

Joachim G. Wünnig/  
Ambrogio Milani (Editor)

# Handbook of Burner Technology for Industrial Furnaces

Fundamentals  
Burner  
Applications

VULKAN



Edition **HEAT  
PROCESSING**

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# **Handbook of Burner Technology for Industrial Furnaces**



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Joachim G. Wünnig / Ambrogio Milani (Editor)

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**Fundamentals  
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## Foreword

The demands made on the energy-efficiency and pollutant emissions of industrial furnaces are rising continuously and have, following the recent increases in energy prices and in view of the discussion concerning the climate changes for which CO<sub>2</sub> emissions are, at least in great part, responsible, attained a new high priority. In numerous companies, including many in the steel industry, and in enterprises operating heat-treatment installations, the saving of energy is now a top-ranking consideration. For this reason, this work focuses unequivocally on the fields of energy-efficiency and emissions reduction.

This book is intended to assist in bridging the gap between theory and practice and thus to be of use both to the committed practitioner and to those in the fields of research and teaching.

The opening chapters of the Handbook of Burner Technology for Industrial Furnaces examine the fundamental theoretical principles of combustion theory, fluid mechanics and heat transfer, focusing only on those aspects of significance for burner systems. Subsequent chapters then deal in more detail with this technology, discussing combustion concepts, pollutant generation and reduction, and the recovery of heat for use in preheating of combustion air, the minimum requirement for enhancement of energy-efficiency. The "Industrial burners" chapter then examines, citing examples, the more important types of industrial burner and their integration into the furnace-system concept. This is followed by chapters on standardization and regulatory legislation, suggestions for further reading, relevant research institutions and an annex containing pertinent physical data.

A large range of tasks will need to be solved in the coming decades to enable mankind to maintain high production levels as resources become ever scarcer. The rational requirement for the lowest possible environmental impact from industrial combustion processes will constitute one of the most important of these challenges. Developments in the field of combustion technology are striding forward extremely rapidly at present, and many of the technical solutions advanced in this book will, without doubt, have been augmented by further developments and innovations within a few years; the underlying principles will remain valid, however. It is therefore vital to remain informed on new developments at all times, and the book thus closes with an attempt to highlight some of the potential sources of further information.

I am particularly grateful, in completing this work, to my two mentors from my period of study in Aachen. The essays on combustion theory (Prof. G. Woelk) and heat transfer (Prof. U. Renz) treat the essential principles of combustion systems in depth. A large range of individuals and companies contributed text and illustrations for Chapter 8, and to them I also extend my most sincere thanks. I also wish to thank Dr. Beneke for the whole of Chapter 9, on Standardization. My gratitude is also due to my co-editor, Dr. Milani, whose ever positive approach and untiring industriousness again and again contributed to making the drafting of this title less strenuous work, and more a pleasure.



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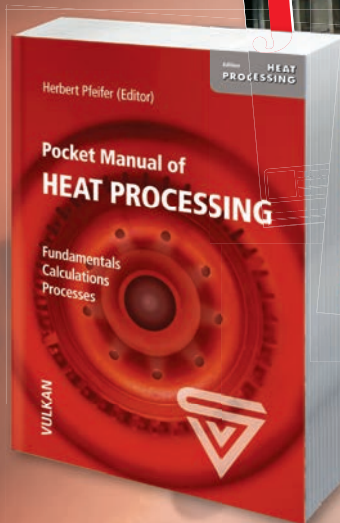
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# Contents

