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TRNSYS-TYPE 370

Add-on to the hitherto existing gas fuelled
boiler-model for a wood-fired boiler with
calorific value usage

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Ergänzung um einen Simulationsmodus zur realitätsnahen
Simulation des Betriebsverhaltens von Gaskesseln mit
Takten

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1. Introduction

Regarding the greenhouse effect and the goal of reducing CO₂-emissions, there are efforts using biomass (i.e. waste wood, wood chips) as a source of energy. As a result of cheap available conventional energy sources, biological energy sources are used rather seldom. Anyhow, biomass can compete with other regenerative energy sources in terms of cost.

The energy potential from wood and straw residual substances related to the final energy consumption lies in Germany with approximately 3,8 %.

Here, the first power plant running with biomass are introduced gradually, mostly as demonstration-facilities. Other European countries are ahead of this stadium.

In Austria and Südtirol, 200 biomass-fuelled power plant with local heat supply plants and an overall performance of more than 320MW were running by the end of the millenium. Most of these plants have a rated output of 0.5 to 5 MW.

The general greywater production during summer consumes only a fraction of the heat necessary in winter. A biomass-fuelled boiler can be operated up to 20-25% of its rated output if one keeps in mind the efficiency and emission value. Therefore, most facilities are used only during spring, autumn and winter.

In combination with a central thermal solar plant, which takes over the water heating in summer is preferable if there is a decent net structure with short distances and a low temperature level.

From these circumstances, the thought occurred of modelling different facility-configurations with the TNSYS-Type and simulate specific according to location and wishes of the applicant. Next to the modelling of a local heat supply net (regarding medium-temperature and, soil-temperature) a Type for simulating a wood-fired boiler was missing.

A correlative facility is sketched in fig.2

The model of the wood-fired boiler is based upon the preceeding TRNSYS-Type 370 which contains the model of a gas-fired boiler. The clocking works with the same principles as in the gas-fuelled boiler

2. Theory

Different to gas or oil, as they are standardised fuels, wood is subject to greater variations due to fluctuation in density, composition and volumetric calorific value.

The wood's specifications depend on

- The type of wood (fraction of bark, coniferous wood, hardwood,...)
- The wood's humidity¹ u [%] .

The calorific value of absolutely dry wood fluctuates less between the different types of wood. Therefore it has a constant average value of

$$h_{u,atr} = 18.5 \text{ MJ/kg} = 5.15 \text{ kWh/kg} .$$

Now, the calorific value is only partly dependent on the wood's humidity and can be calculated as following [1]:

$$h_u = \frac{18500 - 2501 \frac{u}{100}}{1 + \frac{u}{100}} \quad [\text{kJ/kg}] \quad (1)$$

The factor 2501 kJ/kg describes the enthalpy of evaporation of water at standard temperature ($\vartheta = 0.01 \text{ }^\circ\text{C}$). The humidity ratio can be obtained from chart 1 in dependence of the attributes water-free, dry, air-dry, forest-dry and harvest-fresh. With chart 2 one can convert the wood's water content w into the humidity u .

A further problem is the not chronologically constant fuel composition in the batch process. As in fig.3 described, the wood composition stays constant most of the time during burning down. In the last state, wood turns to charcoal and finally into ash.. Regarding automated fuelling, one can assume the fuel composition as constant.

It obeys the chemical formula CH_mO_n :

With $m = 1.44$ and $n = 0.66$. This equals 50 weight-% carbon, 6 weight-% hydrogen and 44 weight-% oxygen.

By formulating the chemical equations for oxidising wood under these circumstances, one can calculate the fuel-constant:

$$A = 1 + \frac{m}{4} + \frac{n}{2} = 1.03 \quad (2)$$

The fuel-constant describes the oxygen-usage for total combustion of 1 mol fuel. The excess of air

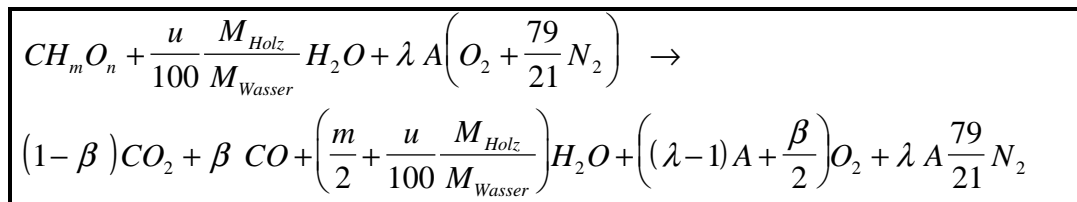
$$\lambda = \frac{\text{actual_amount_of_air}}{\text{stoichiometri_required : amount_of_air}}$$

