collisions, reducing the “diffusion” of the heat. Also the convection motion behaves different. This all results in the exponent of  $1/4$ . In the AMC chamber at 2.5 bar this yields a  $C_{\text{skin}}$  of 18.4 W.

**Conclusion** Heat loss by laminar convection is a moderate component, which increases with pressure but much less than proportional. Body position is a minor parameter. It is independent of the chamber dimensions.

### e. Heat loss by water perspiration from the skin

Water evaporates from the skin since the vapour pressure in the outer skin is higher than the vapour pressure of the surrounding air. Perspiration is the process of water evaporation from the skin without sweating. It is assumed that in the given conditions no liquid sweat is produced. Then, the relevant relation is basically the same as (1.13):

$$E_{\text{skin}} = m \cdot \Delta H_{\text{skin water}}. \quad (1.16)$$

The mass of perspired skin water ( $m$ ) is  $5.8 \times 10^{-6}$  kg/s (0.5 kg/day; Davson and Eggleton, 1962 Ch. 32, gives only 0.35 kg/day), and  $\Delta H_{\text{skin water}}$  is 2428 kJ/kg (Davson and Eggleton, Ch. 33). The latter number is higher than for pure water due to the dissolved minerals in the liquid phase. The calculation yields  $E_{\text{skin}} = 14.0$  W.

$E_{\text{skin}}$  reduces with pressure since the water molecules make more collisions with the air molecules which hampers their diffusion in the surrounding air. This results in a reduction of the water vapour gradient in the boundary layer, reducing the driving force of the perspiration (or evaporation of sweat). The dependent on pressure is  $E_{\text{skin,p}} = E_{\text{skin}}/p^{3/4}$  when  $v < 0.15$  m/s (Parsons, 1994). At 2.5 bar 7.0 W is found. The result is the same for the two chambers.

With sweat production the calculation becomes more complicated since part of the sweat evaporates and the remaining part is cooled and drips off.

**Conclusion:**  $E_{\text{skin,p}}$  is independent of the chamber dimensions and reduces with pressure.

### f. The influence of the components of heat loss on the chamber temperature

At 1 bar in the AMC chamber,  $E_{\text{res}}$  and  $E_{\text{skin}}$  (for  $v < 0.15$  m/s) together is 23.4 W, and  $R_{\text{skin}}$  is 45 W which is about  $1/4$  and  $1/2$  of the production in rest respectively, as is in accordance with Davson and Eggleton (Ch. 32, 1962). On the basis of body area, age and sex, the sitting standard subject is supposed to have a total metabolic production of 88.2 W (calculated from Davson and Eggleton, Chap. 23, 1962), which is close to the obtained values of the total heat loss (see Table 1.3). A 1-degree higher skin temperature gives a nearly perfect match. The metabolic production is the minimal production reached at 29 °C for a naked subject and some (2) degrees lower for a thinly clothed subject. The total loss in the SDR chamber is too low, which implies that there should be a little production of sweat, which evaporates.

Suppose that the chamber wall has the temperature of the skin. Then, there is no radiation at all and consequently the subject has to sweat (with evaporation) to compensate for the lack of radiation. When the air temperature also has the skin temperature  $C_{\text{skin}}$  becomes zero and  $C_{\text{res}}$  becomes practically zero which should be compensated by additional sweat evaporation.

**Table 1.3**Heat transfer to environment ( $v_{\text{air}} < 0.15 \text{ m/s}$ )

component of heat transfer	AMC chamber		SDR chamber	
	1 bar (0 m) (W)	2.5 bar (15 m) (W)	1 bar (0 m) (W)	2.5 bar (15 m) (W)
$C_{\text{res}}$	1.17	2.93	0.88	2.2
$E_{\text{res}}$	9.4	9.4	9.4	9.4
$R_{\text{skin}}$	45	45	22	22
$C_{\text{skin}}$	14.6	18.4	14.8	18.6
$E_{\text{skin}}$	14.0	7.0	14.0	7.0
Total heat loss	84.2	82.7	61.1	59.2

