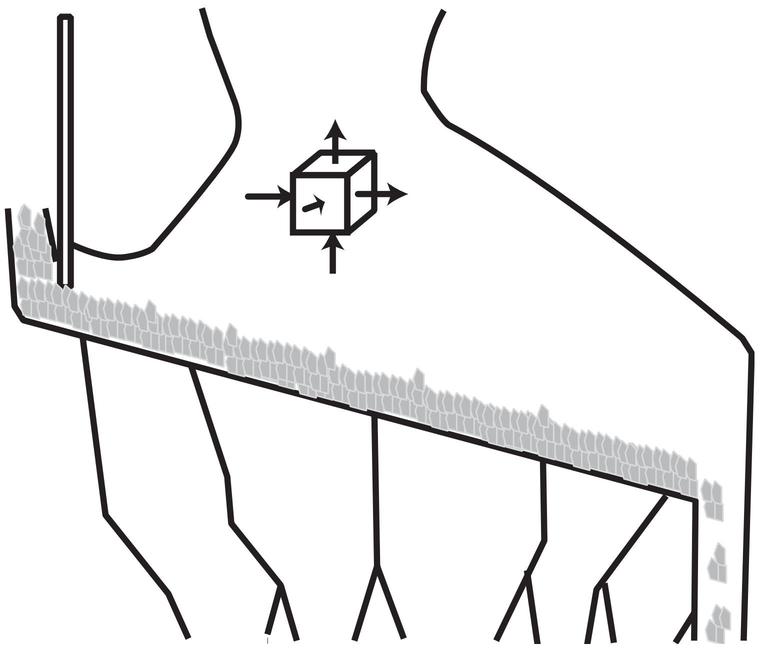
Modelling: Momentum, Heat and Mass Balances



Described by equations for conservation of:

ï Mass

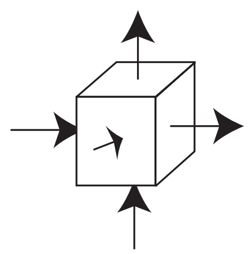
ï Momentum

ï Energy

ï Species

Continuity equation

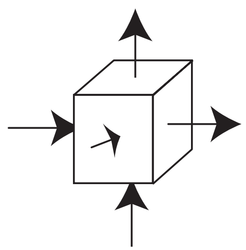
(Conservation of mass)



$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} = 0$$

Mass change in a volume depends on the flow in and out of the volume

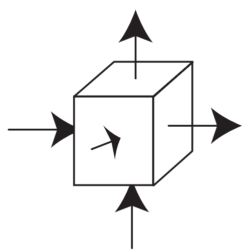
Momentum Equation



$$\rho\frac{\partial u}{\partial t}+\rho u\frac{\partial u}{\partial x}=\frac{\partial u}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)-\frac{\partial p}{\partial x}+\rho g$$

Momentum the forces of movement

Energy Equation

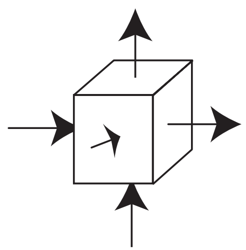


$$\rho \frac{\partial c_p T}{\partial t} + \rho u \frac{\partial c_p T}{\partial x} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \dot{m}''' \Delta H + q_{rad}$$

or

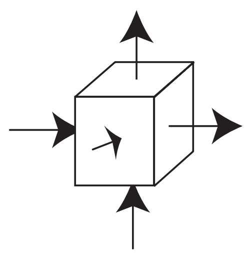
$$\rho \frac{\partial i}{\partial t} + \rho u \frac{\partial i}{\partial x} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + q_{rad}$$

Species Equation



$$\rho \frac{\partial Y_i}{\partial t} + \rho u \frac{\partial Y_i}{\partial x} = \frac{\partial}{\partial x}\left(\rho D_{AB} \frac{\partial Y_i}{\partial x} \right) + \dot{m}_i'''$$

General Form of Conservation Equations



$$\underbrace{\rho\frac{\partial\,\overline{\overline{\;\;}}}{\partial t}}^{1}+\underbrace{\rho u\frac{\partial\,\overline{\overline{\;\;}}}{\partial x}}^{2}=\underbrace{\frac{\partial}{\partial x}\left(-\frac{\partial\,\overline{\overline{\;\;}}}{\partial x}\right)}^{3}+\underbrace{Q}^{4}$$

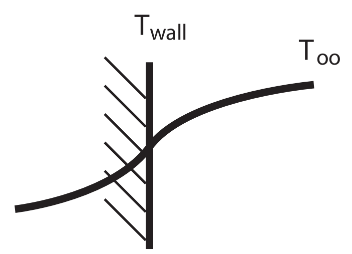
1. Change with time
2. Macroscopic movement
3. Microscopic movement
4. Source term

To get a solution from the Conservation Equations one need:

Boundary Conditions

For example

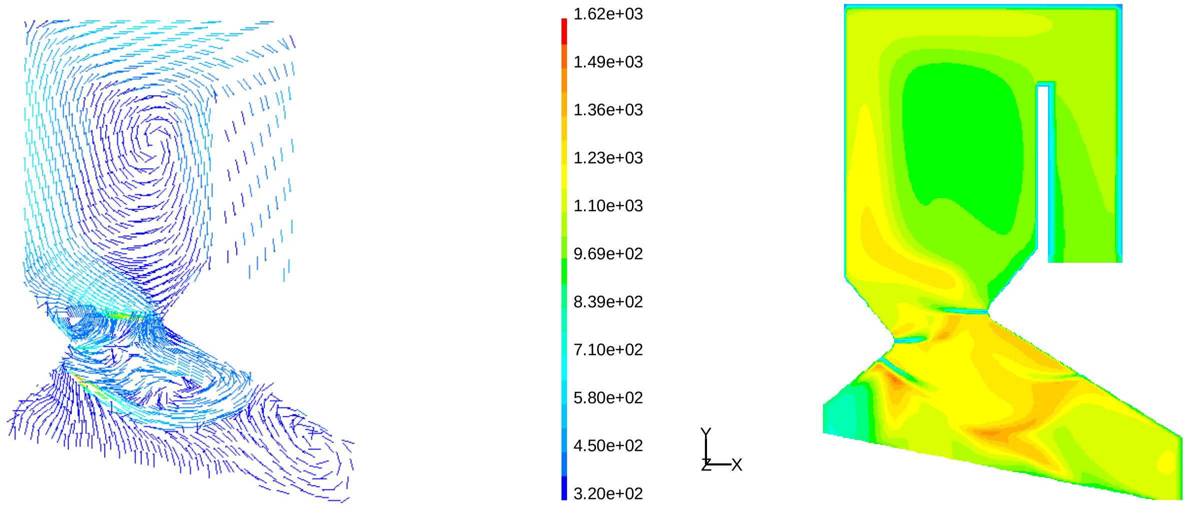
$$-k\frac{\partial T}{\partial x}\bigg|_{wall} = \alpha\left(T_{wall} - T_{\infty}\right)$$



Initial Conditions

The full Equations can be Solved by Different CFD Software Packages

(Computational fluid dynamic)

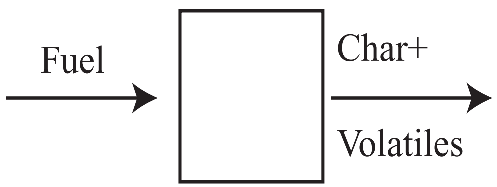


Each type of calculation needs its own set of submodels, e.g. models describing the reactions rate between different species or turbulence.

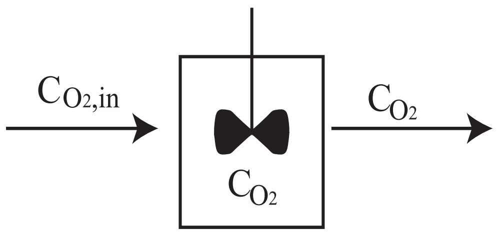
Simplified Models

Zero-order models

Black Box Model

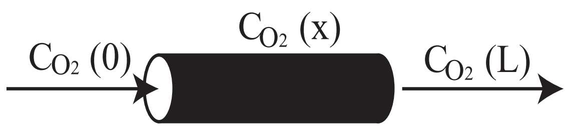


Continously Stirred Reactor (CSTR)

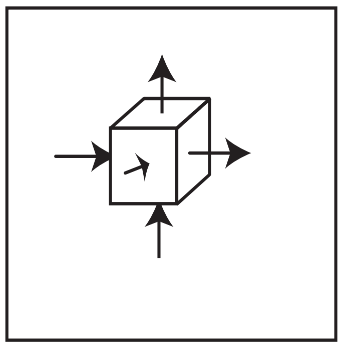


First order model

Plug Flow Reactor (PFR)

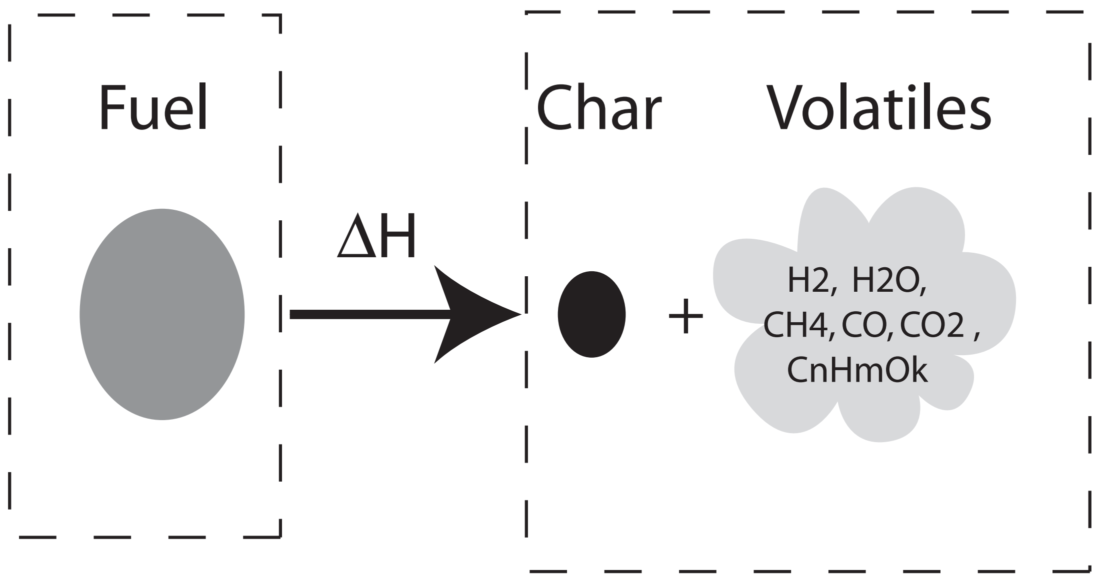


n-order model



Zero Order: Black Box Model

Hi = Hi-ΔH



Volatiles

ï H_2
ï H_2O
ï CO
ï CO_2
ï Hydrocarbons

Hydrocarbons ?

>100 different hydrocarbons are produced during devolatilisation

Characterization of Hydrocarbons

Here, for simplicity the hydrocarbons is characterized if they condense at ambient temperature or not.

Non-condensable hydrocarbons can be approximated by $C_{1.16}H_4$, having a heating value of 49.4MJ/kg

Condensable hydrocarbons can be approximated by $C_6H_{6.2}O_{0.2}$, having a heating value of 37MJ/kg

Heating Value of Volatiles

$$Y_{vol} + Y_{char} = 1$$

$$H_{fuel} - Y_{char} H_{char} - Y_{vol} H_{vol} = \Delta H_{dev}$$

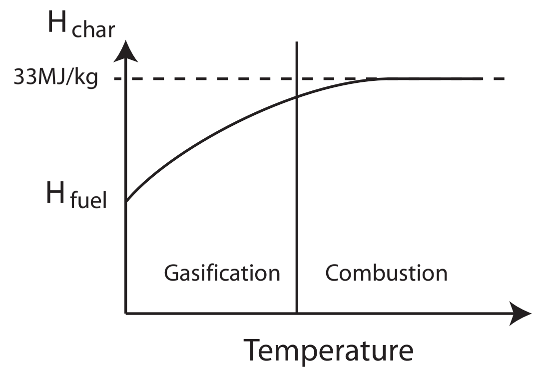
Heating value of wood

$\sim 18.6 MJ/kg_{wood}$

Heat of devolatilisation

$\sim -200 kJ/kg_{wood}$

Heating value char



$$\rightarrow H_{dev} = 14.75 MJ/kg_{volatiles}$$

Mass and Energy Balances of Volatile Species

Mass balance

$$\gamma_{H_2} + \gamma_{H_2O} + \gamma_{CO} + \gamma_{CO_2} + \gamma_{C_{1.16}H_4} + \gamma_{C_6H_{6.2}O_{0.2}} = 1$$

Energy balance

$$\gamma_{H_2} H_{H_2} + \gamma_{H_2O} H_{H_2O} + \gamma_{CO} H_{CO} + \gamma_{CO_2} H_{CO_2} + \gamma_{C_{1.16}H_4} H_{C_{1.16}H_4} + \gamma_{C_6H_{6.2}O_{0.2}} H_{C_6H_{6.2}O_{0.2}} = H_{vol}$$

$$\gamma_{H_2} 120 + \gamma_{H_2O} 0 + \gamma_{CO} 10.25 + \gamma_{CO_2} 0 + \gamma_{C_{1.16}H_4} 49.4 + \gamma_{C_6H_{6.2}O_{0.2}} 37 = 14.75 \quad [MJ/kg]$$

Balance of Element Species
Carbon, Hydrogen, Oxygen

Typical Elemental analysis for wood
(on mass, dry ash free)

50% C, 6% H, 44% O

Typical Elemental analysis for char
during combustion situation
(on mass, dry ash free)

~ 100% C

Balance of Elemental Species of Carbon

$$\gamma_{CO}\frac{M_C}{M_{CO}}+\gamma_{CO_2}\frac{M_C}{M_{CO_2}}+\gamma_{C_iH_j}\frac{M_{C_i}}{M_{C_iH_j}}+\gamma_{C_nH_nO_k}\frac{M_{C_n}}{M_{C_nH_mO_k}}=\frac{Y_C-Y_{char}}{1-Y_{char}}$$

$$\gamma_{CO}0.429+\gamma_{CO_2}0.273+\gamma_{C_iH_j}0.775+\gamma_{C_nH_nO_k}0.885=\frac{0.5-0.2}{1-0.2}=0.375$$

Balance of Elemental Species of Hydrogen and Oxygen

$$\gamma_{H_2} + \gamma_{H_2O}\frac{M_{H_k}}{M_{H_2O}} + \gamma_{C_iHj}\frac{M_{H_j}}{M_{C_iH_j}} + \gamma_{C_nH_nO_k}\frac{M_{H_n}}{M_{C_nH_mO_k}} = \frac{Y_{H_2}}{1-Y_{char}}$$

$$\gamma_{H_2} + \gamma_{H_2O}0.111 + \gamma_{C_iH_j}0.225 + \gamma_{C_nH_nO_k}0.076 = 0.075$$

$$\gamma_{CO}\frac{M_O}{M_{CO}} + \gamma_{CO_2}\frac{M_{O_2}}{M_{CO_2}} + \gamma_{H_2O}\frac{M_O}{M_{H_2O}} + \gamma_{C_nH_nO_k}\frac{M_{O_k}}{M_{C_nH_mO_k}} = \frac{Y_{O_2}}{1-Y_{char}}$$

$$\gamma_{CO}0.571 + \gamma_{CO_2}0.727 + \gamma_{H_2O}0.889 + \gamma_{C_nH_nO_k}0.04 = 0.55$$

Equations Formulated from Balances of Energy and Elemental Species

Energy

$$\gamma_{H_2}120+\gamma_{H_2O}0+\gamma_{CO}10.25+\gamma_{CO_2}0+\gamma_{C_{1.16}H_4}49.4+\gamma_{C_6H_{6.2}O_{0.2}}37=14.75 \quad [MJ/kg]$$

