

Combustion and gasification of alternative fuels

Dariusz Kardaś

ERCOFTAC Spring Festival

Gdańsk, 12-13 may 2011

Department of Renewable Energy

- Dariusz Kardaś
- Tomasz Ochrymiuk
- Sylwia Polesek- Karczewska
- Izabela Wardach-Święcicka
- Tomasz Kamiński
- Jacek Kluska
- Marek Klein
- Tomasz Turzyński

Subjects of interests

Numerical
methods

Combustion of coal and
biomass mixture

- Combustion of biomass
- Gasification of biomass
- Gasification of wastes

Experimental
investigation

Boiler fired fossil fuel

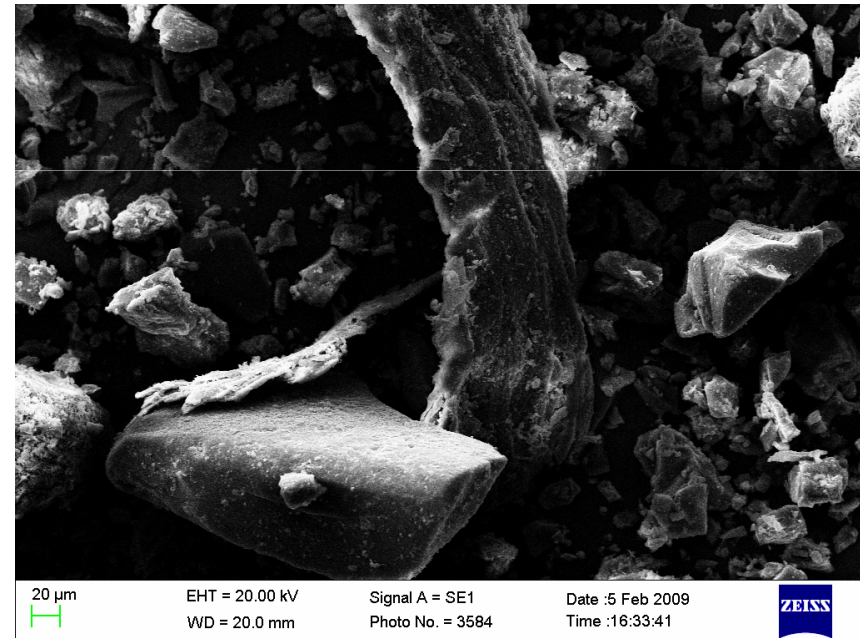
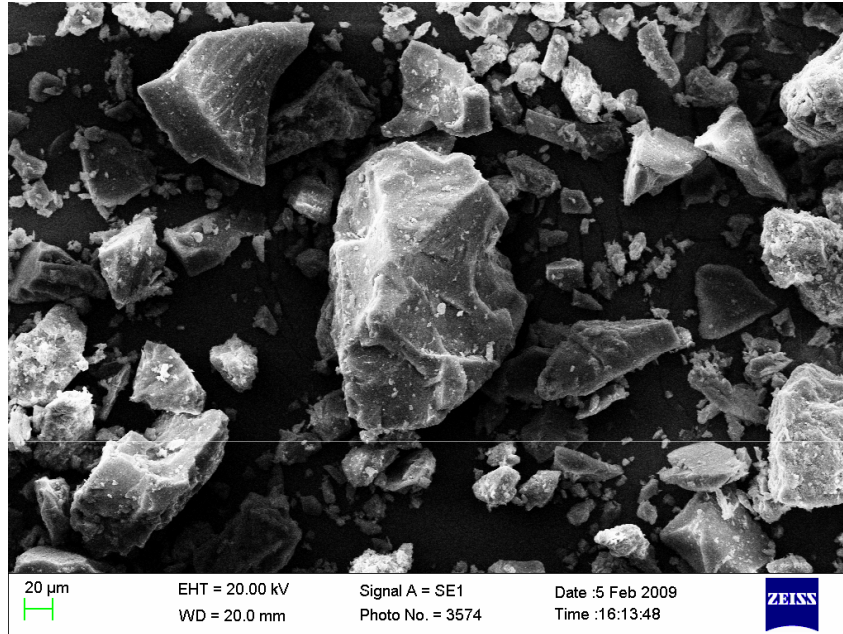
Medium power boiler 200 MW
8 burners for powered coal
4 coal mills
30 tons of fuel