Now it should be discussed whether all components contribute equally to heating the air in the chamber. It is supposed that during the process there is no transfer of heat to the outside air.  $C_{\text{res}}$  and  $C_{\text{skin}}$  directly heat the chamber air and so contribute completely.  $R$  is partly (say 30% directly) absorbed by the chamber wall (paint) and chamber attributes. This will heat the chamber wall and part of this heat is transferred to the chamber air by convection. The multiple reflected infrared light will enhance these processes. Due to the long pathway of the multiple reflected light, also some light energy is absorbed by the air. The net effect of the transfer from  $R$  to the air is assumed to be 75%.  $C_{\text{res}}$  and  $C_{\text{skin}}$ , accounting for the produced water vapour, will partly be transferred to the chamber wall due to condensation, which indirectly (partly) heats the air. The net effect is guessed to be 25%. These estimates yield a heat transfer of 59.2 and 41.4 with  $p = 2.5 \text{ bar}$  for the AMC and SDR chamber respectively. With these numbers, the warming up of the air in the AMC chamber can easily be estimated when there is no ventilation, refreshing air and cooling. The mass of gas is  $m = V \cdot \Delta \cdot (273/T) \cdot p$ . With a net volume of  $75 \text{ m}^3$ ,  $m$  becomes  $75 \times 1.29 \times (273/290) \times 2.5 = 221.6 \text{ kg}$ . With  $c$  (specific heat coefficient) is  $1.00 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ , a temperature rise of  $1 \text{ }^\circ\text{C}$  needs  $226.1 \text{ kJ}$ . With 10 standard subjects it takes  $440 \text{ s}$  (ca.  $7\frac{1}{2} \text{ min}$ ) to raise the temperature with  $1 \text{ }^\circ\text{C}$ . This makes clear that cooling of a clinical chamber is generally a necessity.

In an isolated monoplace chamber with a net volume of  $640 \text{ l}$  with one subject, a  $1 \text{ }^\circ\text{C}$  rise needs  $38 \text{ s}$  when there is no heat transport to the chamber wall. Actually, in such a small chamber there is substantial heat transfer by convection and water precipitation to the wall. This delays the temperature increase, which actually amounts  $5\text{-}10 \text{ }^\circ\text{C}$  per  $30 \text{ min}$  at  $4 \text{ bar}$ .

**Conclusion** The heat produced by residents in large (clinical) multiplace chamber and the heat produced by pressurizing makes temperature control a necessity. Despite the calculations, we know from practise that this does not hold for a monoplace chamber. The reason is that its area/volume ratio is much larger (factor of the order of 5) than a multiplace chamber. This makes the heat transfer to the air outside the chamber highly effective. However, after some  $15 \text{ min}$ , also in monoplace chambers control is needed. This is generally realised by refreshing the air (primarily applied to prevent a too high  $p_{\text{CO}_2}$ ) in the chamber.

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## SI units and derivatives

bar	1 bar / $10^5$ Pa
J	Joule, unit of energy (N·m)
K	Kelvin, absolute temperature; 273.15 K / 0 °C
mol	1 mol gas at 1 bar and 0 °C comprises $6.02 \cdot 10^{24}$ molecules and has a volume of 22.7 l
N	Newton, unit of force ( $\text{kg} \cdot \text{m} \cdot \text{s}^{-2}$ )
Pa	Pascal/ $\text{N}/\text{m}^2$ , 1 ATA / 1 bar / $10^5$ Pa
W	Watt, unit of power, J/s

## Abbreviations, constants and variables

a	length (m)
<i>a</i>	van der Waals constant for volume correction
$\nabla$	heat convection coefficient. $\nabla = 1.35 (T/H)^{1/4}$
A	area ( $\text{m}^2$ )
<i>b</i>	van der Waals constant for interaction
atm	1 atmosphere = 101325 Pa
<i>c</i>	specific heat coefficient (at 0 °C)
C	heat transport by convection (W)
(	$c_p/c_v$ ratio (ratio of heat capacity with constant p and constant V)
E	heat transport by evaporation (W)
,	emittance factor
F	force (N)
FE	specific fraction of expired air
FI	specific fraction of inspired air
H	height (m)
)H	specific evaporation heat (kJ/kg)
L	length of subject (m)

<sup>11</sup> Unfortunately, this publication shows printing errors in equations, unclear definitions of variables and poor derivations.

$m$	molecular mass
$m$	mass (kg)
$M_w$	molecular weight (kg)
$n$	particle concentration, $N/m^3$
$n$	number of kmoles
$N$	number of molecules
$N_A$	number of molecules in 1 kmole is number of Avogadro. It equals $60225 \cdot 10^{24}$ ( $\text{mol}^{-1}$ ).
$p$	pressure (bar, ATA or Pa)
$P$	power (W)
$r$	radius (nm)
$R$	universal gas constant (= 8315 J/kmol·K)
$R$	heat transport by radiation (W)
MRV	respiratory minute volume (l/min)
$\Delta$	specific density at 0 °C ( $\text{kg}/\text{m}^3$ )
$\Phi$	constant of Stefan-Boltzmann; $5.7 \times 10^{-8}$ W/( $\text{K}^4 \cdot \text{m}^2$ )
$t$	temperature in °C
$T$	temperature in Kelvin
$\Phi_m$	total metabolic power (W)
$v$	velocity (m/s)
$V$	volume ( $\text{m}^3$ or l)
$W$	weight (kg)