Elemental Species

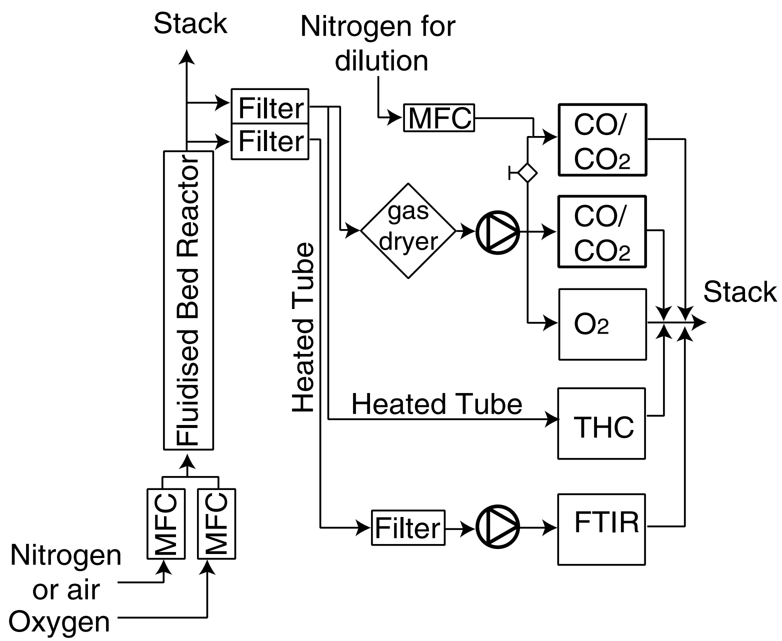
$$\gamma_{H_2}0+\gamma_{H_2O}0+\gamma_{CO}0.429+\gamma_{CO_2}0.273+\gamma_{C_{1.16}H_4}0775+\gamma_{C_6H_{6.2}O_{0.2}}0.885=0.375 \quad [-]$$

$$\gamma_{H_2}+\gamma_{H_2O}0.111+\gamma_{CO}0+\gamma_{CO_2}0+\gamma_{C_{1.16}H_4}0.225+\gamma_{C_6H_{6.2}O_{0.2}}0.076=0.075 \quad [-]$$

$$\gamma_{H_2}0+\gamma_{H_2O}0.889+\gamma_{CO}0.571+\gamma_{CO_2}0.727+\gamma_{C_{1.16}H_4}0+\gamma_{C_6H_{6.2}O_{0.2}}0.04=0.55 \quad [-]$$

6 unknown 4 Equations

Measurements of Compositions of Volatiles



Possible to measure ratios of:

$THC/CO_2 \sim C_{1.16}/CO_2 \sim 3$

$CO/CO_2 \sim 1.5$

H_2O/CO_2

Empirical ratios

CO/CO_2

$$\gamma_{CO} - \gamma_{CO_2} 3 \frac{M_{CO}}{M_{CO_2}} = 0$$

$$\gamma_{CO} - \gamma_{CO_2} 1.9 = 0$$

$C_{1.16}H_4 /CO_2$

$$\gamma_{CO} - \gamma_{C_{1.16}H_4} 1.5 \frac{M_{C_{1.16}H_4}}{M_{CO_2}} = 0$$

$$\gamma_{CO} - \gamma_{C_{1.16}H_4} 0.61 = 0$$

The Equations can be Summarized and Solved by a Matrix operation

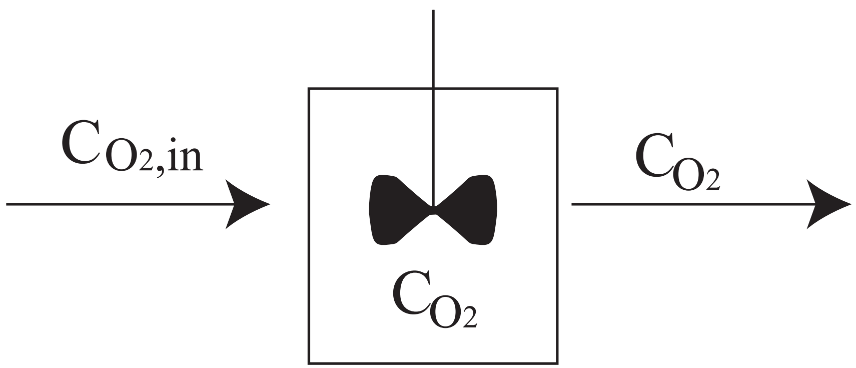
$$\begin{bmatrix} 10.25 & 0 & 0 & 120 & 49.4 & 37 \\ 0.429 & 0.273 & 0 & 0 & 0.775 & 0.885 \\ 0 & 0 & 0.111 & 1 & 0.225 & 0.075 \\ 0.571 & 0.727 & 0.889 & 0 & 0 & 0.04 \\ 1 & -1.9 & 0 & 0 & 0 & 0 \\ 0 & -0.61 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \gamma_{CO} \\ \gamma_{CO_2} \\ \gamma_{H_2O} \\ \gamma_{H_2} \\ \gamma_{C_iH_j} \\ \gamma_{C_nH_mO_k} \end{bmatrix} = \begin{bmatrix} 14.75 \\ 0.375 \\ 0.075 \\ 0.55 \\ 0 \\ 0 \end{bmatrix}$$

$$\gamma_{CO} = 0.361, \quad \gamma_{CO_2} = 0.190, \quad \gamma_{H_2O} = 0.227,$$
$$\gamma_{H_2} = 0.017, \quad \gamma_{C_{1.16}H_4} = 0.116, \quad \gamma_{C_nH_mO_k} = 0.089$$

Summary of Black Box Model

This derivation gives an example of a zero-order model that can be useful in combustion models for solid fuels, even if there is a weakness of the present model that the empirical coefficients are not known for more than one combustion situation.

ZERO-ORDER MODEL: CONTINUOUSLY STIRRED REACTOR



$$\frac{C_{i-1} - C_i}{\tau} = C_i k$$

Give some information on the condition inside the reactor

CONTINUOUSLY STIRRED REACTOR

Main Assumptions

- ïSteady State
- ïIsothermal
- ïNo diffusion
- ïEquimolar

(Fˆ r den givna uttrycke pÂfˆ regÂende OH g‰ller detta, men en tankreaktor kan ‰ven hantera icke ekvimol‰ra reaktioner. Men om man ska skriva ekvationen som en funktion av concentrationer mÂste ekvationen kompleteras med funktioner som tar h‰nsyn till ‰ndringen av totalt antal mol.)

CONTINUOUSLY STIRRED REACTOR

The general conservation equations can be simplified

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}=0$$

$$\rho\frac{\partial u}{\partial t}+\rho u\frac{\partial u}{\partial x}=\frac{\partial u}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)-\frac{\partial p}{\partial x}+\rho g$$

$$\rho\frac{\partial i}{\partial t}+\rho u\frac{\partial i}{\partial x}=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+q_{rad}$$

CONTINUOUSLY STIRRED REACTOR

The general conservation equations can be simplified

AngÂende diskusion med Anker Jensen som pÂpekade att en tank ‰en volum och inte att betrakta som ett avstÂnd. Om du tittar pÂderiveringen av concerverings ekavationerna I nÂgon bok ser du att arean f˜r kortas bort, sÂf˜r det endimensionella fallet ‰dY/dx≡AdY/dV convectiv term och d/dx(Ö) ≡d/dV(AÖ) f˜r den diffusiva termen, alltsÂdx motsvarar en volum f˜r ett endimensionellt fall.

$$\rho \frac{\partial Y_i}{\partial t} + \rho u \frac{\partial Y_i}{\partial x} = \frac{\partial}{\partial x}\left(\rho D_{AB} \frac{\partial Y_i}{\partial x} \right) + \dot{m}_i'''$$

No Diffusion, Backward discretisation in space

$$\rho \frac{\partial Y_i}{\partial t} + \rho u \frac{Y_{i-1} - Y_i}{\Delta x} = +\dot{m}_i'''$$

CONTINUOUSLY STIRRED REACTOR

The general conservation equations can be simplified

Equimolar, Isothermal, give that is can be expressed by molar concentrations

$$\frac{\partial C_i}{\partial t} + u\frac{C_{i-1} - C_i}{\Delta x} = C_i k$$

Steady state, formulated the equation for the residence time in the reactor, $\tau = \Delta x/u$

$$\frac{C_{i-1} - C_i}{\tau} = C_i k$$

$$\frac{dC}{dt} = Ck \qquad k = A\exp\left(-E/\Re T\right)$$

CONTINUOUSLY STIRRED REACTOR

Given for n-reactions not necessarily first order

$$\frac{dC_1}{dt} = -\frac{C_{1,0} - C_1}{\tau} + \sum_{i=1}^{N_{rek}} \Omega_{1i} A_i \exp\left(-E_i / \Re T\right) \prod_{j=1}^{n} C_j^{\gamma_{ij}}$$

$$\frac{dC_2}{dt} = -\frac{C_{2,0} - C_2}{\tau} + \sum_{i=1}^{N_{rek}} \Omega_{2i} A_i \exp\left(-E_i / \Re T\right) \prod_{j=1}^{n} C_j^{\gamma_{ij}}$$

$$\frac{dC_3}{dt} = -\frac{C_{2,0} - C_2}{\tau} + \sum_{i=1}^{N_{rek}} \Omega_{3i} A_i \exp\left(-E_i / \Re T\right) \prod_{j=1}^{n} C_j^{\gamma_{ij}}$$

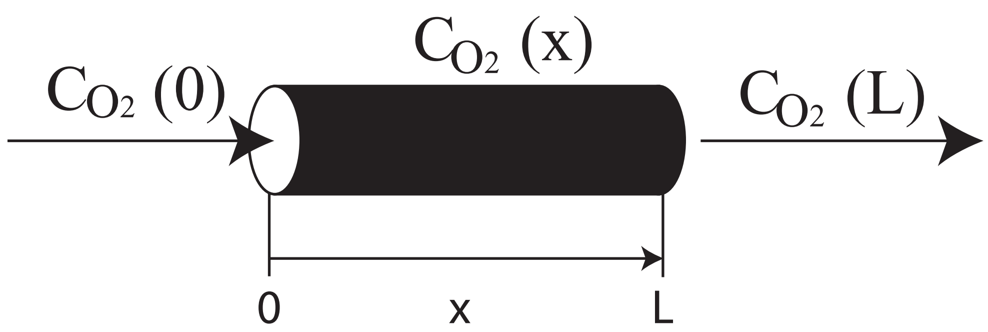
$$\vdots$$

$$\frac{dC_n}{dt} = -\frac{C_{n,0} - C_n}{\tau} + \sum_{i=1}^{N_{rek}} \Omega_{ni} A_i \exp\left(-E_i / \Re T\right) \prod_{j=1}^{n} C_j^{\gamma_{ij}}$$

Solution found when all derivatives are zero

FIRST-ORDER MODEL: PLUG FLOW REACTOR

Plug Flow Reactor (PFR)



PLUG FLOW REACTOR

The general conservation equations can be simplified

$$\rho \frac{\partial Y_i}{\partial t} + \rho u \frac{\partial Y_i}{\partial x} = \frac{\partial}{\partial x}\left(\rho D_{AB} \frac{\partial Y_i}{\partial x} \right) + \dot{m}_i'''$$

No Diffusion, Steady state

$$\rho u \frac{\partial Y_i}{\partial x} = \dot{m}_i'''$$

PLUG FLOW REACTOR

The general conservation equations can be simplified

Equimolar, Isothermal, give that the equation can be expressed by molar concentrations, formulated the equation for the residence time in the reactor, $\tau = \Delta x/u$

$$\frac{dC_i}{d\tau} = C_i k$$

PLUG FLOW REACTOR

Given for n-reactions not necessarily first order

$$\frac{dC_1}{d\tau} = \sum_{i=1}^{N_{rek}} \Omega_{1i} A_i \exp(-E_i / \Re T) \prod_{j=1}^{n} C_j^{\gamma_{ij}}$$

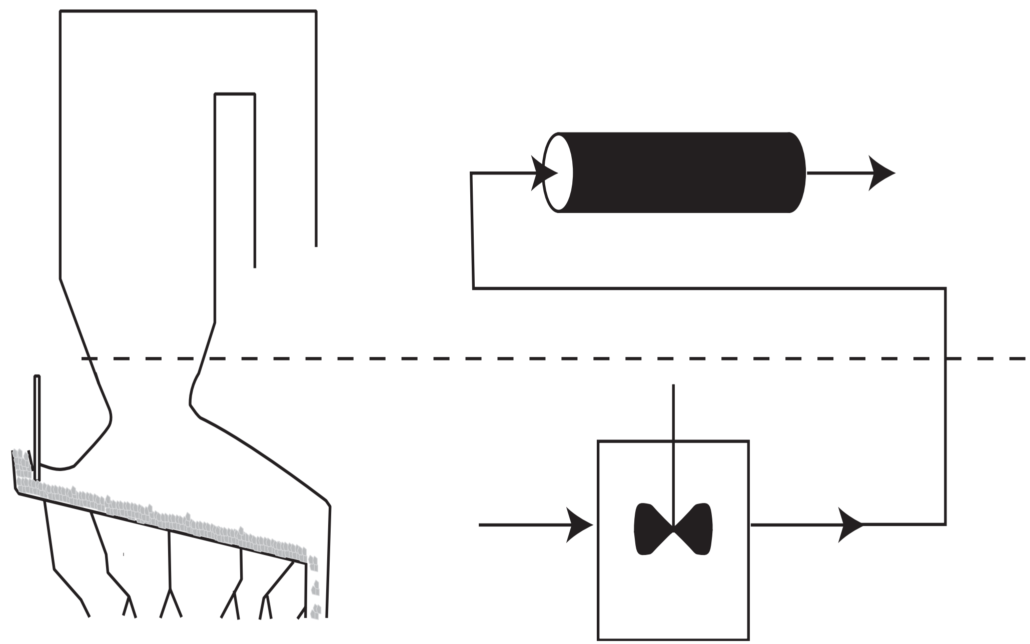
$$\frac{dC_2}{d\tau} = \sum_{i=1}^{N_{rek}} \Omega_{2i} A_i \exp(-E_i / \Re T) \prod_{j=1}^{n} C_j^{\gamma_{ij}}$$

$$\frac{dC_3}{d\tau} = \sum_{i=1}^{N_{rek}} \Omega_{3i} A_i \exp(-E_i / \Re T) \prod_{j=1}^{n} C_j^{\gamma_{ij}}$$

$$\vdots$$

$$\frac{dC_n}{d\tau} = \sum_{i=1}^{N_{rek}} \Omega_{ni} A_i \exp(-E_i / \Re T) \prod_{j=1}^{n} C_j^{\gamma_{ij}}$$

SYSTEM OF REACTORS CAN DESCRIBE A COMBUSTOR



Summary

- The level of information and the character of the problem decide the details that are needed to describe combustion system.
- A model should be as simple as possible, to give a possibility to investigate the basic behavior of the problem.

DIMENSIONLESS NUMBERS TO BE USED TO UNDERSTAND AND COMPARE COMBUSTION SITUATIONS

The dimensional numbers:

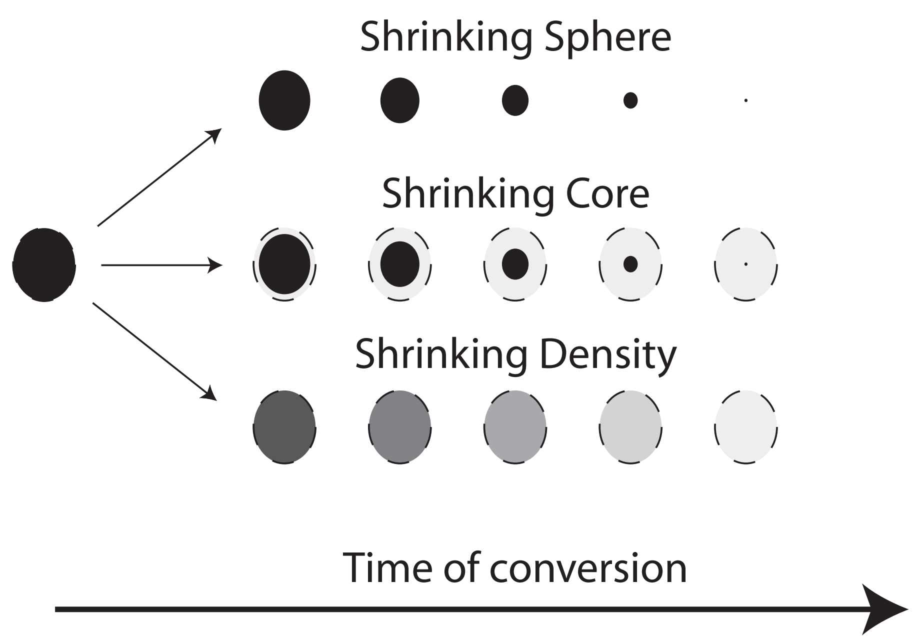
ïCategorise different combustion situations.

ïAllow comparison of different combustion situations with each other.

ïReveal the most important phenomena.

ïSupport the choice of simplified models.

DEMONSTRATION OF THE USE OF DIMENSIONLESS NUMBERS



Different simplified models for char combustion
- When can they be used?