<b>Foreword</b> .....	V
<b>Authors</b> .....	VII
<b>1. Combustion</b> .....	1
1.1 Stoichiometry .....	1
1.1.1 Reaction elements of technical fuels .....	1
1.1.2 Characteristic values for the composition of gaseous fuels .....	2
1.1.2.1 Characteristic amount of atoms for gaseous fuels .....	2
1.1.3 Combustion calculation .....	4
1.1.3.1 Calculation of the air requirements .....	5
1.1.3.2 Calculation of the exhaust gas amount and exhaust gas composition .....	7
1.2 Energy flux in the furnace .....	10
1.2.1 Characteristic furnace interfaces .....	10
1.2.2 Characteristic energies and heat flux .....	11
1.2.3 Energy balance .....	13
1.2.4 Efficiency factors .....	13
1.2.4.1 Combustion efficiency .....	14
1.2.4.2 Furnace efficiency .....	16
1.2.4.3 Heating efficiency .....	16
1.2.5 Saving of fuel with preheating of the air .....	16
<b>2. Fluid Dynamics</b> .....	19
2.1 The ideal gas .....	19
2.2 Equation of continuity .....	21
2.3 Equation of Bernoulli .....	22
2.4 Turbulent free jet .....	25
2.5 Pressure losses in pipings .....	26
<b>3. Heat Transfer</b> .....	28
3.1 Mechanisms of heat transfer .....	28
3.2 Heat radiation .....	30
3.2.1 Electromagnetic spectrum .....	30
3.2.2 Stefan-Boltzmann's law .....	31
3.2.3 Planck's distribution law .....	31
3.2.4 Reflection, absorption, transmission .....	32
3.2.5 Kirchhoff's law .....	33

3.2.6	Radiation from a diffuse surface and direction-dependent radiation .....	34
3.2.7	Radiation transfer .....	34
3.2.7.1	Radiation flux .....	34
3.2.7.2	Radiation transfer between two bodies .....	34
3.2.8	Gaseous radiation .....	39
3.3	Heat conduction .....	39
3.3.1	Differential equations of the temperature field .....	39
3.3.2	Steady state, one-dimensional heat conduction .....	40
3.3.2.1	Plane walls with given surface temperatures .....	40
3.3.2.2	Plane walls with convective heat transfer .....	41
3.3.3	Unsteady state heat conduction without heat sources .....	41
3.3.3.1	Bodies with high values of thermal conductivity .....	41
3.4	Convection .....	43
3.4.1	Application of the dimensional analysis for heat transfer .....	44
3.4.2	Cylinders in a flow parallel and perpendicular to their longitudinal axis .....	45
<b>4.</b>	<b>Burner Technology .....</b>	<b>49</b>
4.1	Combustion techniques .....	49
4.1.1	Wood fire .....	50
4.1.2	Ope grate fire .....	50
4.1.3	Simple furnace .....	50
4.1.4	Firing with burners .....	51
4.1.5	Flame formation .....	51
4.1.6	Flame velocity .....	53
4.1.7	Subdivision of flames .....	54
4.2	Classification of burners and flames .....	55
4.2.1	Air supply .....	55
4.2.2	Fuel and fuel preparation .....	55
4.2.3	Way of stabilization .....	55
4.2.4	Flame colour .....	56
4.2.5	Air or fuel staging .....	56
4.2.6	Flame shapes .....	57
4.2.7	Flow velocity .....	57
4.2.8	Direct and indirect heating .....	58
4.2.9	Air preheating .....	58
4.2.10	Stoichiometry .....	59
4.2.11	Turndown .....	60
4.3	Flameless oxidation .....	60
4.3.1	Principle .....	61
4.3.2	Computations and experimental results .....	64
4.3.3	Field measurements .....	66