and the coefficient

¹One distinguishes between wood humidity¹ u and the **watercontent** w . The watercontent is defined by the rate of kg water to kg clammy wood. The humidity is the rate of kg water to kg dry wood. [%]

$$\beta = \frac{[CO]}{[CO] + [CO_2]}$$

result in the chemical reaction formula (3) for the combustion of wood [3]. One can extract from this formula the stoichiometric coefficients for the exhaust. The coefficient β , which is to be entered by the user, states the carbonmonoxide content of the dry exhaust related to the C-content of the fuel.. It describes the performance of the fuel. If there is no CO, the oxidation is complete, the combustion ideal.



(3)

The following presumptions were made for the reaction equation and the calculation of the efficiency:

- All hydrocarbons (Dioxine, Furane, ...) in the soot and exhaust are neglected. The incomplete combustion is incorporated by the formation of CO.
- Further obnoxious substances like nitrogen oxide und sulphur dioxide are neglected.
- All exhaust gases behave like ideal gases, which means that the pressure is assumed to be constant.
- The air for the combustion contains of 21 vol-% oxigen and 79 vol-% nitrogen. The humidity is assumed 0 %.

2.1 Efficiency

The firing efficiency can be calculated with the thermal and chemical loss. Important parameters are:

- The exhaust temperature
- The excess of air λ
- The amount of CO in the exhaust

The boiler's efficiency also contains radiation losses during firing and rust losses. radiation-, rust- and losses during readiness for service are manufacturer data. This data is made available for the Type in the input-list.

Thermal losses:

The exhausts enthalpy-difference describes the thermal losses of the boiler, resulting in the cooling of the exhaust, assuming that all components are gases in the temperature-range and that there is no condensation. Only the sensitive heat i of the following components is regarded:

- Carbon dioxide
- Carbon monoxide
- Oxygen
- Steam
- Nitrogen.

Under these premises, the equation describing the thermal losses is derived [3].

$$V_{therm} = 100 \frac{\int_{T_{amb}}^{T_{abg}} \sum_i v_i C p_i(T) dT}{M_{Br} h_u} \quad [\%] \quad (4)$$

The stoichiometric coefficients v_i of the exhaust for all i 's can be obtained from equation (3). Since all terms but the specific heat capacity are independent from the temperature, one can write them in front of the integral. The integral itself is approximated with a polynomial approach (T in K) [7].

$$\Delta h_i = \int C p_i(T) dT = a_i (T_{abg} - T_{amb}) + \frac{b_i}{2} (T_{abg}^2 - T_{amb}^2) + \frac{c_i}{3} (T_{abg}^3 - T_{amb}^3) \quad [\text{kJ/kmol}]$$

Another term in equation (4) is the molar mass of the fuel [3]

$$M_{Br} = M_{Holz} \left(1 + \frac{u}{100} \right) \quad [\text{kg/kmol}]$$

where $M_{Holz} = 24 \text{ kg/kmol}$ means the molar mass of absolutely dry wood, composed as mentioned before.

Chemical losses:

The chemical losses describe the losses due to incomplete combustion. The not entirely burned exhaust-components, hydrocarbons, carbonmonoxide and –dioxide, make no contribution to the reaction enthalpy. Only the carbonmonoxide is regarded.

Regarding a volumetric calorific value $h_{u,CO} = 11567 \text{ kJ/m}^3$ (preassure of 1.013 bar and temperature of 25 °C), the chemical losses can be calculated as follows [3]:

$$V_{chem} = 100 \frac{[CO]V_{Atr}h_{u,CO}}{h_u} \quad [\%] \quad (5)$$

The dry exhaust volume $V_{Atr} [\text{m}^3_{\text{Abgas}}/\text{kg}_{\text{Brennstoff}}]$ is calculated via the molar quantity of dry exhaust (3) and the molar mass of the clammy wood. The volumetric share of carbonmonoxide in the dry exhaust is obtained with β .

Rust losses can be considered via the chemical losses.

Radiaton losses:

Radiation losses are calculated regarding the average heating temperature, the ambient temperature and the Anlagenbelegung. The manufacturer data regarding maximum average heating temperature and radiation loss coefficient are required. For determining the efficiency of the boiler, the radation losses are based on the calorific value. Radiation losses only occur when the burner is running. The losses during readiness are calculated equally.