SOLVE THE GOVERMENTAL CONSERVETION EQUATIONS IN DIMENSIONLESS FORM FOR SIMPLIFIED PROBLEMS

The combustion of char is solved from the conservation equation of species for a isothermal spherical particle:

$$\frac{\partial}{\partial t}\left(\varepsilon\rho_g Y_{O_2}\right)+\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\varepsilon\rho_g u Y_{O_2}\right)=\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\rho_g D_{AB,eff}\frac{\partial Y_{O_2}}{\partial r}\right)+\dot{m}_i'''$$

Effective diffusion coefficient in- and outside the char particle

$$D_{AB,eff}=\varepsilon^2 D_{AB}$$

SOLVE THE GOVERMENTAL CONSERVETION EQUATIONS IN DIMENSIONLESS FORM FOR SIMPLIFIED PROBLEMS

Assume: Quasi steady state

Carbon converted directly to CO2 ($C+O_2 \rightarrow CO_2$)

$$0 = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho_g D_{AB,eff} \frac{\partial Y_{O_2}}{\partial r} \right) + \dot{m}_i'''$$

Source term

$$\dot{m}''' = -k_{O_2} \rho_g Y_{O_2}$$

SOLVE THE GOVERMENTAL CONSERVETION EQUATIONS IN DIMENSIONLESS FORM FOR SIMPLIFIED PROBLEMS

Write the equations in dimension less form

Dimensionless Radius

$$\xi = \frac{r}{R_p}$$

R_p radius of particle

Dimensionless Oxygen concentration

$$\psi = \frac{Y_{O_2}}{Y_{O_2\infty}}$$

$Y_{O2\infty}$ oxygen concentration far from surface of the particle

SOLVE THE GOVERMENTAL CONSERVETION EQUATIONS IN DIMENSIONLESS FORM FOR SIMPLIFIED PROBLEMS

Write the equations in dimension less form, insert dimensionless radius and oxygen concentration in species equation.

$$0 = \frac{1}{\xi^2}\frac{\partial}{R_p \partial \xi}\left(\xi^2 D_{AB,eff}\frac{Y_{O_2\infty}\partial \psi}{R_p \partial \xi}\right) - k_{O_2} Y_{O_2\infty}\psi$$

which can be written as

$$0 = \frac{1}{\xi^2}\frac{\partial}{\partial \xi}\left(\xi^2 \frac{\partial \psi}{\partial \xi}\right) - Th^2 \psi \qquad \text{where} \qquad Th = R_p \sqrt{\frac{k_{O_2}}{D_{AB,eff}}}$$

SOLVE THE GOVERMENTAL CONSERVETION EQUATIONS IN DIMENSIONLESS FORM FOR SIMPLIFIED PROBLEMS

Thiele Modulus

$$Th = R_p \sqrt{\frac{k_{O_2}}{D_{AB,eff}}}$$

Th>>1

Surface reaction

Tidigare stod ì Diffusion Controlledî , vilket ‰ fel

Th<<1

Even reaction over the interior of the particle

Tidigare stod ì Kinetic Controlledî , vilket ‰ fel

SOLVE THE GOVERMENTAL CONSERVETION EQUATIONS IN DIMENSIONLESS FORM FOR SIMPLIFIED PROBLEMS

The general solution of the dimensionless species equation

$$\psi = \frac{1}{\xi}\left(A\exp\left(Th\xi\right) + B\exp\left(-Th\xi\right)\right)$$

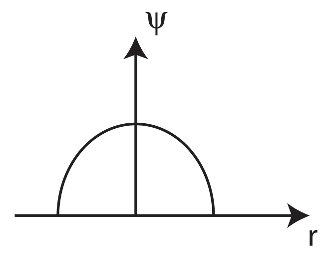
Boundary conditions

1. Symmetry condition at particle centre
2. Mass transfer condition through particle surface

SOLVE THE GOVERMENTAL CONSERVETION EQUATIONS IN DIMENSIONLESS FORM FOR SIMPLIFIED PROBLEMS

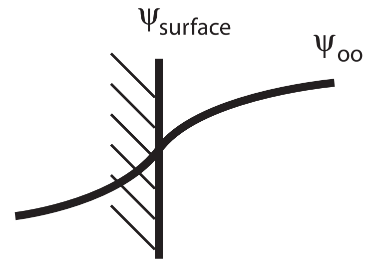
Symmetry condition

$$\frac{\partial \psi}{\partial \xi} = 0$$



Mass transfer condition

$$-SD_{AB,eff} \frac{\partial Y_{O_2}}{\partial r}\bigg|_{Surface} = S\beta\left(Y_{O_2} - Y_{O_2\infty}\right)$$



Dimensionless form

$$-D_{AB,eff} \frac{Y_{O_2\infty} \partial \psi}{R_p \partial \xi} = \beta\left(Y_{O_2\infty}\psi - Y_{O_2\infty}\right)$$

SOLVE THE GOVERMENTAL CONSERVETION EQUATIONS IN DIMENSIONLESS FORM FOR SIMPLIFIED PROBLEMS

The dimensionless mass transfer condition can be written

$$-\frac{\partial \psi}{\partial \xi} = \frac{R_p \beta}{D_{AB,eff}}(\psi - 1) = Bi_m(\psi - 1)$$

Bi_m is the Biot number related to mass

Bi>>1	Bi<<1
Controlled by internal mass transfer	Controlled by external mass transfer

SOLVE THE GOVERMENTAL CONSERVETION EQUATIONS IN DIMENSIONLESS FORM FOR SIMPLIFIED PROBLEMS

$\mathrm{Bi_m} = R_p\beta/D_{AB,eff}$, has the same form as the Sherwood number.

$$Sh = \frac{2R_p\beta}{D_{AB}} = 2 + 0.6\,\mathrm{Re}^{1/2}\,Sc^{1/3}$$

Sherwood number is a measure of the thickness of the boundary layer through which the molecules have to diffuse. Biot number can alterativly be written

$$Bi_m = \frac{R_p}{D_{AB,eff}}\frac{D_{AB}\left(2 + 0.6\,\mathrm{Re}^{1/2}\,Sc^{1/3}\right)}{2R_p} = \frac{\left(1 + 0.3\,\mathrm{Re}^{1/2}\,Sc^{1/3}\right)}{\varepsilon^2}$$

$$\mathrm{Re} = \frac{2R_pU}{\nu} \qquad Sc = \frac{\nu}{D_{AB}}$$

SOLVE THE GOVERMENTAL CONSERVETION EQUATIONS IN DIMENSIONLESS FORM FOR SIMPLIFIED PROBLEMS

The boundary condition give the constants A and B

Symmetry condition give

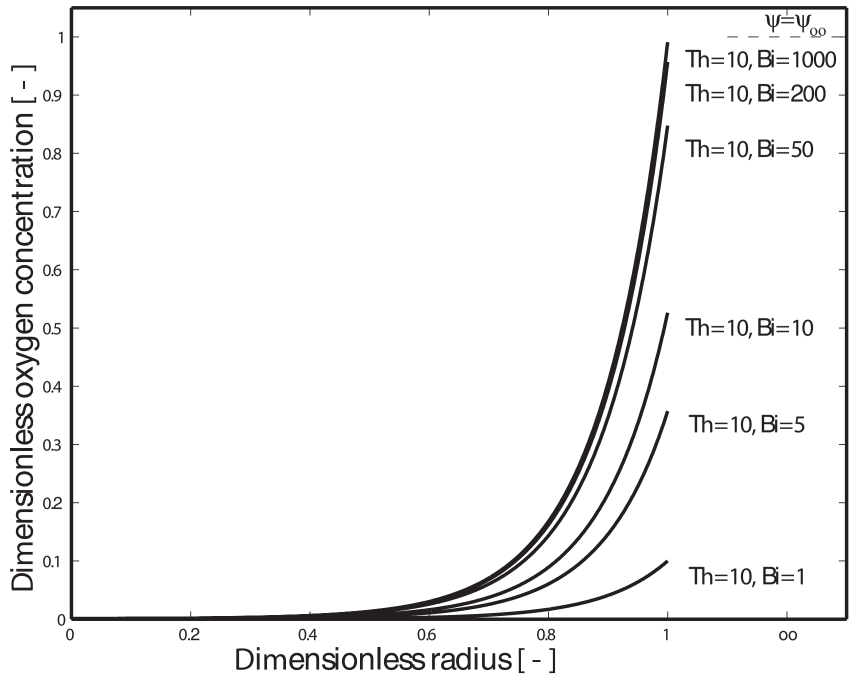
$$0 = -A - B \Rightarrow A = -B$$

Mass transfer condition give

$$A = \frac{Bi_m}{(Bi_m + Th - 1)\exp(Th) + (Th + 1 - Bi_m)\exp(-Th)} = -B$$

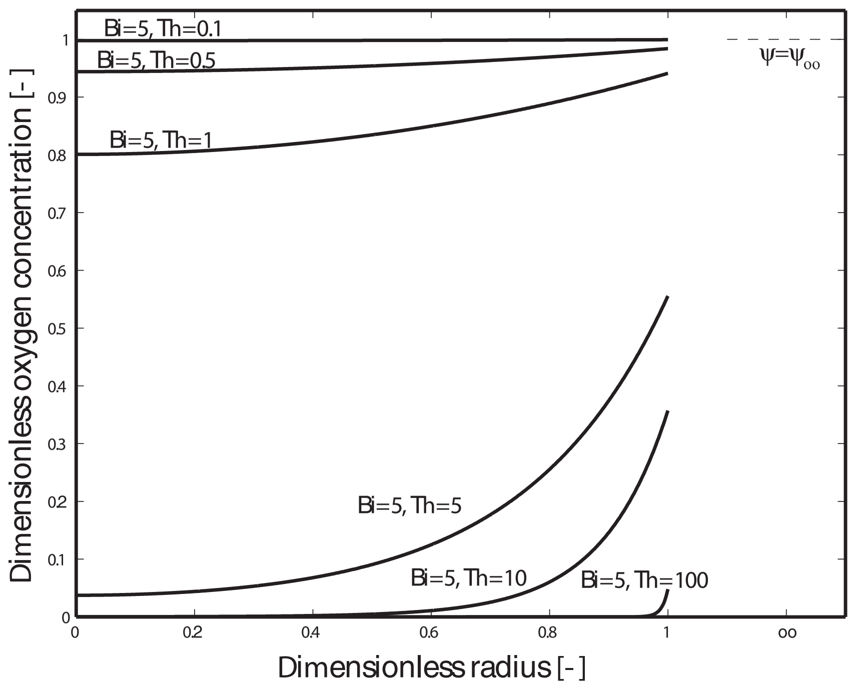
SOLVE THE GOVERMENTAL CONSERVETION EQUATIONS IN DIMENSIONLESS FORM FOR SIMPLIFIED PROBLEMS

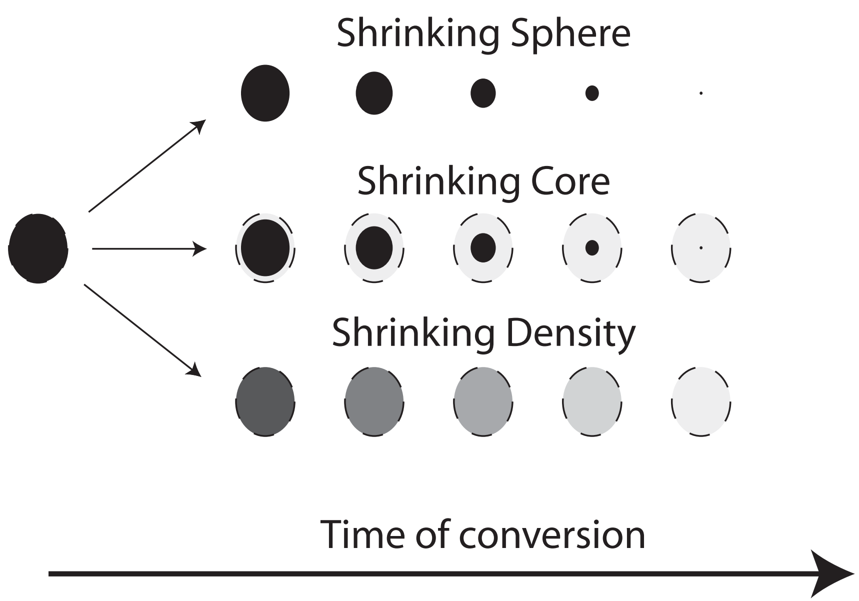
Solution for various Bi_m



SOLVE THE GOVERMENTAL CONSERVETION EQUATIONS IN DIMENSIONLESS FORM FOR SIMPLIFIED PROBLEMS

Solution for various Th





DIMENSIONLESS NUMBERS TO BE USED TO UNDERSTAND AND COMPARE COMBUSTION SITUATIONS

The dimensional numbers:

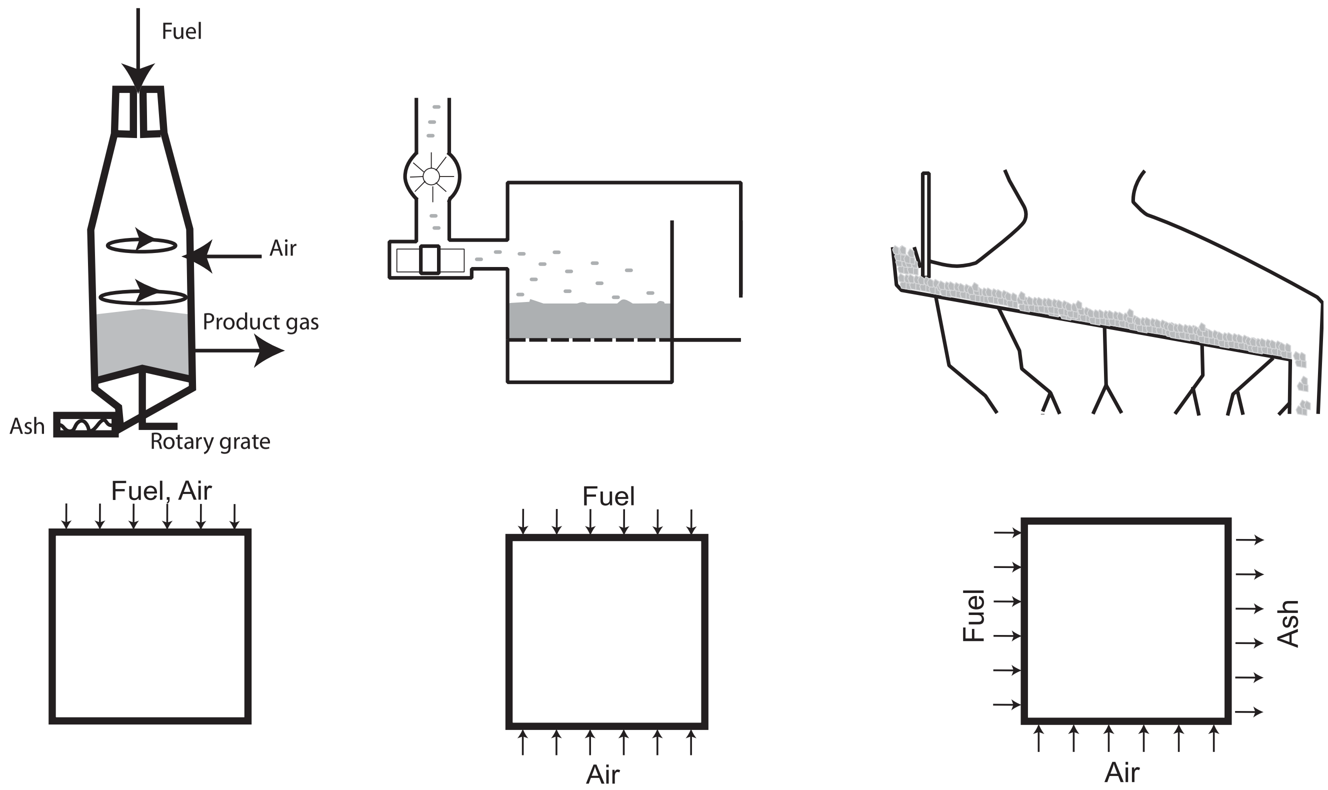
ïCategorise different combustion situations.

ïAllow comparison of different combustion situations with each other.

ïReveal the most important phenomena.

ïSupport the choice of simplified models.