4.3.4	Applications .....	69
4.3.5	Essential features .....	70
<b>5.</b>	<b>Computer Simulation .....</b>	<b>71</b>
5.1	Assembly of input data .....	71
5.1.1	Computational mesh .....	71
5.1.2	Stationary and non-stationary calculations .....	73
5.1.3	Material properties .....	73
5.1.4	Boundary conditions .....	74
5.1.5	Computing models .....	75
5.2	Solution of equations .....	77
5.3	Presentation of the results .....	78
<b>6.</b>	<b>Reduction of Pollutants .....</b>	<b>81</b>
6.1	NO <sub>x</sub> reduction by flame cooling .....	83
6.2	Lean premixed combustion .....	84
6.3	Flame staging .....	84
6.4	Recirculation of combustion products .....	85
6.5	Oxygen combustion .....	86
6.6	Limits of air-preheating .....	86
6.7	Reduction of fuel NO <sub>x</sub> .....	86
6.8	NO <sub>x</sub> – removal .....	87
6.9	NO <sub>x</sub> Units .....	87
6.10	NO <sub>x</sub> measurements .....	87
<b>7.</b>	<b>Heat Exchangers .....</b>	<b>90</b>
7.1	Basic design .....	91
7.2	Characteristics .....	94
7.3	Determination of the efficiency .....	97
7.3.1	Determination of the idle value .....	97
7.3.2	Measurement of the air preheating temperature .....	101
7.3.3	Measurement of the flue gas temperature .....	101
<b>8.</b>	<b>Industrial Burners .....</b>	<b>103</b>
8.1	Cold air burners .....	103
8.1.1	Premix burners .....	103
8.1.2	Nozzle mix burners .....	103
8.1.3	Fan burners .....	108

8.1.4	Surface burners .....	108
8.1.5	Porous burners .....	109
8.1.6	Flat flame burners .....	110
8.1.7	Burners for low calorific and special fuel gases .....	111
8.1.8	Multi-fuel burners .....	111
8.1.9	Burners for oxygen-enriched air .....	113
8.2	Hot air burners .....	114
8.2.1	Proportionally controlled hot air burners with central recuperator .....	117
8.2.2	Pulse-fired hot air burners with central recuperator .....	118
8.2.3	Hot air burners with central regenerator .....	124
8.2.4	Steady controlled hot air burner with zone recuperator or regenerator .....	124
8.3	Recuperative burners .....	126
8.3.1	Recuperative burners with eductor .....	129
8.3.2	Recuperative burner with flue gas valve .....	132
8.4	Regenerative burners .....	132
8.4.1	Regenerative burners pair .....	133
8.4.2	Regenerative burner .....	136
8.5	Radiant tubes .....	137



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8.5.1	Types of radiant tubes .....	137
8.5.2	Heat recovery with radiant tubes .....	140
8.5.3	Temperature uniformity .....	143
8.5.4	Control of radiant tubes .....	144
8.5.5	Arrangement of radiant tubes .....	145
<b>9.</b>	<b>Standardization for Industrial Burners .....</b>	<b>148</b>
9.1	Introduction and principle .....	148
9.2	Standards organizations and designations of standards .....	148
9.3	Standards and their domain .....	149
9.4	Fundamentals about European standardization work .....	150
9.4.1	New approach .....	150
9.4.2	Connection between directives and standardization .....	151
9.4.3	Application of European harmonized standards .....	152
9.5	Machinery Directive (MD) .....	152
9.5.1	EU declaration of conformity for machinery .....	153
9.5.2	Declaration by the manufacturer .....	154
9.5.3	CE-Marking .....	154
9.5.4	New Machinery Directive dated 26 Feb 2009 .....	155
9.6	Additional EU - Directives .....	157
9.6.1	Pressure Equipment Directive (PED) .....	157
9.6.2	Gas Appliance Directive (GAD) .....	157
9.7	Operation of plants and accident prevention regulations .....	158
9.8	Standardizations structure for the machine directive .....	158
9.9	Important standards for Type A and Type B standards for industrial burners .....	160
9.9.1	Important Type A standards for thermoprocessing equipments and industrial burners .....	160
9.9.1.1	EN ISO 14121-1 .....	160
9.9.1.2	EN 60204 - 1 .....	160
9.9.1.3	EN ISO 12100 - 1 .....	160
9.9.1.4	EN ISO 12100 - 2 .....	161
9.9.2	Important Type A standards for thermoprocessing equipment and industrial burners .....	161
9.9.2.1	EN ISO 13850 .....	161
9.9.2.2	EN ISO 13732 - 1 .....	162
9.9.2.3	EN 953 .....	162
9.9.2.4	EN 61496 - 1 .....	163
9.10	Important Type C standards for industrial burner .....	163
9.10.1	EN 746 - 1 .....	163
9.10.2	EN 746 - 2 .....	164
9.11	Standards for components of industrial burners .....	165