Exhaust condensation:

Facilities with exhaust condensation are called condensing boilers. With cooling down the exhaust underneath the dew point temperature, a fraction of the energy lost by vaporising the wood's water can be reclaimed. This is also valid for the water occurring during the reaction.

Instead of the standard calorific value, the by the vaporisation heat of the condensed water increased calorific value can be used.

Assumptions for exhaust condensation are:

- Exhaust condensatiopn is only profitable in facilities with a firing power bigger than 500 kW. The reason lies in the burn regulation, which has to provide for a certain excess air. In addition the exhaust condensation requires for materials corrosion resistant and therefore more expensive materials in the exhaust heat exchanger and fire-place.
- The excess air should be $\lambda < 1.8$.
- The return temperature must be at least 10 °C underneath the dew point of the exhaust.
- The water content w should not be smaller than 30 % and the wood's humidity u not smaller 43 %.

The condensate can be fed into the sewers without further treatment if the combustion is high quality ($[\text{CO}] < 250 \text{ mg/Nm}^3$, 11 Vol-% O_2).

The latent heat is calculated as follows:

The saturation heat and vaporisation pressure are calculated with polynomials depending on the exhaust temperature [6], the dew point temperature is calculated depending on the steam volumetric concentration in the exhaust [5].

Is the actual steam's partial pressure bigger than the saturation pressure, water will condense until the partial pressure equals the saturation pressure. The condensed molar quantity of water per mol of dry wood is calculated according equation (6), solving for n_{kond} .

$$x_{W_sat} = \frac{P_{W_sat}}{P_{amb}} = \frac{V_W - n_{kond}}{n_{abg} - n_{kond}} \quad (6)$$

This value is used to determine the condensed mass of water based on 1kg of fuel with the help of the molar mass of water and fuel. The heat gain through exhaust condensation is:

$$V_{kond} = 100 \cdot \frac{r(\vartheta_{RL}) m_{kond}}{h_u} \quad [\%] \quad (7)$$

The condensation enthalpy is based on the return temperature, since condensate occurs at this temperature.

SO the efficiencies are:

1. Firing efficiency: [2]

$$\boxed{\eta_F = 100 - V_{therm} - V_{chem} + V_{kond}} \quad [\%]$$

2. Boiler efficiency [2]

$$\eta_K = \eta_F - V_{rad} \quad [\%]$$

With the introduced terms and equations, all other variables like heating power, mass flow, amount of condensate... can be calculated.

3. Type - description

The figure below shows a schematic description of all parameters, inputs and outputs of the TRNSYS-Type 370. In addition to the 29 outputs, 13 parameters and 9 inputs are queried. For details look into the list below.

