SINTEF

Wood stove data treatment

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Introduction

Fuelsim - Transient is a relatively simple, but useful, mass, volume and energy balance spreadsheet for batch combustion applications, but can also be used for other thermal conversion processes where solid fuel is converted to a fuel gas mixture of O_2, CO, NO, NO_2, UHC (unburned hydrocarbons), SO_2, N_2O, H_2, NH_3, HCN, Tar, CO_2, N_2, Ar and H_2O.

The fuel is supposed to be a solid fuel, while the oxidant can either be ISO 2533 Standard air, with a user defined relative humidity, or any gas mixture of O_2, N_2, CO_2, Ar and H_2O.

Preheating, relative to an ambient temperature, of solid fuel (including moisture content) and oxidant (separated into primary and secondary air) is possible. The temperature of the products is calculated assuming adiabatic conditions (no heat loss), and also by specifying a heat flux factor to the surroundings.

With optional preheating

Solid fuel:
C,H,N,S,O,H_2O(l)

+

With optional preheating

Oxidant:
ISO 2533 Standard Air, with a user defined relative humidity, or any gas mixture of O_2, N_2, CO_2, Ar and H_2O

=

Adiabatic temperature

Products:
Combustion, gasification or pyrolysis gas products: O_2, CO, NO, NO_2, UHC, SO_2, N_2O, H_2, NH_3, HCN, Tar, CO_2, N_2, Ar and H_2O

Conservation of mass and energy

Fuelsim - Transient uses thermodynamic data on CHEMKIN format for all gas species and also liquid water, while the specific heat capacity of a solid is user defined. The heating value of unburnt gases (heat loss) is calculated directly from the thermodynamic data, while the heating value for the solid fuel composition is estimated from the elemental composition using an empirical expression.

Transient models for drying and elemental fuel compositions are necessary and are included. These models can be changed by the user if wanted.

Thermal efficiency (using a user defined transient chimney inlet temperature), combustion efficiency and total efficiency are calculated, together with further useful mass, volume and energy balance output.

Main input:

- Transient wood weight
- Transient fuel composition, including moisture
- Oxidant composition
- Ambient temperature
- Transient preheating temperatures
- Transient chimney inlet temperature
- Transient product gas composition (N_2, CO_2, Ar, H_2O and SO_2 are calculated from the combustion equation)

Output examples:

- Mass and volume flows
- Excess air ratio
- Adiabatic combustion temperature
- Heating values
- Efficiencies
- Heat output
- Emissions in various denominations

Conservation of mass and energy

Fuelsim - Transient calculates transient emission levels in g/kg dry fuel and weighted average emissions in selected other denominations. However, coupled to Fuelsim - Average, weighted average emissions in various denominations can be calculated based on the results from Fuelsim - Transient. Also, additional useful information is then calculated. The necessary input to Fuelsim - Average is transferred from Fuelsim - Transient by a single push on a push-button.

The emission conversion procedure is based directly on the combustion equation, no simplified expressions are applied. When converting emission levels between different oxygen concentrations, the defined oxidant is added to, or removed from, the given flue gas composition until the calculated oxygen concentration equals the reference oxygen concentration.

Emissions

NO_X as NO_2 eqv.	mg/kg fuel	UHV	1.129E+02	
N_2O	mg/MJ	EHV	5.891E+00	
NH_3	mg/kWh	Gross	1.520E+00	
HCN	mg/kWhe	Net	1.206E+00	
CO	g/h		1.250E+03	
UHC as C_xH_y / CH_4	ton/year	Dry fuel/FG	5.902E+02	6.442E+02
SO_2	mg/Nm3 FG	Wet fuel/FG	2.987E+02	
Tar as $C_{xt}H_{yt}$ / CH_4			6.970E+02	8.589E+02
Particles	mg/kg dry fuel	5000	7.474E+02	

Fuelsim - Transient is an Excel spreadsheet and uses programmed functions and procedures in addition to formulas inserted directly in the spreadsheet cells. The user interface consists of input cells (marked with the colour white) various push-buttons (marked with the colour grey), input forms (revealed when pushing a push-button), option-buttons (black: option is selected, white: option is not selected) and pull-down menus. Cells marked with the colour green are not user changeable.