---

9.11.1	EN 161 .....	165
9.11.2	EN 225 - 1 .....	165
9.11.3	EN 225 - 2 .....	165
9.11.4	EN 230 .....	165
9.11.5	EN 264 .....	166
9.11.6	EN 298 .....	166
9.11.7	EN 1643 .....	167
9.11.8	EN 1854 .....	167
9.11.9	EN 12067 - 1 .....	167
9.11.10	EN 12067 - 2 .....	168
9.12	Standard for package burner .....	168
9.12.1	EN 267 .....	168
9.12.2	EN 676 .....	168
9.13	Standards for thermoprocessing equipment .....	169
9.13.1	EN 746 - 3 .....	169
9.13.2	EN 746 - 4 .....	170
9.13.3	EN 746 - 5 .....	170
9.13.4	prEN 746 - 6 .....	171
9.13.5	prEN 746 - 7 .....	172
9.13.6	EN 746 - 8 .....	173
9.13.7	EN 1547 .....	173
9.13.8	EN 1539 .....	174
9.14	Principles for the design of a standard .....	175
9.14.1	How does one read a standard .....	175
9.14.2	Structure of a type C standard according to the machinery directive .....	176
<b>Appendix</b>	.....	178
Heat table	.....	178
Heat processing keywords	.....	193
Further technical information	.....	196
<b>Index</b>	.....	199
<b>Index of Advertisers</b>	.....	203

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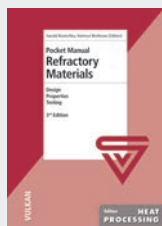
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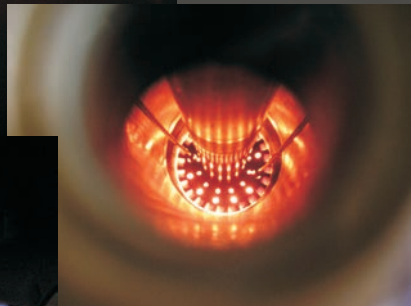
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# 1. Combustion

Günther Woelk

## 1.1 Stoichiometry

### 1.1.1 Reaction elements of technical fuels

Technical fuels usually contain, next to the inert (not participating in reactions) components, only three elements in changing composition which provide energy for a process by reacting with the element oxygen.

- hydrogen (H)  
as pure hydrogen in molecular state or in combination with other reaction elements,
- carbon (C)  
as pure carbon or in combination with hydrogen and/or oxygen
- sulphur (S)  
in combination with other reaction elements.

The reaction partner is oxygen (O) in molecular state as  $O_2$ . Normally, the oxygen is taken out of the air. The composition of dry air is simplified to be:

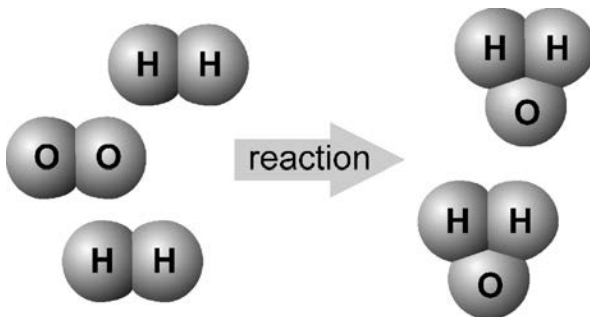
$$0.2099 \text{ mol } O_2 + 0.7901 \text{ mol } N_2 = 1 \text{ mol air} \quad (1.1)$$

The substance amount fraction of oxygen in combustion air  $n(O_2)_a$  (index a for air) is assumed to be 0.2099 – 0.21.