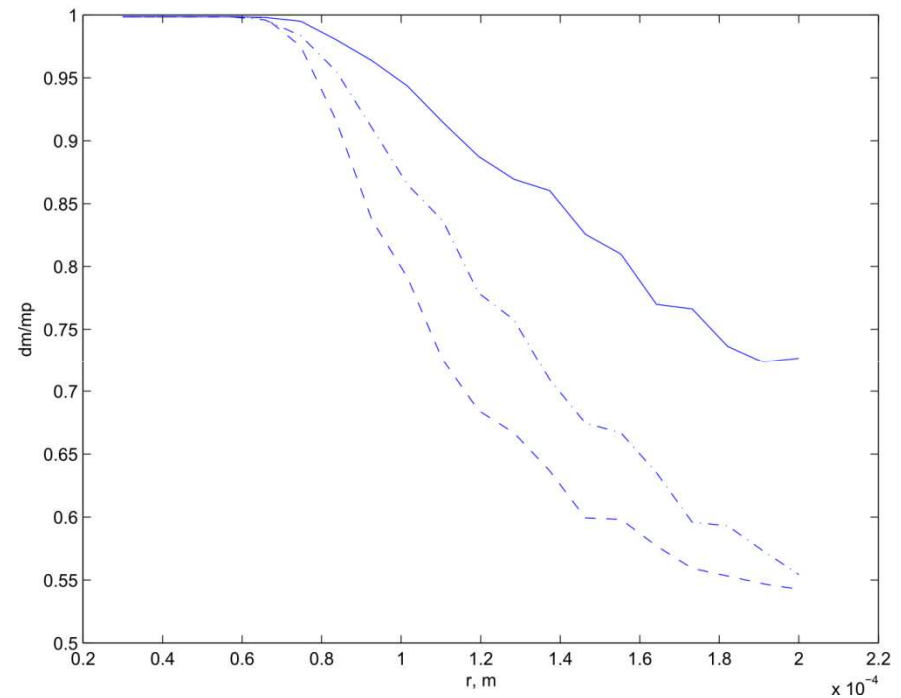
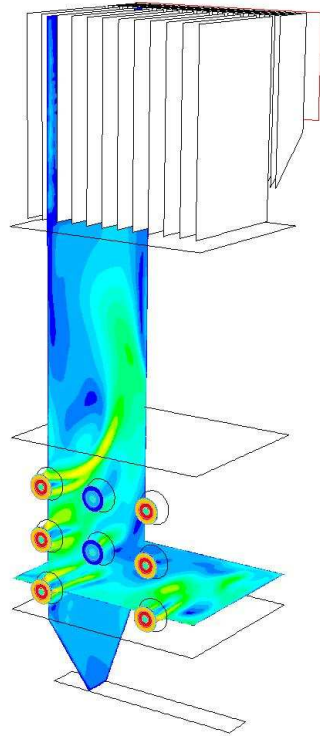
	Coal	Wood
Ash, Ya	20.3	0.4
Volatiles, Yvol	23.3	82.6
Coke, Yc	56.4	17.0
Heating value, MJ/kg	22.32	16

CO₂ reduction of emmision
6-10% biomass in fuel
-Lower efficiency
-Deposits on the heaters and walls
-Higher content of comustible parts

Coal and biomass



Coal and biomass combustion modelling



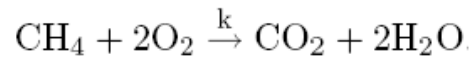
- Residence time of wood particles in a combustion chamber is shorter than coal one

CHEMICAL EQUILIBRIUM – METHANE COMBUSTION

Table. Methane combustion, lean and rich mixture, T=1000K, P=1013hPa.