Input cells:

Initial weight of wet fuel [kg]	3	Time int.(s)
Initial water content [mass frac., wet basis]	0.18	120

Pull-down menu:

1 - Spruce / Pine

Push-button:

or Treat experiment

Option-button:

Weight curve

Model

Experiment

Input box (Fuelsim - Average):

Volume fraction		Weight fraction
0.3	C	0.447109662163949
0.45	H	5.62818455565949E-02
0.0004	N	6.95190819089684E-04
0.0002	S	7.9571199580528E-04
0.2494	O	0.495117589464561

O is calculated by difference

Go to worksheet "Gas conversion" to convert a gas composition to an elemental composition for input to Fuelsim - Average!

Calculate | Insert | Close

Theory

The global combustion equation used in Fuelsim - Transient (F-T) is shown in Equation 1. By balancing this equation mass and volume flow calculations can be carried out. By also introducing thermodynamic data for the reactants and products, energy calculations can be carried out in addition. Additionally, the solid fuel may contain water in F-T. Further formulas are given in Appendix 1.

$$a \cdot \left(Y_C + Y_H + Y_O + Y_N + Y_S\right)_{Fuel} + \frac{z}{Y_{O_2}} \cdot \left(Y_{O_2} + Y_{N_2} + Y_{Ar} + Y_{CO_2} + Y_{H_2O}\right)_{Air}$$

$$\Rightarrow \quad b_{CO_2} + c_{H_2O} + d_{O_2} + e_{N_2} + f_{CO} + g_{NO} + h_{NO_2} + i_{C_xH_y}$$

$$+ j_{SO_2} + k_{N_2O} + l_{H_2} + m_{NH_3} + n_{HCN} + o_{C_{xt}H_{yt}} + p_{Ar} + q_{CO_{2,Air}} + r_{H_2O_{Air}}$$

Equation 1

Theory

H_2O mass fraction in wet fuel:

$$X_{H_2O,w} = \frac{\overline{X_{H_2O,w}}}{\overline{X_{H_2O,w,\mathrm{Ref}}}} \cdot \left(\widehat{a1} + \widehat{a2} \cdot PWC + \widehat{a3} \cdot PWC^2 + \widehat{a4} \cdot PWC^3\right)$$

The coefficients a1-a4 are explained in the spreadsheet documentation

$$\text{Constraint: } \int_{PWC=0}^{PWC=100} X_{H_2O,w} = \overline{X_{H_2O,w}}$$

Theory

Mass fraction of carbon in dry ash free fuel:

$$X_C = \frac{\overline{X_C} \cdot \left[b_1 \cdot \left(PDC_i - PDC_{i-1} \right) + \frac{b_2}{2} \cdot \left(PDC_i^2 - PDC_{i-1}^2 \right) + \frac{b_3}{3} \cdot \left(PDC_i^3 - PDC_{i-1}^3 \right) + \frac{b_4}{4} \cdot \left(PDC_i^4 - PDC_{i-1}^4 \right) \right]}{PDC_i - PDC_{i-1}}$$

The coefficients b1-b4 are explained in the spreadsheet documentation

Constraint: $\int_{PDC=0}^{PDC=100} X_C = \overline{X_C}$

Theory

Mass fraction of hydrogen in dry ash free fuel:

$$X_H = \frac{\overline{X_H} \cdot \left[c_1 \cdot \left(PDC_i - PDC_{i-1}\right) + \frac{c_2}{2} \cdot \left(PDC_i^{\,2} - PDC_{i-1}^{\,2}\right) + \frac{c_3}{3} \cdot \left(PDC_i^{\,3} - PDC_{i-1}^{\,3}\right) \right]}{PDC_i - PDC_{i-1}}$$