If oxygen-enriched air (a-air) is used, the following correlation is applied for the composition:

$$1 \text{ mol } O_2 + \frac{1 - n(O_2)}{n(O_2)} \text{ mol } N_2 = \frac{1}{n(O_2)} \text{ mol a-air} = 4.76 \text{ mol air} / \text{mol } O_2 \quad (1.2)$$

The most important chemical reactions are shown in **figures 1.1, 1.2 and 1.3** as well as in equation 1.3.



**Fig. 1.1:** Hydrogen – oxygen – reaction

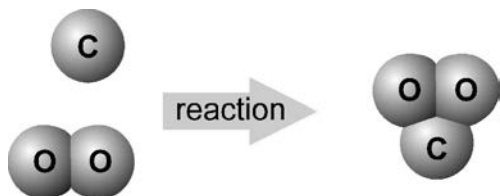


Fig. 1.2: Carbon – oxygen – reaction

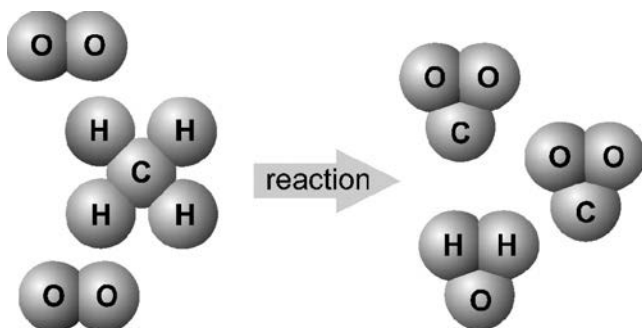
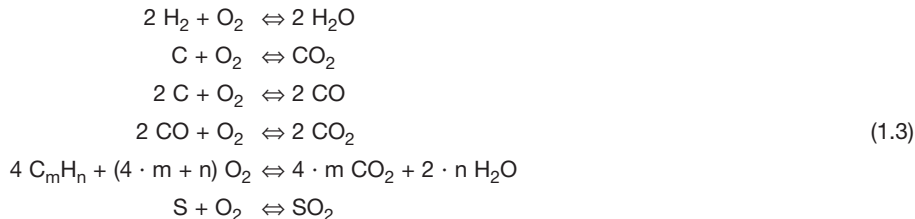


Fig. 1.3: Methane – oxygen – reaction



### 1.1.2 Characteristic values for the composition of gaseous fuels

For calculating the air requirement and exhaust gas amount of reaction of fuel and air, it is of no interest of which chemical compounds the fuel consists. During combustion, most of the compounds will be broken.

It proved to be beneficial to split up the fuels into the elements carbon, hydrogen, nitrogen, oxygen and sulphur as if they would exist in atomic state.

The individual amounts of elements are calculated for gaseous, liquid and solid fuels in different ways.

#### 1.1.2.1 Characteristic amount of atoms for gaseous fuels

Since liquid and solid fuels are rarely used in industrial furnaces, the relevant formulas are left out here. Gaseous fuels are mainly used where supply grids exist.

Gaseous fuels derive from different sources with partly natural and partly technical origin. **Table 1.1** contains a typical breakdown into percentage of substance (volume or molar fraction) of relevant technical fuel gases.