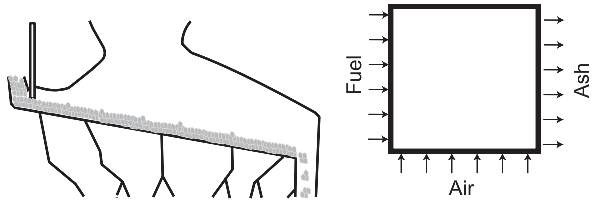
Combustion in a Fixed Bed



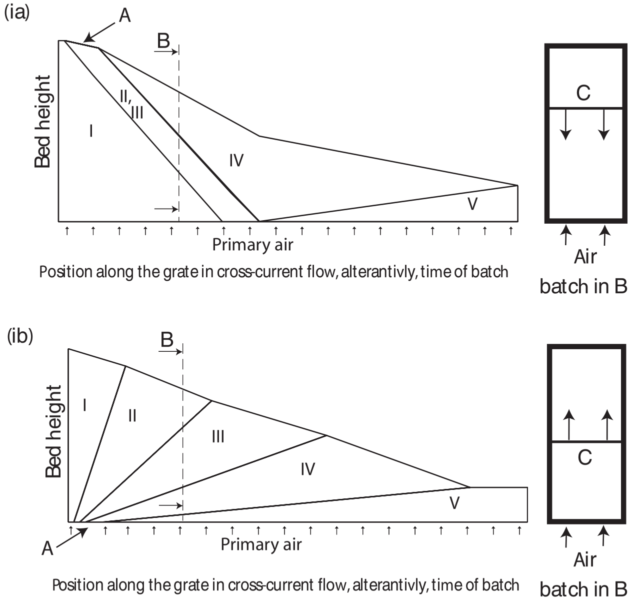
Basic Concepts of Fixed bed Combustion

Cross-Current

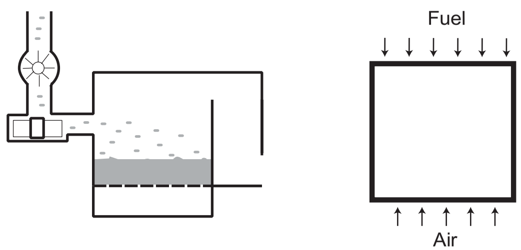
i)



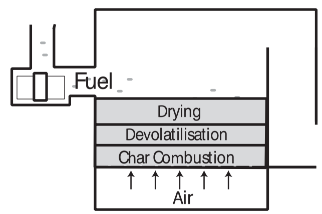
(ia)
(ib)



ii)

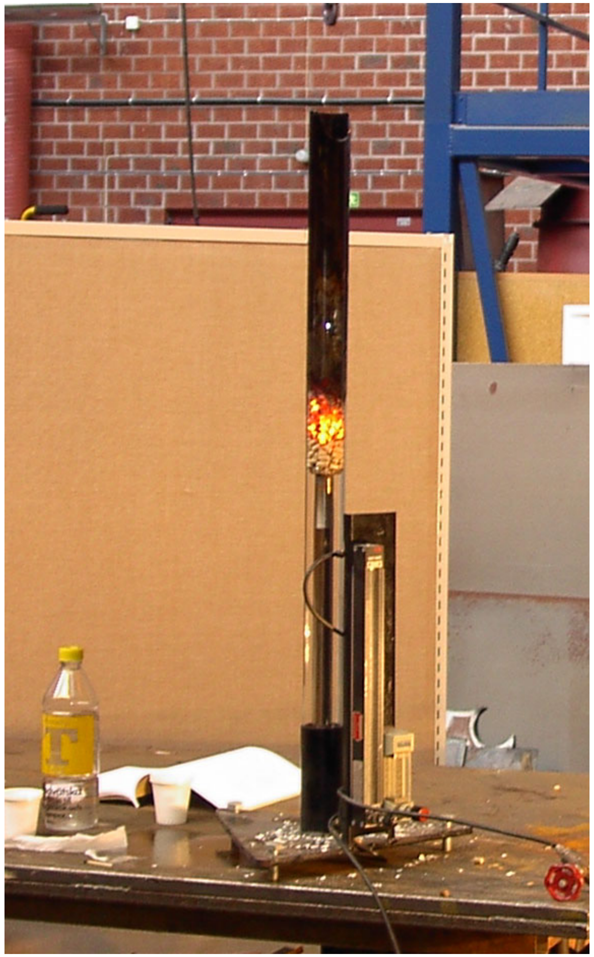


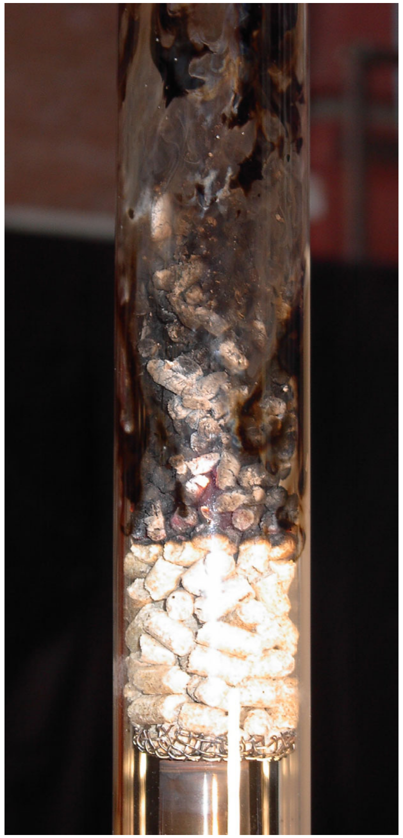
(iia)



Co-Current

Counter-Current Fixed Bed Combustion





Low airflow

Medium airflow

Processes Inside the Bed

Heat transfer:

ï Convective

ï Conductive

ï Radiative

Mass transport :

ï Convective

ï Diffusive

Reactions:

ï Endothermic

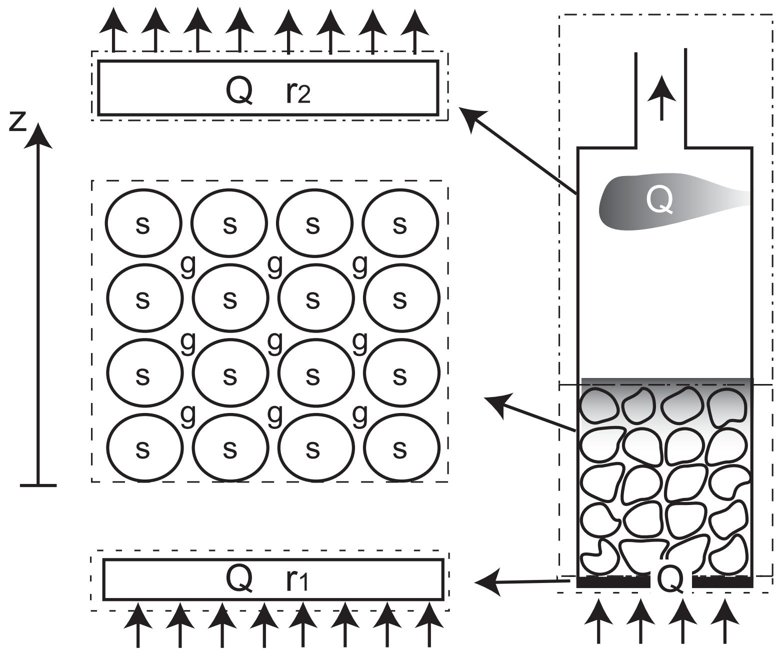
ï Exothermic

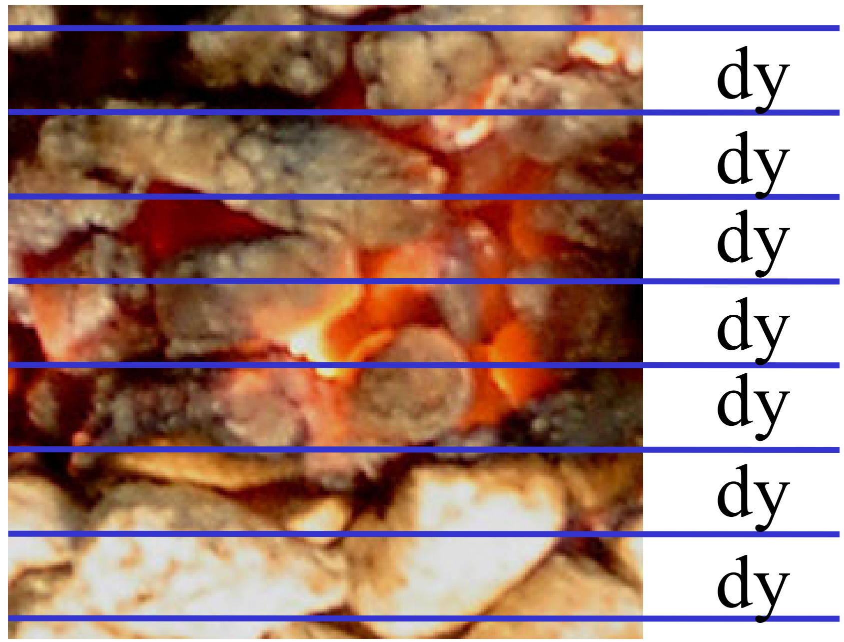
Processes Inside the Bed

Special for the solid phase:

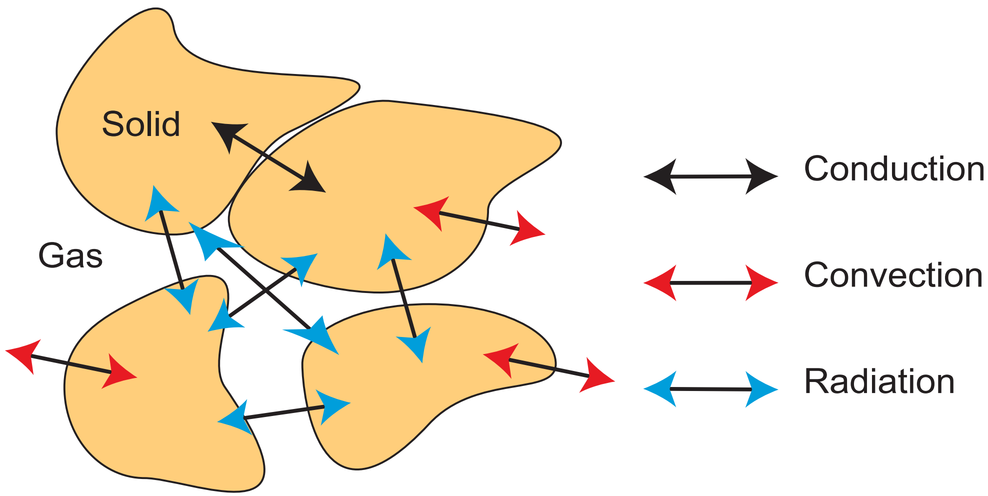
ïOften thermally large fuel particles
ïShrinking particles
ïComplex shapes of the fuel particles