The coefficients c1-c3 are explained in the spreadsheet documentation

$$\text{Constraint: } \int_{PDC=0}^{PDC=100} X_H = \overline{X_H}$$

Theory

Mass fraction of nitrogen in dry ash free fuel:

$$X_N = \frac{\overline{X_N}}{\overline{X_C}} \cdot X_C$$

Mass fraction of sulphur in dry ash free fuel (used only as an example):

$$X_S = \frac{\overline{X_S}}{\overline{X_H}} \cdot X_H$$

Mass fraction of oxygen in dry ash free fuel:

$$X_O = 1 - X_C - X_H - X_N - X_S$$

Theory

See formulas in the pre-prepared spreadsheet

See Extract from Transient-report.pdf

Procedure for treatment of experimental results

- Copy experimental results to the predefined input columns/cells in the sheet “Transient”. Alternatively, these columns/cells may be linked to a separate sheet containing the experimental results
  - Copy Weight of wet fuel (kg) to column J. Make sure that the last value in the column is zero!
  - Copy vol% O2 in dry flue gas (FG) to column K
  - Copy Temperature at chimney inlet (°C) to column U
  - Insert an arithmetic mean ambient temperature (°C) in cell D24 in the sheet “Average”
  - Insert an inlet fuel (and moisture) temperature (°C) in cell D28 in the sheet “Average”. The specific heat capacity of the solid fuel can be changed in cell D29
  - Insert a relative air humidity (%) in cell D32 in the sheet “Average” if Standard ISO air (around cell B33) has been chosen as oxidant. Alternatively you can mix your own oxidant with a user defined moisture content by changing the Defaults
  - Check that the fuel type (around cell C49) has been set to solid fuel in the sheet “Average”, and also set the ash content to zero in cell D60
  - Check the Defaults located in the sheet “Average” and change these if required
- These are the only “transient” experimental input needed to perform mass, volume and and heat balances. However several other transient inputs may be inserted if available:
  - Emissions of unburnt: CO, CxHy (hydrocarbons), CxtHyt (tar) in column L, M and N

- Devolatilisation/gasification products: H2, NH3, HCN in column O, S and T
- NOx (NO and NO2) and N2O in column P, Q and R
- Primary and secondary air temperature (°C), and weight fraction primary air of total air in column V, W and X

- Set the input for the concentration of species not measured to zero, alternatively you can estimate an emission level. There is no need to copy these columns downward to the same length as the other transient input if the emission level is zero.
- If primary and secondary air temperature have not been measured, these temperatures should be set equal to ambient temperature (insert "=TAmb" in the cells). If these columns are not copied downward to the same length as the other transient input, this will be done automatically later. Note that preheating means external preheating (increased adiabatic combustion temperature) if not stated otherwise under Defaults in the sheet "Average". If internal preheating is chosen, the calculated temperatures will be independent of the air "preheating" temperatures
- Choose the fuel in the pull-down menu in cell A3. The average fuel composition and the necessary transient models for fuel composition and drying are predefined. However, the transient models can be changed in the sheet "Models"
- Insert the initial weight of wet fuel in cell B6. This value should be larger than the first transient value in cell J3, which should be the value after one timestep

- Insert the initial moisture fraction on wet basis in cell B7
- Insert the timestep between each set of experimental values in seconds in cell C7
- Click on the “Experiment”option button for the weight curve located around cell B34
- Click on one of the option buttons in “Smooth weight?” located around cell B34. Notice the change in the “dry weight burnt in interval” curve in the figure to the right
- Other experimental results which are not needed for the calculations can be copied to the sheet “Exp-data”. Charts including these curves have been prepared in the sheet “Charts”
- You are now ready to treat the experiment by clicking on “Treat experiment” in the sheet “Transient”. Click on “Copy to Average” when finished.
- If you have measured an average particle emission level, insert this (mg/kg dry fuel) in cell H64 in the sheet “Average”
- Emission conversion to various denomination can now be performed in the sheet “Average”, see Documentation for details
- View the transient results in the sheet “Charts” and choose the wanted x- and y-axis denominations
- Print all charts by pushing the print button in Excel, or copy selected charts to for example PowerPoint or Word

Demonstration

of one experiment

You can try the other one afterwards

Tasks to be carried out

- Convert the raw data into useful and quality controlled results using pre-prepared Excel worksheet (explanation/theory and demonstration on Thursday)
- Extract the following key data for each fuel
  - Average and transient burning rate
  - Weighted and transient thermal efficiency
  - Weighted and transient combustion efficiency
  - Weighted and transient total efficiency
  - Average particle emission level in g/kg dry fuel (calculate)
  - Transient temperatures and draft
- Compare the above data for the two fuels
- Suggest explanations for differences in the results
- Discuss within your group: How would you design an experimental setup revealing transient "input data"?