**Table 1.1:** Fuel gas analysis

Con. No.	Component		molar mass in kg/kmol	city gas	coke oven gas	natural gas L	natural gas H	liquid gas
1	Carbon	C	12.01					
2	Methane	CH <sub>4</sub>	16.04	19	25	81.30	93.30	
3	Ethane	C <sub>2</sub> H <sub>6</sub>	30.07			2.85	3.38	
4	Propene	C <sub>3</sub> H <sub>6</sub>	42.08	2	2			
5	Propane	C <sub>3</sub> H <sub>8</sub>	44.10			0.37	0.88	57.2
6	Butane	C <sub>4</sub> H <sub>10</sub>	58.12			0.14	0.36	42.8
7	Pentane	C <sub>5</sub> H <sub>12</sub>	72.15			0.04	0.15	
8	Hexane	C <sub>6</sub> H <sub>14</sub>	86.18			0.05	0.07	
9	Heptane	C <sub>7</sub> H <sub>16</sub>	100.20				0.04	
10	Octane	C <sub>8</sub> H <sub>18</sub>	114.23				0.01	
11	Carbon monoxide	CO	28.01	18	6			
12	Carbon dioxide	CO <sub>2</sub>	44.01	4	2	0.89	1.06	
13	Hydrogen	H <sub>2</sub>	2.02	51	55			
14	Nitrogen	N <sub>2</sub>	28.02	6	10	14.35	0.75	
15	Oxygen	O <sub>2</sub>	32.00			0.01		

The composition of gas fuels is usually presented as a standard analysis:

$$\begin{aligned}
 & x(\text{CH}_4)_f + x(\text{C}_2\text{H}_4)_f + x(\text{C}_2\text{H}_6)_f + x(\text{C}_3\text{H}_6)_f + x(\text{C}_3\text{H}_8)_f + x(\text{C}_4\text{H}_{10})_f + x(\text{C}_5\text{H}_{12})_f \\
 & + x(\text{C}_6\text{H}_{14})_f + x(\text{C}_7\text{H}_{16})_f + x(\text{C}_8\text{H}_{18})_f + x(\text{CO})_f + x(\text{CO}_2)_f + x(\text{H}_2)_f + x(\text{H}_2\text{O})_f \\
 & + x(\text{N}_2)_f + x(\text{O}_2)_f + x(\text{SO}_2)_f = 1
 \end{aligned} \quad (1.4)$$

As an example,  $x(\text{CO})_f$  means the fraction of substance amount of carbon in the fuel (index f for fuel).

The fraction of substance amount  $x(i)$  is the ratio of the amount of the component i and the total amount of substance in a mixture:

$$x(i) = \frac{N(i)}{\sum_j N(j)}$$

The amounts of substance of the elements in the fuel can be combined to amounts of atoms.

The amount of atoms of carbon in the fuel is:

$$\begin{aligned} AAC_f = & x(CH_4)_f + 2 \cdot [x(C_2H_4)_f + x(C_2H_6)_f] + 3 \cdot [x(C_3H_6)_f + x(C_3H_8)_f] \\ & + 4 \cdot x(C_4H_{10})_f + 5 \cdot x(C_5H_{12})_f + 6 \cdot x(C_6H_{14})_f + 7 \cdot x(C_7H_{16})_f + 8 \cdot x(C_8H_{18})_f \\ & + x(CO)_f + x(CO_2)_f \end{aligned} \quad (1.6)$$

The amount of atoms of hydrogen is:

$$\begin{aligned} AAH_f = & 4 \cdot [x(CH_4)_f + x(C_2H_4)_f] + 6 \cdot [x(C_2H_6)_f + x(C_3H_6)_f] \\ & + 8 \cdot x(C_3H_8)_f + 10 \cdot x(C_4H_{10})_f + 12 \cdot x(C_5H_{12})_f + 14 \cdot x(C_6H_{14})_f \\ & + 16 \cdot x(C_7H_{16})_f + 18 \cdot x(C_8H_{18})_f + 2 \cdot [x(H_2)_f + x(H_2O)_f] \end{aligned} \quad (1.7)$$

The amount of atoms of nitrogen is:

$$ASN_b = 2 \cdot x(N_2)_b \quad (1.8)$$

The amount of atoms of oxygen is:

$$AAO_f = x(CO)_f + x(H_2O)_f + 2 \cdot [x(CO_2)_f + x(O_2)_f] \quad (1.9)$$

The amount of atoms of sulphur is:

$$AAS_f = x(SO_2)_f \quad (1.10)$$

Since gaseous fuels usually contain only little amounts of sulphur, the sulphur fraction can be neglected in most cases.