Model Thinking

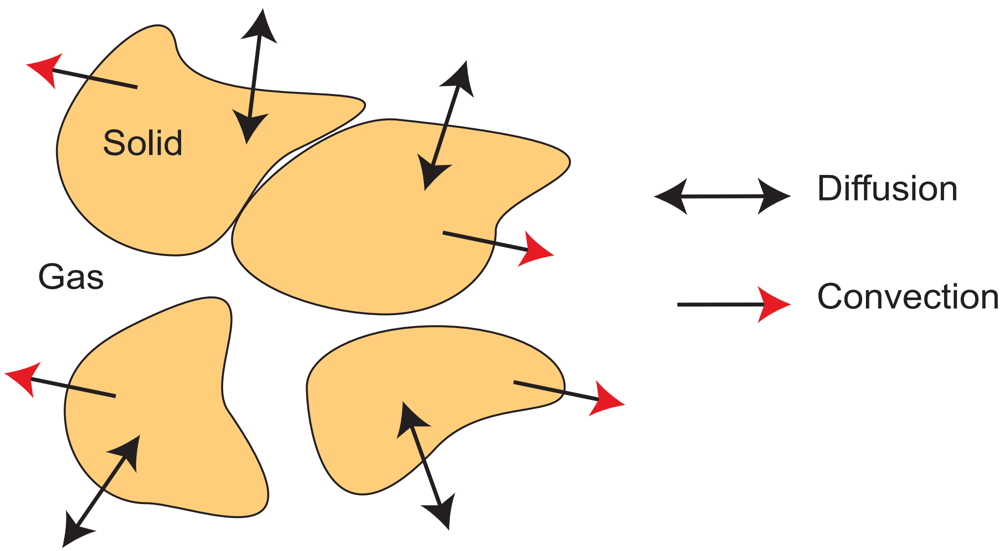




Heat Transfer



Mass transfer



Reactions

Evaporation

Heterogeneous reactions

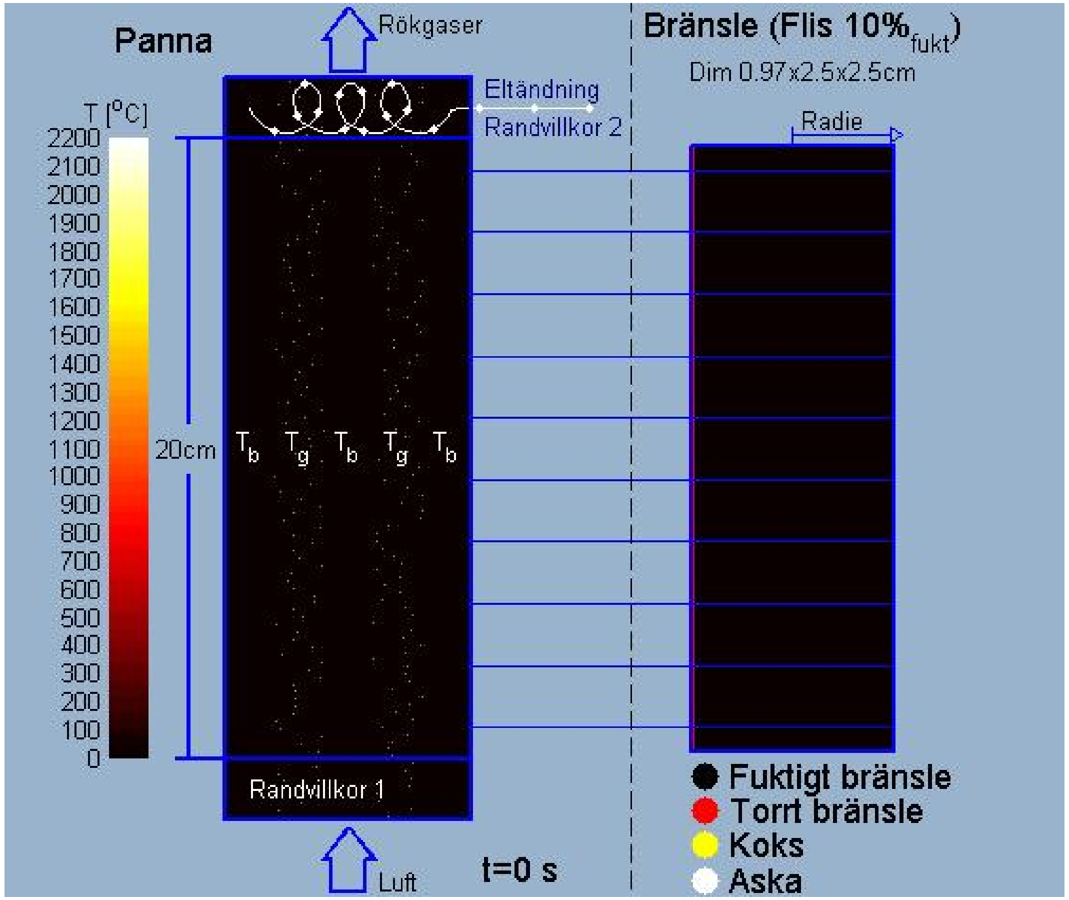
-Devolatilisation

-Char combustion

Homogenous reactions

Solid Phase

Illustration of Counter-Current Combustion



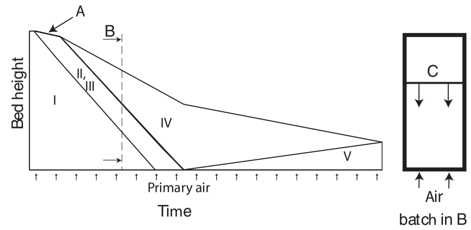
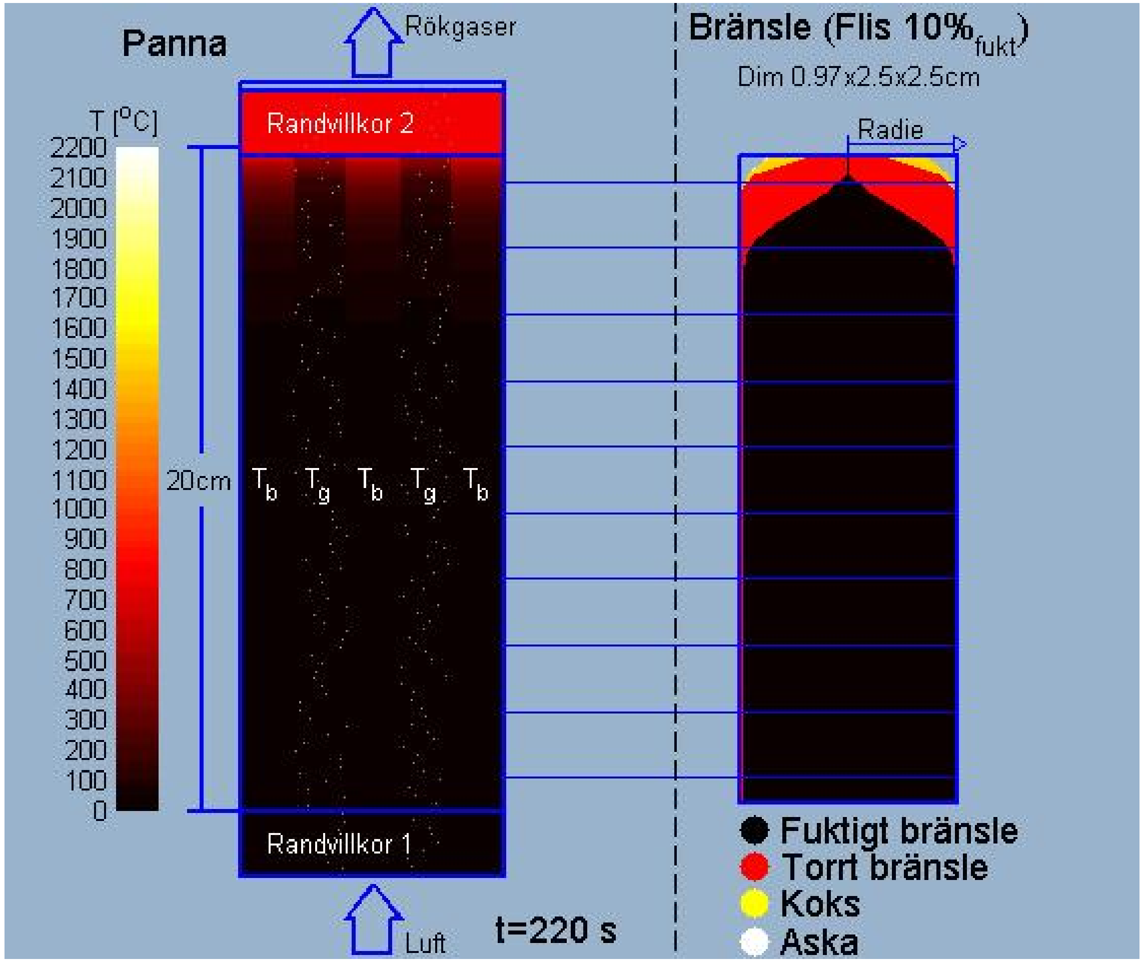
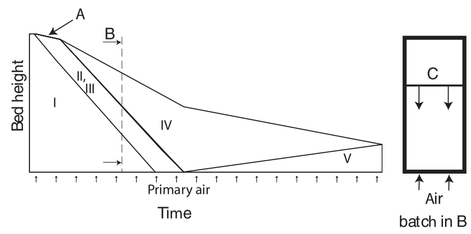


Illustration of Counter-Current Combustion





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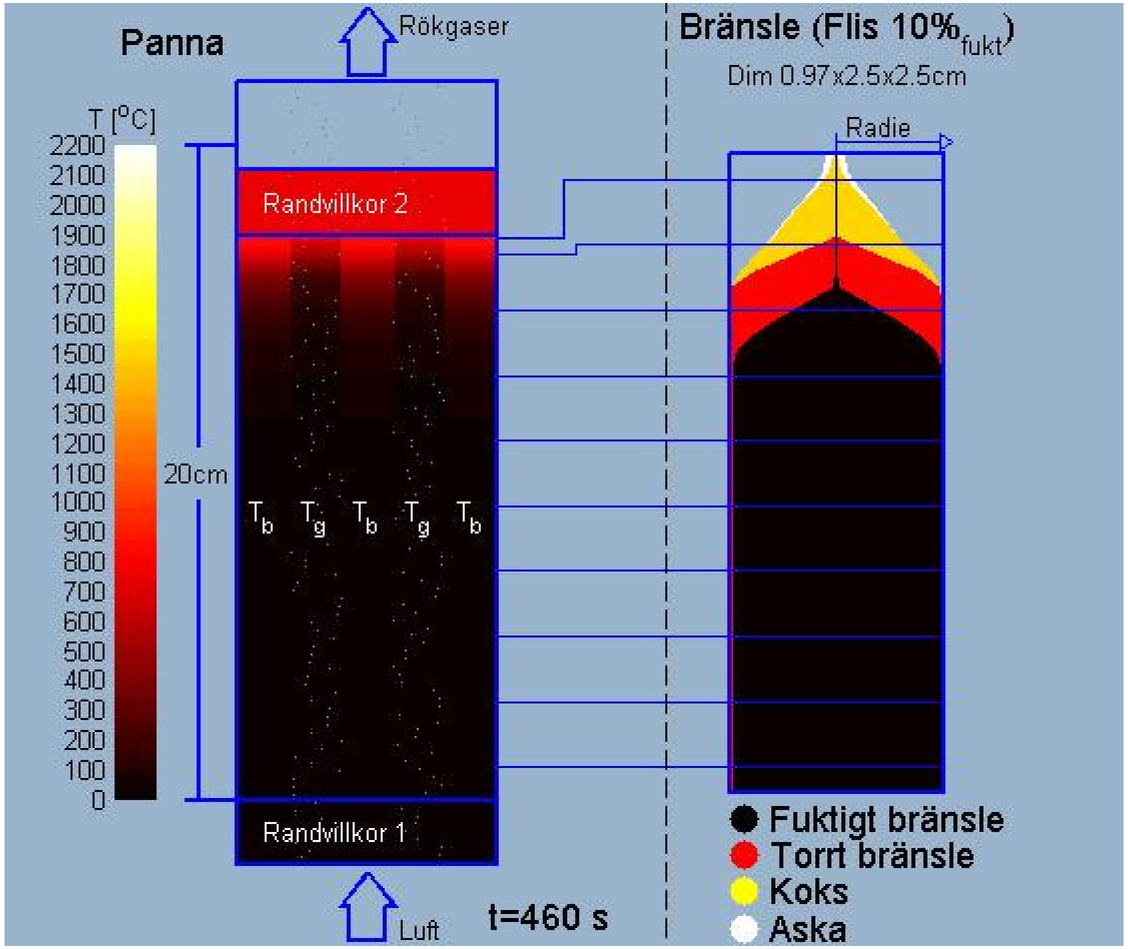

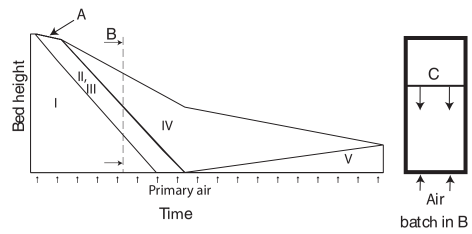

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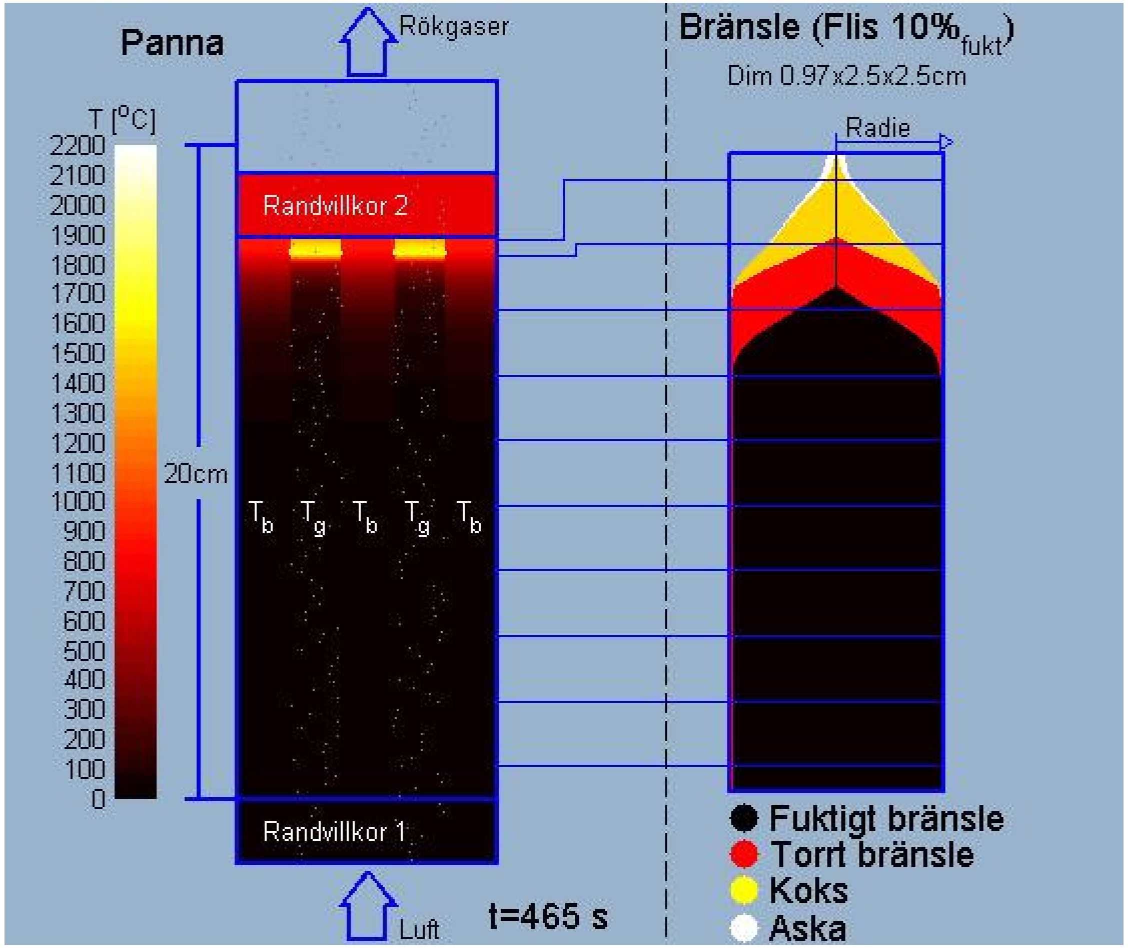
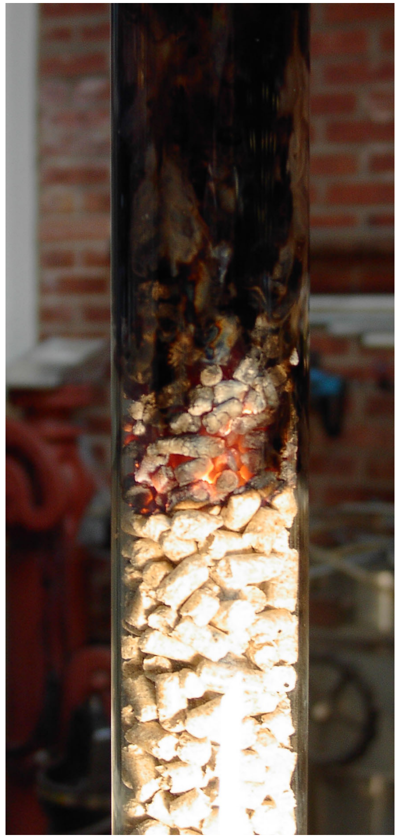




Temperatures and Gas Composition

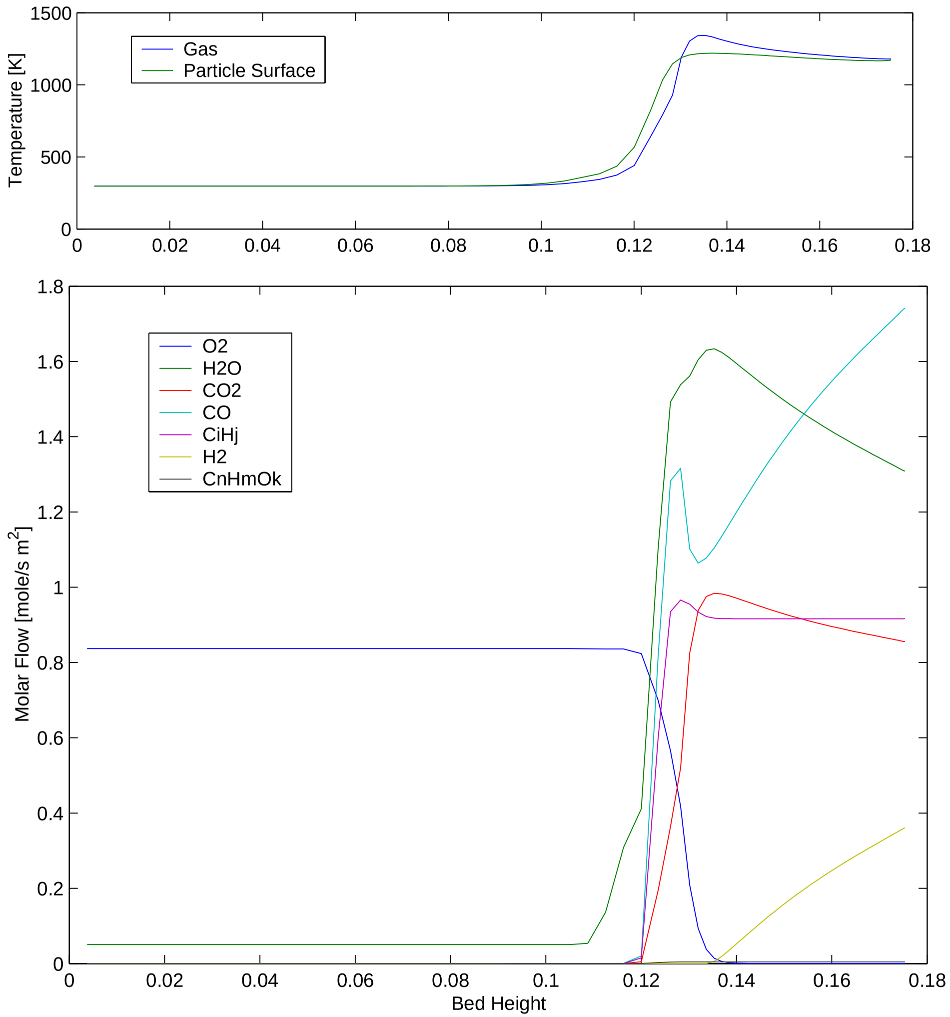
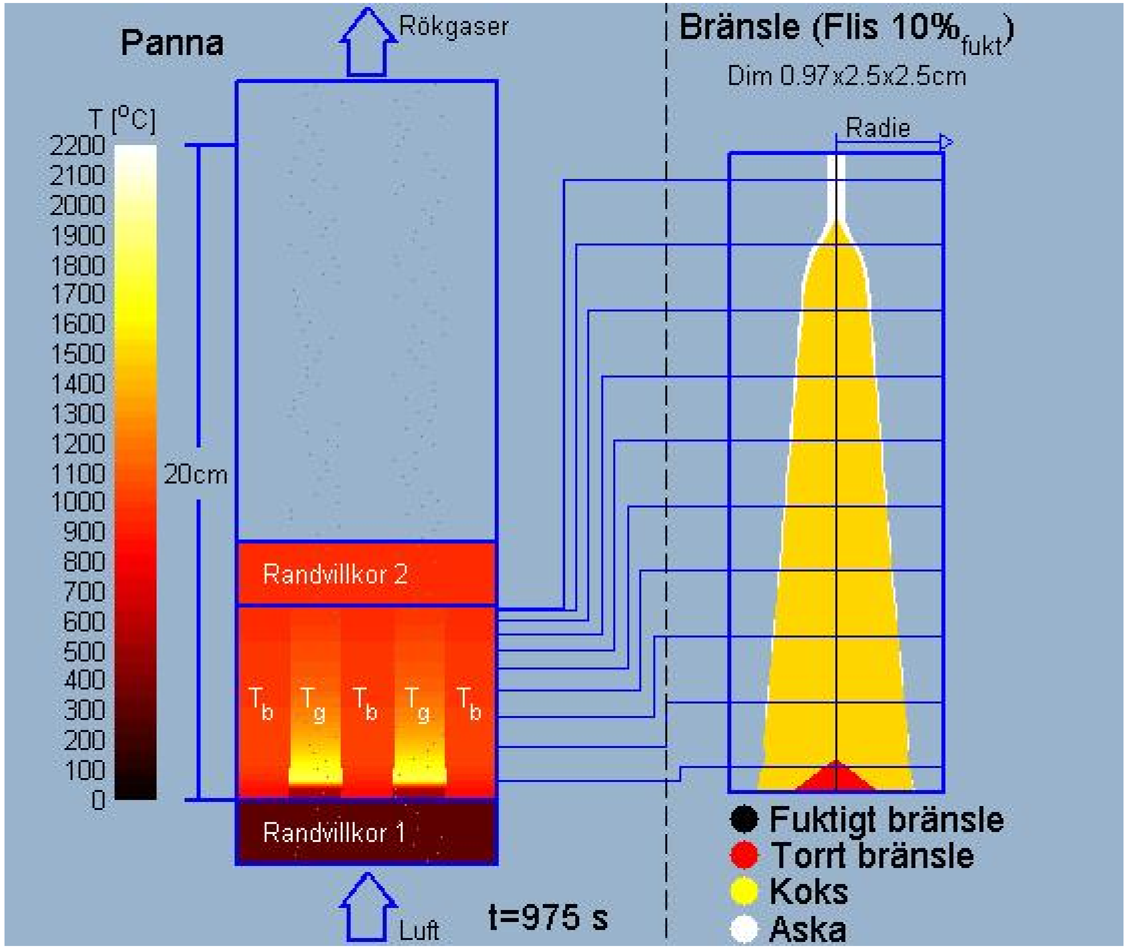