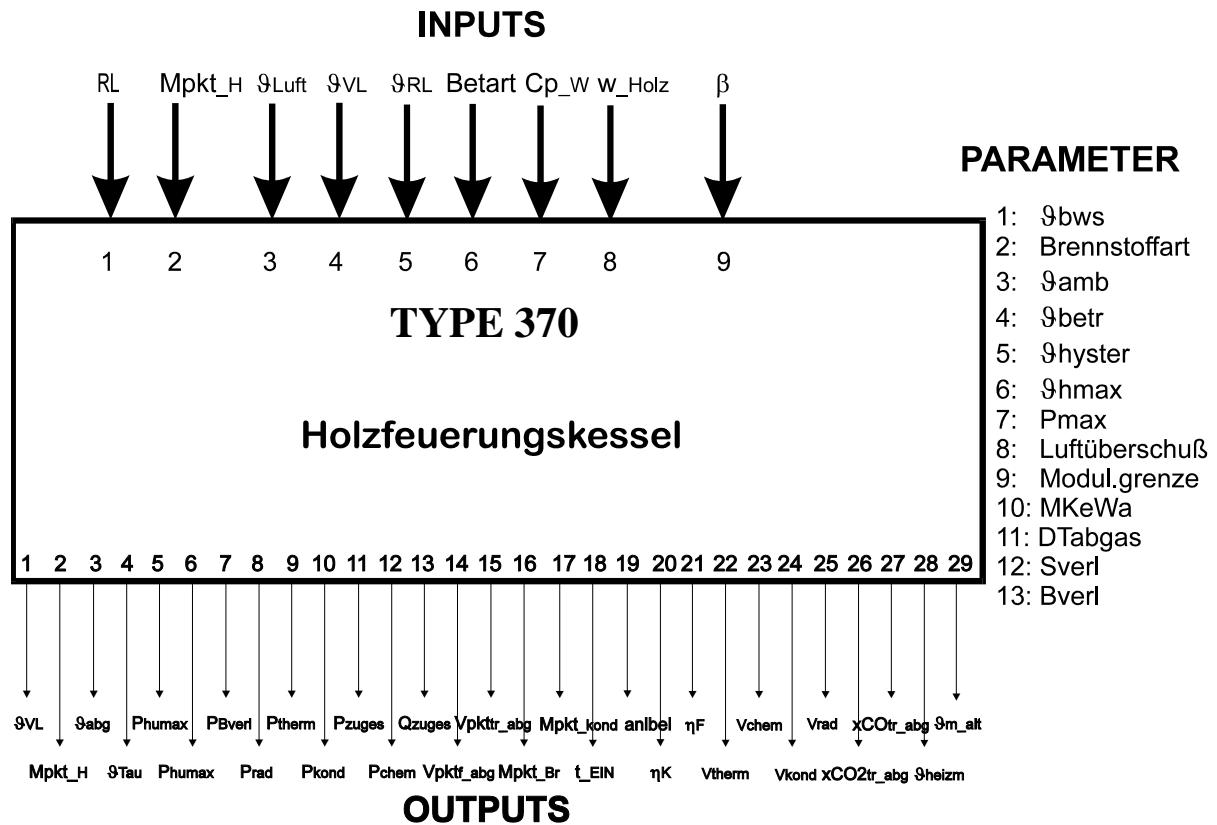


Abb.1: Schematic display of inputs, outputs and parameters

Description of PARAMETERS, INPUTS and OUTPUTS

PARAMETER 13

- 1 ϑ_{bws} (TSET) - supply temperature ϑ_{bws} for domestic hot water heat exchanger. °C
This parameter has an impact if INPUT(6) = 0.
- 2 BRSTO - kind of combustible -
1 = natural gas L,
2 = natural gas H,
3 = liquid gas,
4 = wood
- 3 ϑ_{amb} (TRAUM) - room temperature near the boiler °C
- 4 ϑ_{betr} (TBETRB) – stand by temperature of the boiler °C
During the stand by mode of the burner the temperature of the boiler is set to ϑ_{betr} if the boiler temperature falls below the lower temperature of the hysteresis given by PAR(5).
- 5 ϑ_{hyster} (HYSTER) – Hysteresis for PAR(4) °C
- 6 ϑ_{hmax} (THMAX) – Maximum mean boiler water temperature °C
Based on this temperature the maximum longwave radiation as well as stand by losses are calculated.
- 7 P_{max} (PMAX) – maximum heating power of the boiler kJ/h
- 8 λ (LAMBDA) – excess air coefficient -
gas boiler : approx. 1.1 - 1.3
wood fired boiler: approx. 1.5 - 2.5 (Table 3)
- 9 MODGR - lower boundary of modulation (part load operation) %
- 10 MKeWa – Mass of the boiler water content kg
remark: By adapting the PAR(10) the thermal mass of the boiler itself can be considered
- 11 DTabgas – temperature difference between flue gas and return temperature within the heat exchanger. °C
- 12 Sverl – longwave radiation losses (manufacturer data) %
The coefficient determines the maximum radiation losses at the rate of the maximum heating power of the boiler PAR(7).
- 13 Bverl – standby losses (manufacturer data) %
The coefficient determines the standby losses at the rate of the maximum heating power of the boiler PAR(7).

INPUTS 9

- 1 **RL** - return temperature °C
- 2 **Mpkt_H** – mass flow rate of the heat transfer fluid kg/h
- 3 **ϑ_{Luft}** – temperature of the inlet fresh air applied to the combustion process °C
- 4 **ϑ_{VL}** – set point for inlet temperature of the Controller °C
- 5 **ϑ_{RL}** - set point for return temperature of the Controller °C
- 6 **BtrArt** – mode of operation -
0 = domestic hot water,
1 = heating and domestic hot water
- 7 **Cp_w** – specific heat capacity of the heat transfer fluid (generally water) kJ/kg/K
Cp < 0.0 => specific heat capacity is set internally
Cp > 0.0 => specific heat capacity provided externally

Attention: If during simulation the heating mediums heat capacity is used in another type, CP_w should have the same value!