The characteristic amounts of atoms of fuel gases are based on the amount of fuel and, therefore, non-dimensional. It has to be considered that the values, in contrast to the substance amount fraction, can be larger than one. An example for natural gas from table 1.1 is:

$$AAC_f = 0.9006 \quad AAH_f = 3.4784 \quad AAN_f = 0.2870 \quad AAO_f = 0.0180 \quad AAS_f = 0.0000$$

### 1.1.3 Combustion calculation

Technical combustion differentiates between:

- complete combustion

This is a reaction which is completed. For complete combustion, the exhaust can contain unburned components if the combustion was performed under air deficiency. It is not possible that oxygen and unburned components coexist. In this case, it would be an

- incomplete combustion

because the reactions were not finished. The incomplete combustion is usually technically unintentional.

For both cases, the dissociation of combustion products, which occurs at high temperatures, is disregarded.

A further differentiation of technical combustion is the amount of combustion air. It is known how much oxygen is needed so that every fuel molecule can react. When the combustion is carried out with the correlating amount of air, the combustion is called “stoichiometric”. If more air is provided, it is called “overstoichiometric” or “excess air” or “lean” combustion. If less air is provided, the combustion is described as substoichiometric or “air deficiency” or “rich” combustion.

### 1.1.3.1 Calculation of the air requirement

The amount of air  $N(O_2)_{st}$  for a stoichiometric reaction with the amount of fuel  $N_f$  is:

$$N(O_2)_{st} = N_f \left( AAC_f + AAS_f + 0.25 \cdot AAH_f - 0.5 \cdot AAO_f \right) \quad (1.11)$$

The index “st” indicates a stoichiometric reaction. The related amount of dry air for the stoichiometric amount of oxygen is:

$$N_{a,dry,st} = 4.764 \cdot N(O_2)_{st} \quad (1.12)$$

The index “dry” indicates dry air. The stoichiometric air fuel ratio  $l_{dry,st}$  can be calculated by relating the amount of air  $N_{a,dry,st}$  to the amount of fuel.

$$\frac{N_{a,dry,st}}{N_f} = l_{dry,st} = 4.764 \cdot \left( AAC_f + AAS_f + 0.25 \cdot AAH_f - 0.5 \cdot AAO_f \right) \quad (1.13)$$

When burning the fuel with a different amount of air than the stoichiometric amount of air, the ratio is called “air factor –”.

$$\lambda = \frac{l_{dry}}{l_{dry,st}} \Rightarrow l_{dry} = \lambda \cdot l_{dry,st} \quad (1.14)$$

So far, the calculations were performed for dry air. In reality, the combustion air contains a variable amount of water vapour which depends on temperature, pressure and relative humidity.

Relative humidity – of a gas (air in this case) is the ratio of water vapour  $N_w$  to the maximum amount of water vapour  $N_{w,s}$  which a gas can hold at a given temperature and pressure without condensation (saturation point).

According to the ideal gas law, the ratio of amount of substance is equal to the ratio of partial pressures. It is:

$$\varphi = \frac{N_w}{N_{w,s}} = \frac{p_w}{p_{w,s}} \Rightarrow p_w = \varphi \cdot p_{w,s} \quad (1.15)$$

The saturation pressure  $p_{w,s}$  of water vapour in air is predominantly a function of temperature  $p_{w,s}(-)$  as listed in **Table 1.2**. This function can be approximately written as:

$$\frac{p_{w,s}}{\text{mbar}} = 5.87 \cdot \exp \left[ 0.078 \cdot \frac{\vartheta}{^\circ\text{C}} - 0.00039 \cdot \left( \frac{\vartheta}{^\circ\text{C}} \right)^2 \right] - 20^\circ\text{C} \leq \vartheta \leq 40^\circ\text{C} \quad (1.16)$$