Illustration of Counter-Current Combustion



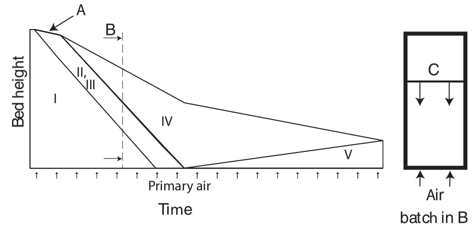
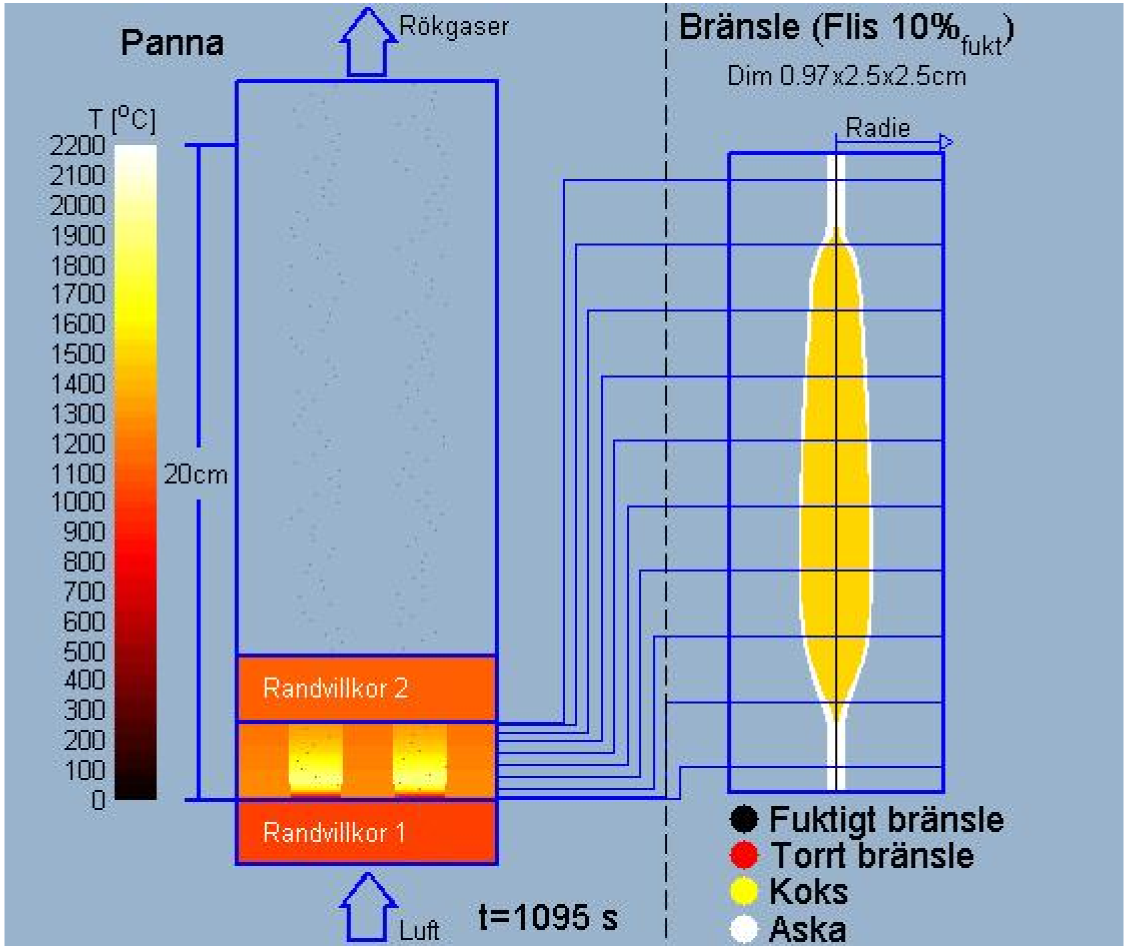
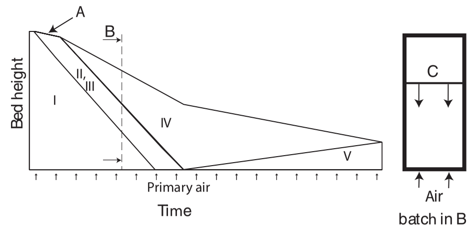
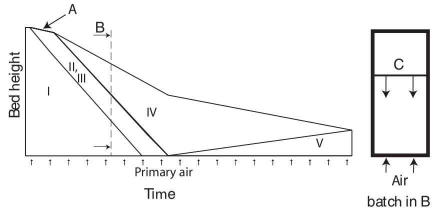


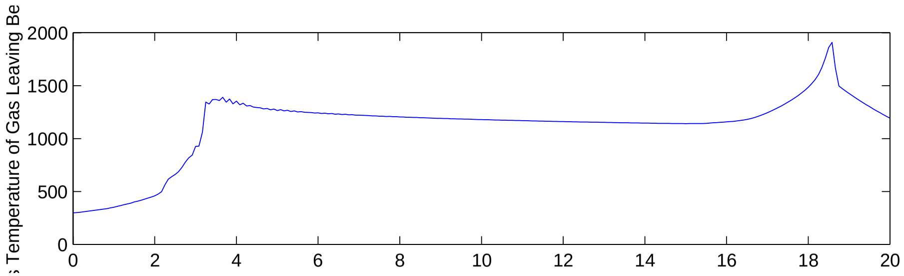
Illustration of Counter-Current Combustion





Gas Temperatures and Gas Composition





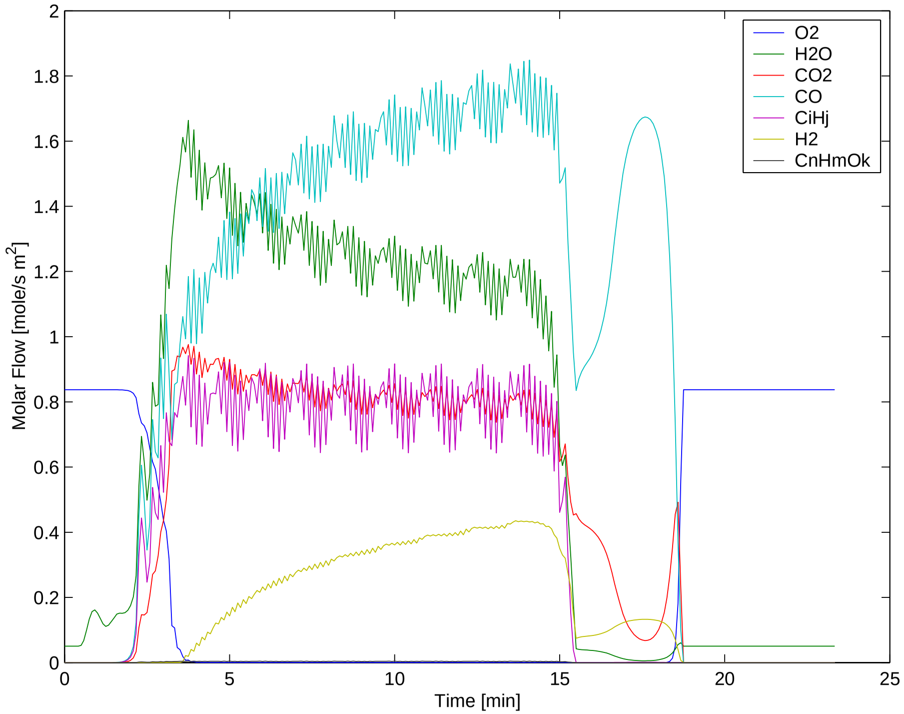
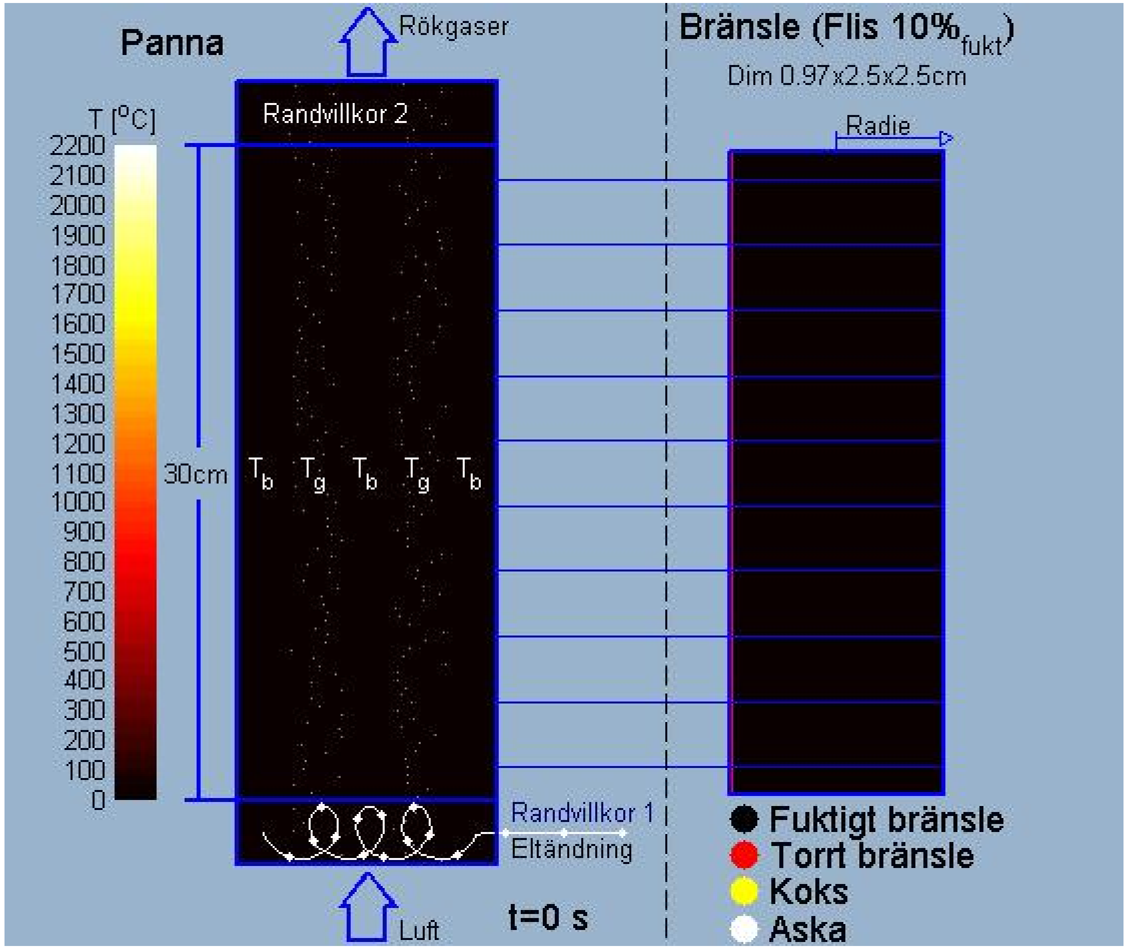


Illustration of Co-Current Combustion



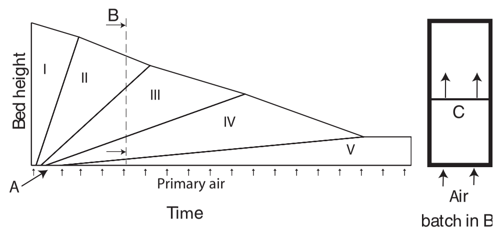
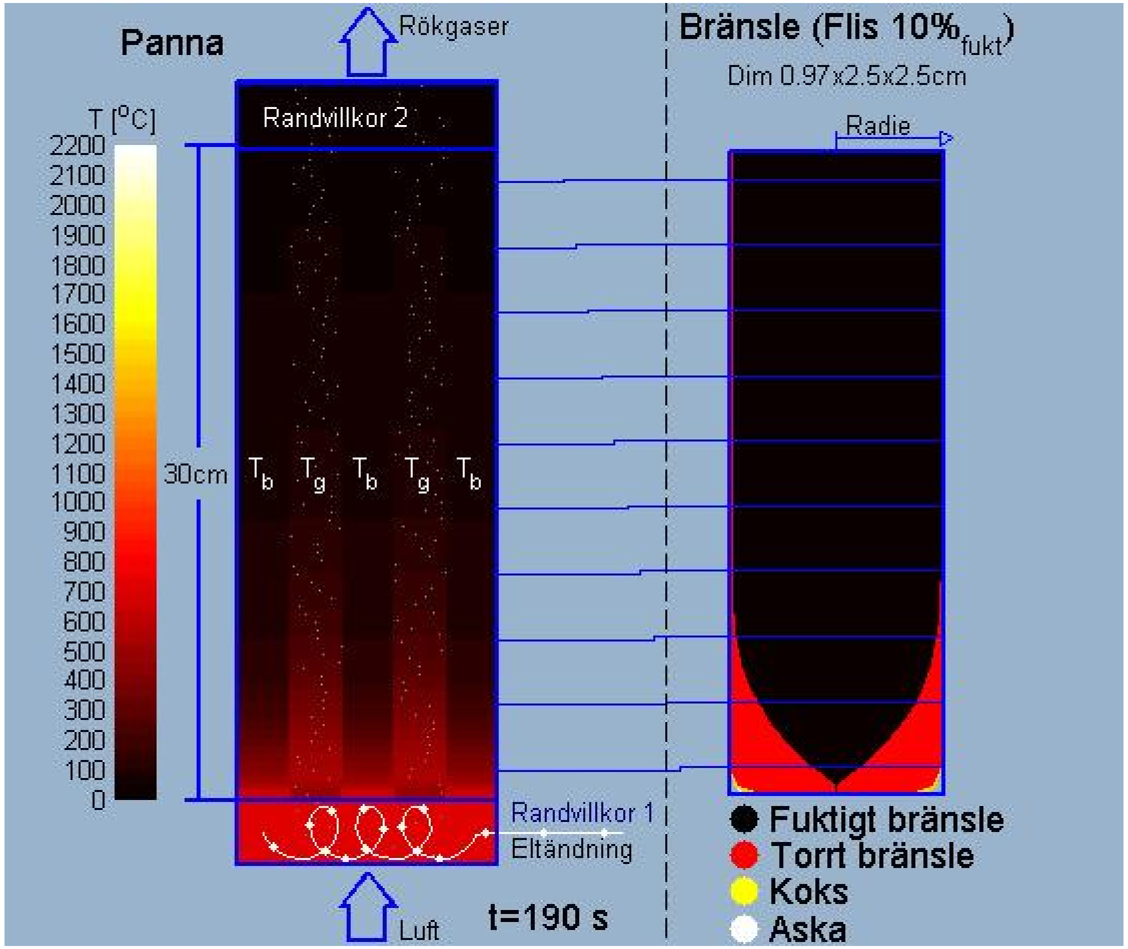
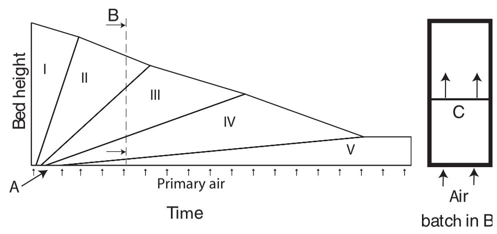