The following INPUTS (8,9) are only necessary for the wood fired boiler mode

- 8 **w_Holz** – water content of the fired wood %
With the water content given in PAR(8) the moisture of the wood is
calculated internally. is
- 9 **β** - CO-content of the flue gas based on the total C-content of the wood %
The coefficient determines the rate of the incomplete combustion
that means $\beta = 0$ => complet Oxidation of carbon to CO₂
 $\beta = 1$ => total Carbon oxidizes to CO only

OUTPUTS 29

1	ϑ_{VL}	boiler inlet temperature	°C	
2	M_{pkt_H}	mass flow of the heat transfer fluid	kg/h	
3	ϑ_{abg}	flue gas temperature at the inlet of the heat exchanger	°C	
4	ϑ_{Tau}	Dew point temperature at beginning of condensation	°C	
5	P_{hmax}	total supplied heat by combustible (according to H_o)	kJ/h	
6	P_{hmax}	total supplied heat by combustible (according to H_u)	kJ/h	
7	P_{Bverl}	standby loss	kJ/h	
8	P_{rad}	long wave radiation losses during operation of boiler	kJ/h	
9	P_{therm}	heat losses by flue gases	kJ/h	
10	P_{kond}	heat flux due to condensation	kJ/h	
11	P_{zuges}	supplied heat considering the boiler efficiency	kJ/h	
12	P_{chem}	losses caused by incomplete combustion / oxidation	kJ/h	*
13	Q_{zuges}	heat flux exchanged with the heating loop	kJ	
14	V_{pktf_abg}	volume rate of the wet flue gases	m ³ /h	
15	V_{pktr_abg}	volume rate of the dry flue gases	m ³ /h	
16	$Verbr$	consumption of combustible - natural gas	m ³ /h	
16	M_{pkt_Br}	consumption of combustible – wood	kg/h	
17	M_{pkt_kond}	mass flow rate of the condensate	kg/h	
18	t_{Ein}	on-time during one cycle time	h/h	
19	$anlbel$	working load	%	
20	η_K	boiler efficiency rated to H_u	%	
21	η_F	boiler efficiency rated to H_u	%	
22	V_{therm}	thermal losses of flue gases rated to H_u	%	*
23	V_{chem}	chemical losses due to incomplete combustion rated to H_u	%	*
24	V_{kond}	heat gains caused by flue gas condensation rated to H_u	%	*
25	V_{rad}	long wave radiation losses rated to H_u	%	
26	x_{CO2tr_abg}	volume rated concentration of CO ₂ in dry flue gas	%	
27	x_{COtr_abg}	volume rated concentration of CO in dry flue gas	%	
28	ϑ_{Heizm}	mean heat transfer fluid temperature in boiler at actual time	°C	
29	ϑ_{m_alt}	mean heat transfer fluid temperature in boiler at time before actual	°C	

The outputs marked with ‘ * ‘ are available for wood fired mode only.