Illustration of Co-Current Combustion





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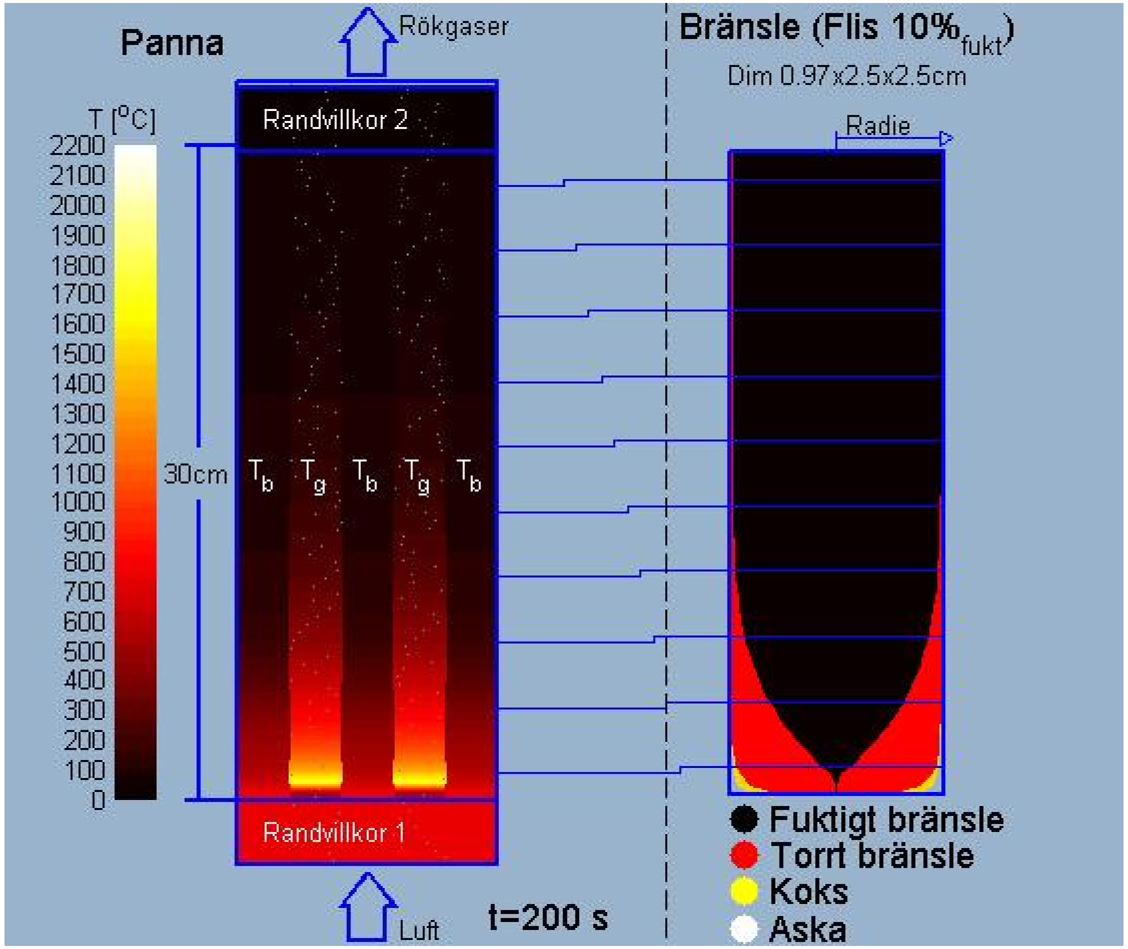
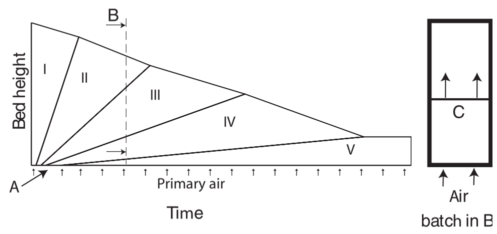
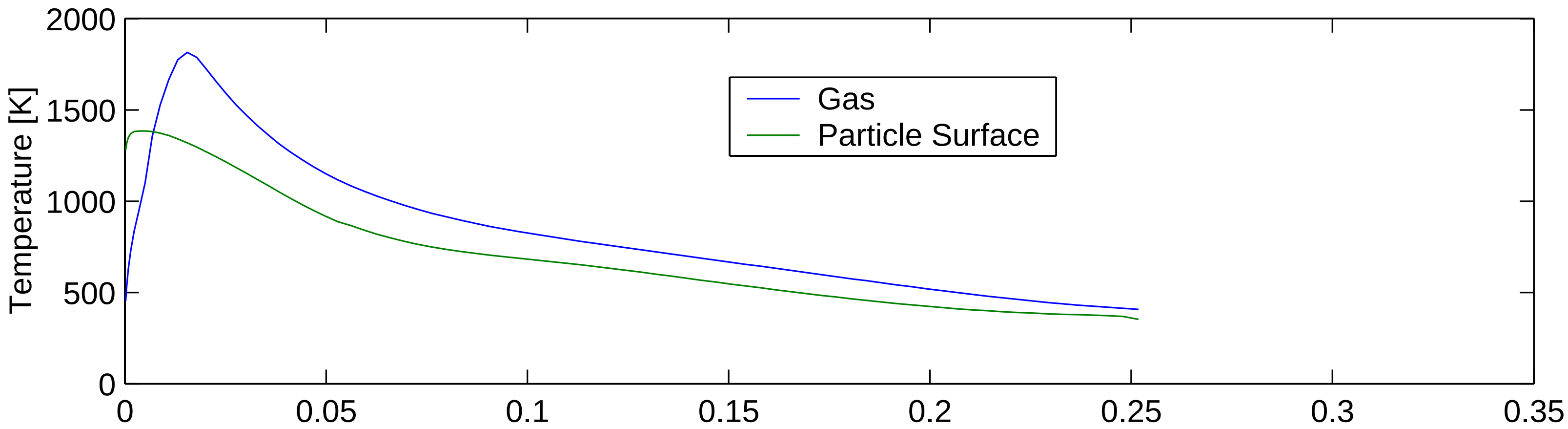




Temperatures and Gas Composition



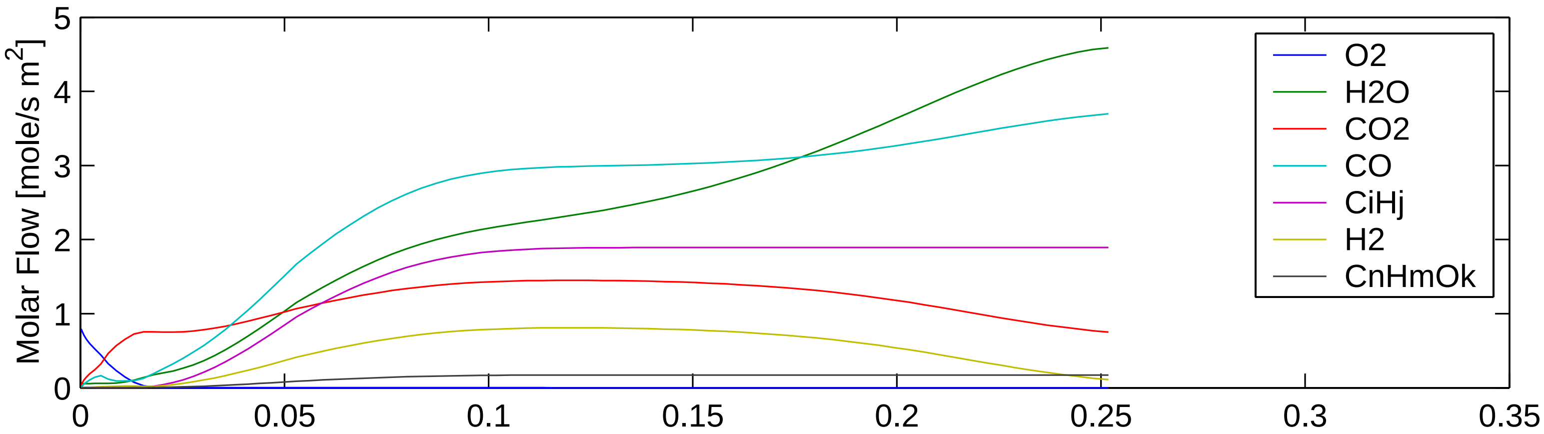
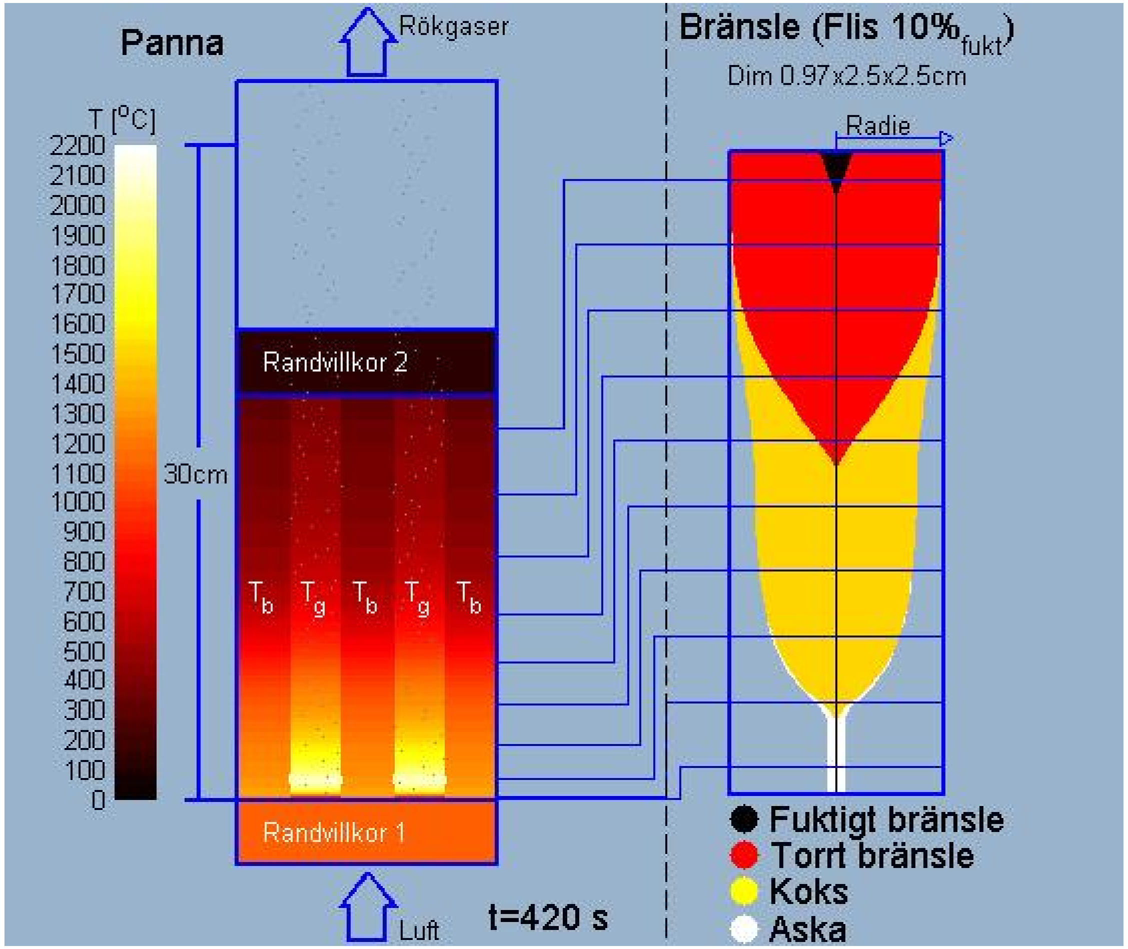
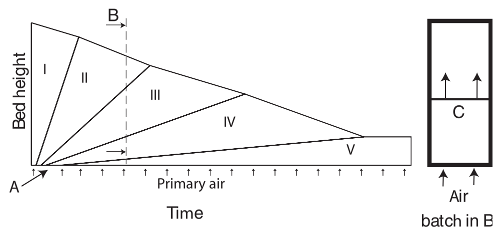


Illustration of Co-Current Combustion





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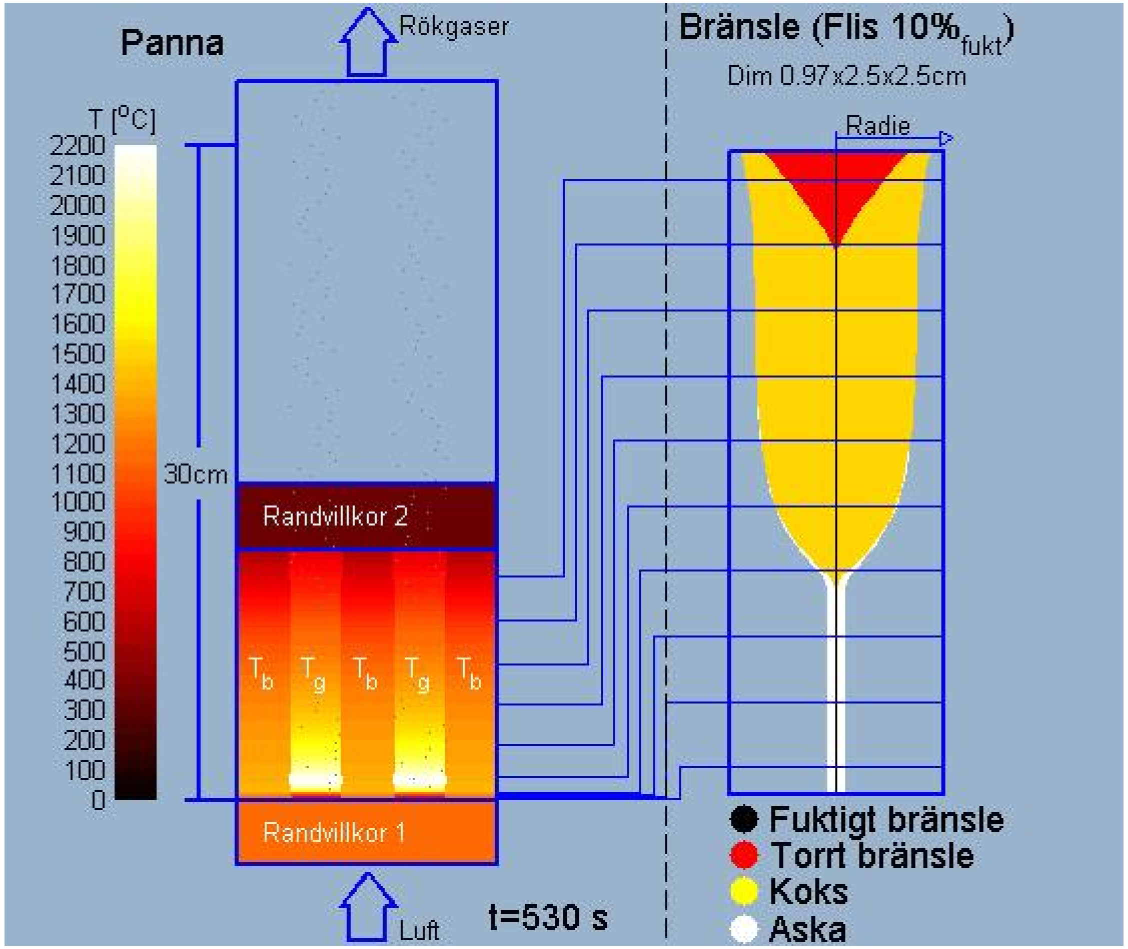


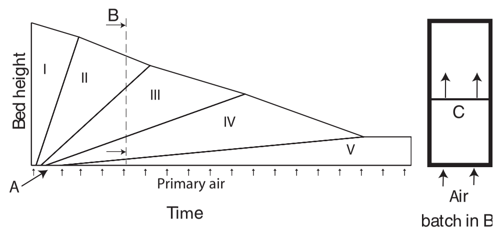
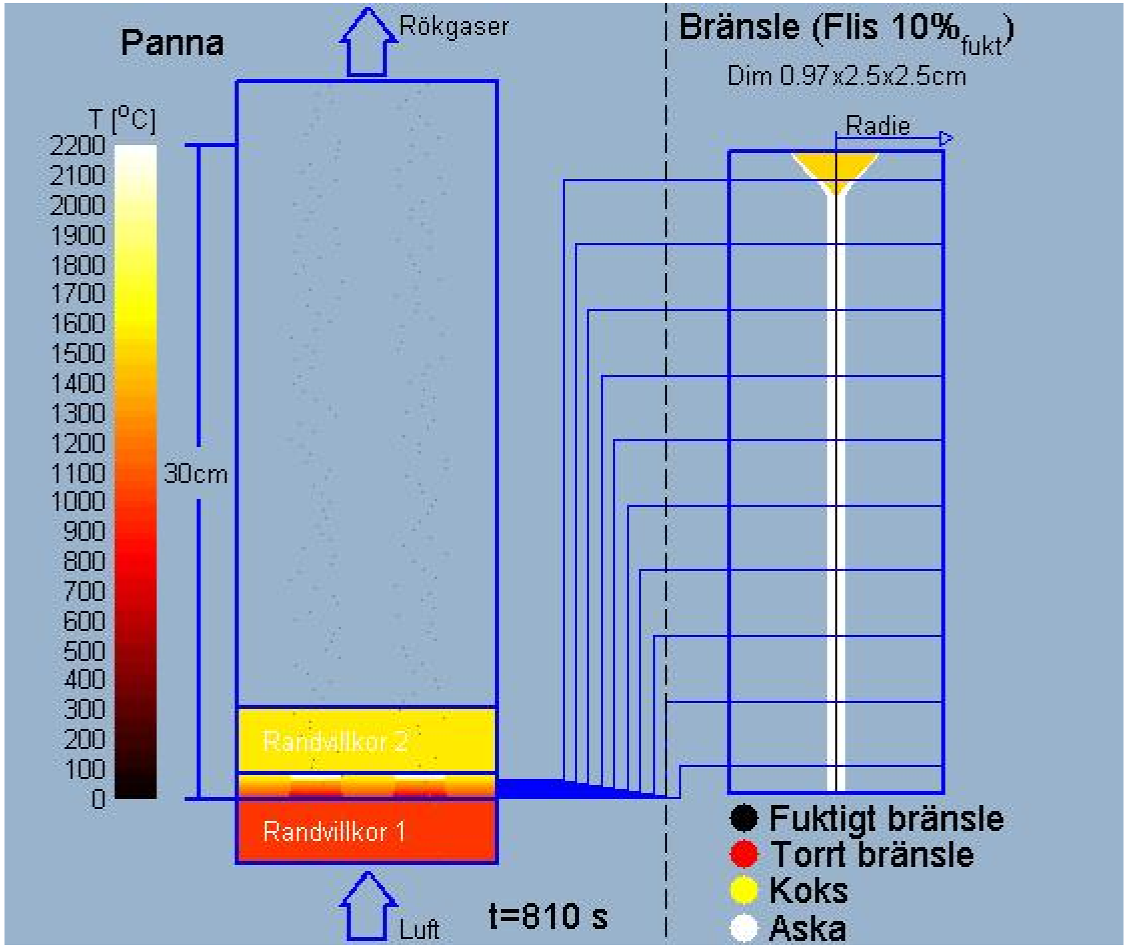
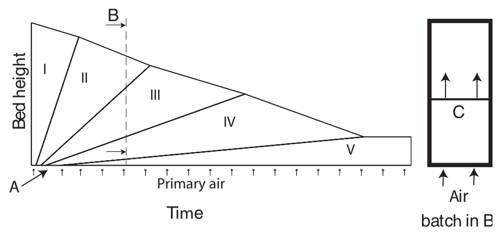
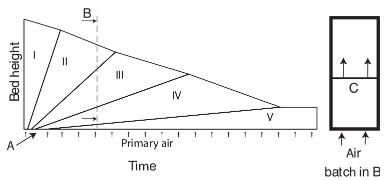


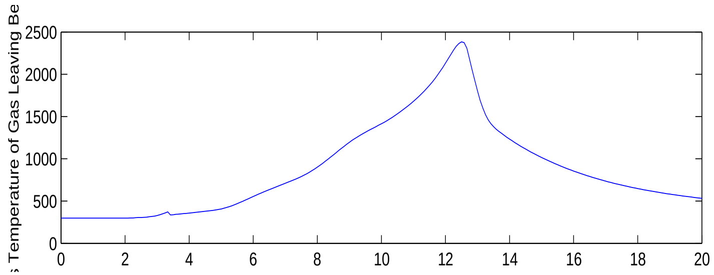
Illustration of Co-Current Combustion

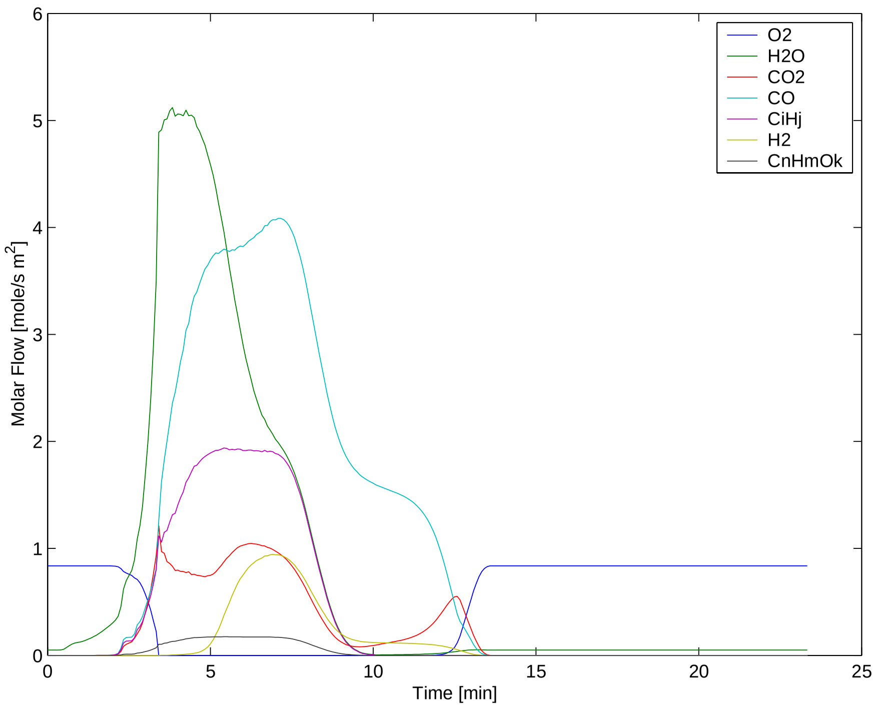




Gas Temperatures and Gas Composition



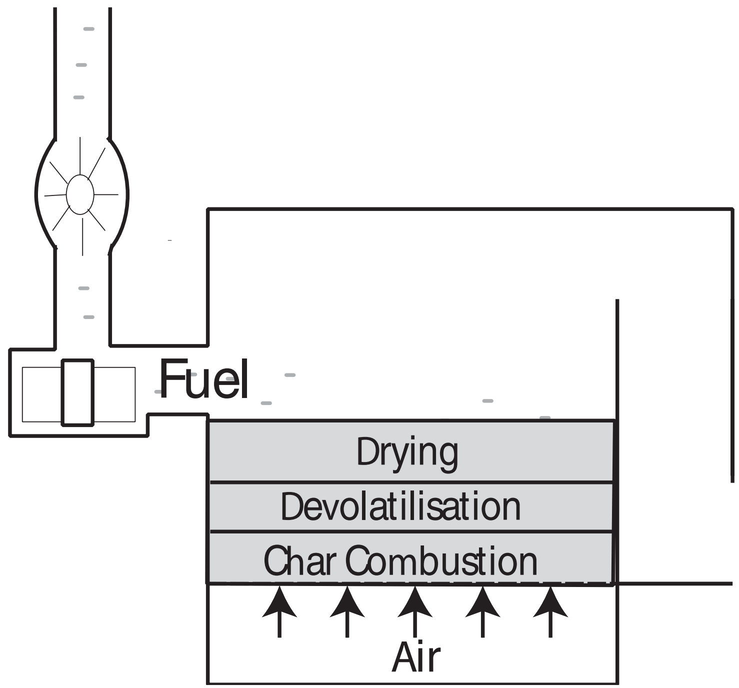




Summary

- Continuous combustion on a grate can be configured in basically three different ways (Fuel and air feed on same side, opposite side and perpendicular).
- The combustion can take place in two basically different ways, Co- and Counter-current.

A SIMPLE MODEL FOR CONVERSION RATE OF A FIXED BED OPERATING IN A CONTINIOUS CO-CURRENT MODE



A SIMPLE MODEL FOR CONVERSION RATE OF A FIXED BED OPERATING IN A CONTINIOUS CO-CURRENT MODE

Assuming:

ï Heat and mass transport inside the bed is dominated by convective heat flow

ï Bed contain of char, which is assumed to be pure carbon and ash

ï Char is converted to carbon dioxide

ï Fuel particles keep its size during conversion

ï Solid and gas have the same temperature

A SIMPLE MODEL FOR CONVERSION RATE OF A FIXED BED OPERATING IN A CONTINIOUS CO-CURRENT MODE

The consumption of oxygen and char and the production of carbon dioxide can be described by the following set of eqns

$$\frac{\partial U_g \rho_g Y_{O_2}}{\partial x} = -\varepsilon A_{eff} \rho_g k_{eff} Y_{O_2}$$

$$\frac{\partial U_g \rho_g Y_{CO_2}}{\partial x} = \varepsilon A_{eff} \rho_g k_{eff} Y_{O_2}$$

$$(1-\varepsilon)\frac{\partial u_s \rho_s X_C}{\partial x} = -\varepsilon A_{eff} \Omega \rho_g k_{eff} Y_{O_2}$$

A SIMPLE MODEL FOR CONVERSION RATE OF A FIXED BED OPERATING IN A CONTINIOUS CO-CURRENT MODE

The temperature of the gas and the solid fuel are given by:

$$\frac{\partial U_g c_{pg} \rho_g T_g}{\partial x} = \varepsilon A_{eff} h\left(T_s - T_g\right)$$

$$(1-\varepsilon)\frac{\partial u_s c_{ps} \rho_s T_s}{\partial x} = -\varepsilon A_{eff} h\left(T_s - T_g\right) + \varepsilon A_{eff} \Omega \rho_g k_{eff} Y_{O_2} \Delta H$$

where

$$A_{eff} = \frac{6(1-\varepsilon)}{d} \qquad \lambda = \frac{\Omega Y_{O_2 0} \rho_{g0} U_{g0}}{u_{s0} \rho_{s0} (1-\varepsilon)}$$

A SIMPLE MODEL FOR CONVERSION RATE OF A FIXED BED OPERATING IN A CONTINIOUS CO-CURRENT MODE

Boundary conditions are given the gas given on the end where the air enter, and for the fuel on the end the fuel enter

To solve the equations a temperature distribution along the height has to be assumed to make the reaction to take place.

A SIMPLE MODEL TO ESTIMATED THE LIMITATION OF THE PROPAGATION RATE OF THE REACTION FRONT IN A FIXED BED OPERATING IN A COUNTER-CURRENT MODE

For counter-current combustion radiation and diffusive heat flow make the ignition front to move against the gas flow, and the convective heat flow holds back the propagation of the conversion front.

Here, the interest is in the maximum possible velocity, and therefore the convection is neglected.

A SIMPLE MODEL TO ESTIMATED THE LIMITATION OF THE PROPAGATION RATE OF THE REACTION FRONT IN A FIXED BED OPERATING IN A COUNTER-CURRENT MODE

The radiation and heat conduction are modelled by an effective thermal conductivity

$$k_{eff} = 4\varepsilon\sigma d_s T^3 + (1-\varepsilon)k_s$$

A SIMPLE MODEL TO ESTIMATED THE LIMITATION OF THE PROPAGATION RATE OF THE REACTION FRONT IN A FIXED BED OPERATING IN A COUNTER-CURRENT MODE

The heat flux across the reaction front must be equal to or smaller than the energy contained in the fuel entering the front. If the thickness of the reaction front is x, this gives,

$$\frac{k_{eff,\max}}{x}\left(T_{ad}-T_0\right)\leq u_s H\rho_s\left(1-\varepsilon\right)$$

The width of the reaction front is estimated by the drying time t of the particles

$$x=u_s t$$

A SIMPLE MODEL TO ESTIMATED THE LIMITATION OF THE PROPAGATION RATE OF THE REACTION FRONT IN A FIXED BED OPERATING IN A COUNTER-CURRENT MODE

The maximum velocity of the reaction front is now obtained

$$u_s = \sqrt{\frac{k_{eff,\max}\left(T_{ad} - T_0\right)}{H\rho_s\left(1-\varepsilon\right)t}}$$

A SIMPLE MODEL TO ESTIMATED THE LIMITATION OF THE PROPAGATION RATE OF THE REACTION FRONT IN A FIXED BED OPERATING IN A COUNTER-CURRENT MODE

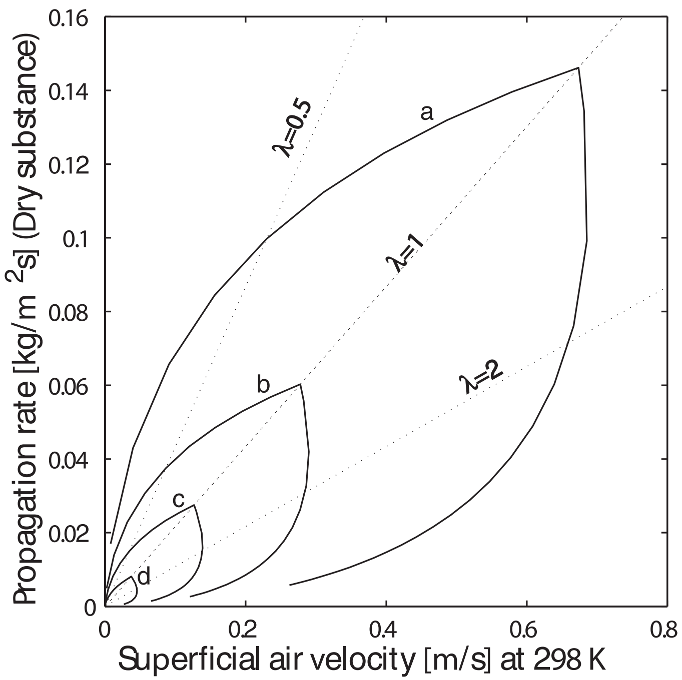
The radiative heat flux, received by the surface of the particle, is transported to the drying front within the particle by thermal diffusion, and The adiabatic temperature is calculated from the air to fuel ratio.

$$\sigma\left(T_{ad}^4 - T_s^4\right) = \frac{2k_s}{d_s - d_m}\left(T_s - T_b\right) = -\frac{dd_m/2}{dt}\rho_s \frac{X_m}{1-X_m}\frac{1}{M_{H2O}}\left(H_{vap} + \int_{T_0}^{T_s} c_{p,H2O}\,dT\right)$$

The drying time is then:

$$t = -\int_{d_{p,m}}^{0} \frac{X_m}{1-X_m}\frac{\rho_s}{M_{H2O}}\left(H_{vap} + \int_{T_0}^{T_s} c_{p,H2O}\,dT\right)\frac{d_s - d_m}{4k_s\left(T_s - T_b\right)}\,dd_m$$

A SIMPLE MODEL TO ESTIMATED THE LIMITATION OF THE PROPAGATION RATE OF THE REACTION FRONT IN A FIXED BED OPERATING IN A COUNTER-CURRENT MODE



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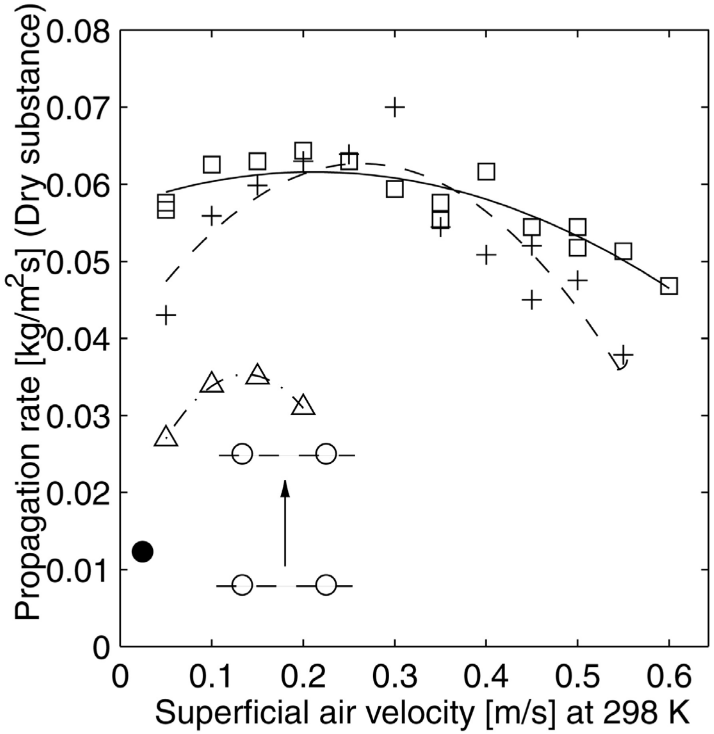

30mm wood cubes, 10%moisture (Δ)
10mm wood cubes, 10% moisture (+)
10 mm wood cubes, 30% moisture (□)
Forest waste 43.6% moisture (o)
Forest waste 56.6% moisture (•)

A SIMPLE MODEL TO ESTIMATED THE LIMITATION OF THE PROPAGATION RATE OF THE REACTION FRONT IN A FIXED BED OPERATING IN A COUNTER-CURRENT MODE

This evaluation shows on limitations for the propagation of a reaction front in counter-current combustion case.