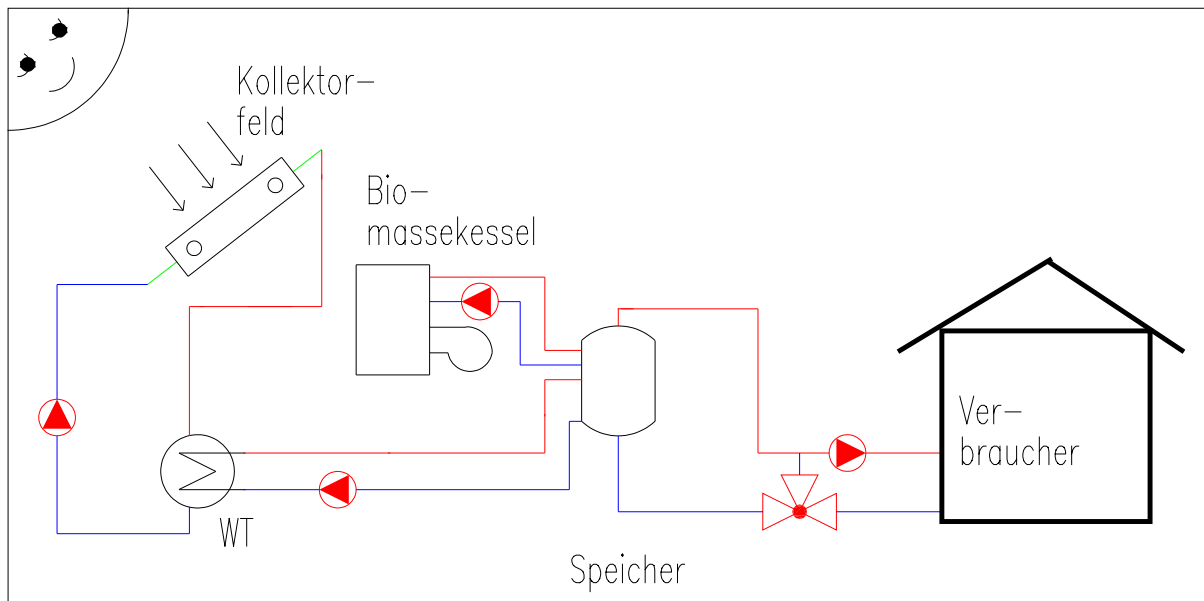


Abb.2: Solar heating net with biomass boiler for heating period

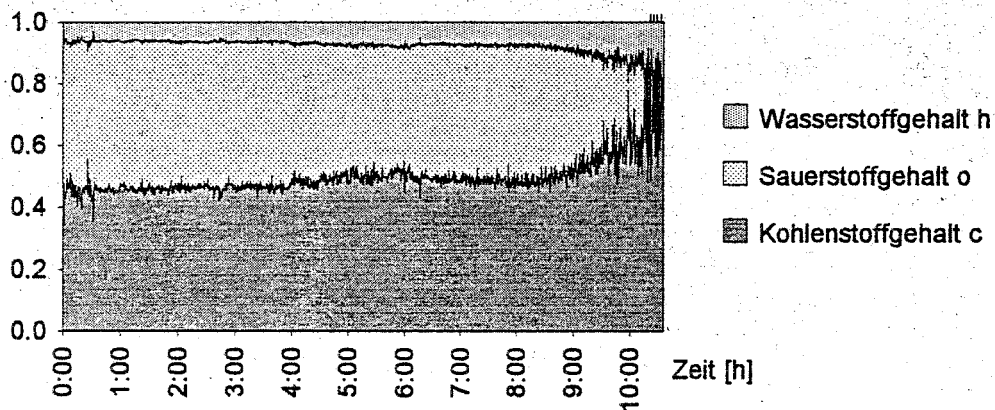


Abb. 3: Course of the fuel composition during a typical burn-up of wood [4].

	Waterfree	Dry	Air-dry	Forrest-dry	fresh
watercontent w of the wood [%]	0	10	17	30	50

Chart 1: Typical values of the watercontent in wood.

unknown known	u [%]	w [%]
u [%]	-	$w = \frac{u}{100 + u} 100$
w [%]	$u = \frac{w}{100 - w} 100$	-

Chart 2: Chart for transforming w into u.

			TA Luft (ab 1 MW)
Excess air	Goal typical	1.5 - 1.8 1.5 - 2.5	
Exhaust temperature	Goal typical	< 160 °C 120 - 250 °C	
Firing efficiency	Goal typical	92 % 80 - 90 %	
CO < 1 MW < 5 MW	typical typical	< 1000 mg/Nm ³ < 250 mg/Nm ³	250 mg/Nm ³
NO _x wood chips Leftover wood	typical typical	< 300mg/Nm ³ < 600mg/Nm ³	500mg/Nm ³
Dust	typical	< 150mg/Nm ³	150mg/Nm ³

Chart 3: Typical emission and operating values of automated wood-fired cyclones without exhaust-condensation.

Symbols:

Latin symbols

A	-	Fuel constant
C _p	kJ/kmol/K	Specific heat capacity
[CO]	-	Volumetric concentration in dry exhaust
h _u	kJ/kg	Calorific value
m _{kond}	kg/kmol	Mass of condensed water
M _{Br}	kg/kmol	Molar mass of clammy wood
M _{Holz}	kg/kmol	Molar mass of dry wood
n	kmol	Molar mass
p	N/m ²	Pressure
r	kJ/kg	Vaporisation enthalpy of water
T _{abg}	°C	Exhaust temperature
T _{amb}	°C	Ambient temperature
u	%	Wood humidity
V	%	Losses
w	%	Watercontent

Greek symbols

β	-	Grade of incomplete combustion
η	%	Efficiency
λ	-	Excess air
ν	-	stoichiometric coefficient
ϑ _{RL}	°C	Return temperature

Indices

abg	-	Exhaust
amb	-	Ambience
Atr	-	Dry exhaust
Br	-	Fuel, clammy wood
chem	-	chemical
F	-	Firing efficiency
Holz	-	Absolutely dry wood
K	-	Boiler efficiency
kond	-	Exhaust concentration, condensate
rad	-	radiativ
RL	-	Return
sat	-	Saturation
therm	-	Thermal
VL	-	Inlet
W	-	Water

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