	obliczenia	dane	błąd	obliczenia	dane	błąd
FUEL	$3,31 \times 10^{-1}$	$3,30 \times 10^{-1}$	$6,07 \times 10^{-4}$	$6,67 \times 10^{-1}$	$6,67 \times 10^{-1}$	$6,01 \times 10^{-4}$
OXYGEN	$6,69 \times 10^{-1}$	$6,70 \times 10^{-1}$	$6,07 \times 10^{-4}$	$3,33 \times 10^{-1}$	$3,33 \times 10^{-1}$	$6,01 \times 10^{-4}$
CH ₄	$4,05 \times 10^{-23}$	0	$4,05 \times 10^{-26}$	$2,02 \times 10^{-1}$	$6,23 \times 10^{-1}$	$1,39 \times 10^{-1}$
CO	$7,93 \times 10^{-6}$	$1,98 \times 10^{-10}$	$7,93 \times 10^{-6}$	$2,14 \times 10^{-1}$	$2,87 \times 10^{-1}$	$7,28 \times 10^{-2}$
CO ₂	$3,32 \times 10^{-1}$	$3,30 \times 10^{-1}$	$2,06 \times 10^{-3}$	$4,15 \times 10^{-2}$	$2,57 \times 10^{-2}$	$1,58 \times 10^{-2}$
H ₂ O	$6,64 \times 10^{-1}$	$6,60 \times 10^{-1}$	$4,13 \times 10^{-3}$	$8,34 \times 10^{-2}$	$3,66 \times 10^{-2}$	$4,68 \times 10^{-2}$
H ₂	$2,41 \times 10^{-7}$	$5,7 \times 10^{-10}$	$2,41 \times 10^{-7}$	$4,28 \times 10^{-1}$	$5,89 \times 10^{-1}$	$1,60 \times 10^{-1}$
O ₂	$8,26 \times 10^{-3}$	$1,0 \times 10^{-2}$	$1,74 \times 10^{-3}$	$3,78 \times 10^{-2}$	$2,88 \times 10^{-23}$	$3,78 \times 10^{-2}$
Δ _C	0,35%	-	-	0,48%	-	-
Δ _H	0,18%	-	-	0,41%	-	-
Δ _O	0,26%	-	-	0,46%	-	-

The comparison of the results from the equilibrium state with the numerical analysis results including the kinetics of the chemical reaction:



$$k(T) = AT^b \exp\left(-\frac{E_A}{R_u T}\right)$$

$$\frac{d[\text{CH}_4]}{dt} = -k[\text{CH}_4][\text{O}_2]^2$$

$$\frac{d[\text{O}_2]}{dt} = -2k[\text{CH}_4][\text{O}_2]^2$$

$$\frac{d[\text{CO}_2]}{dt} = k[\text{CH}_4][\text{O}_2]^2$$

$$\frac{d[\text{H}_2\text{O}]}{dt} = 2k[\text{CH}_4][\text{O}_2]^2$$

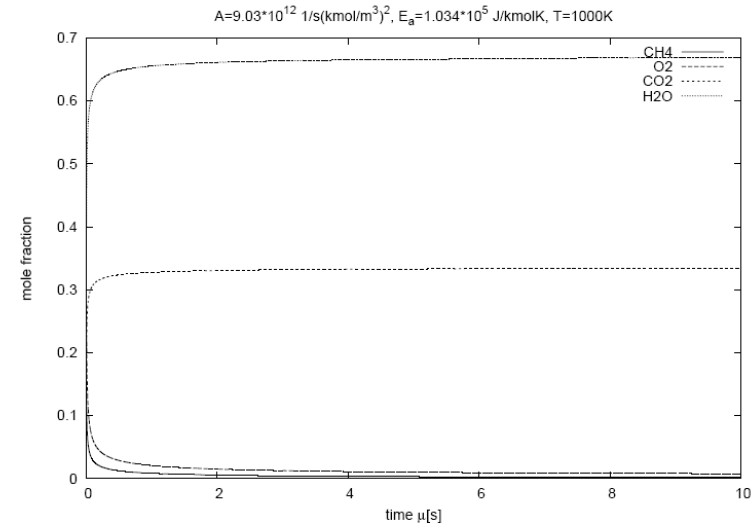


Fig. Methane combustion lean mixture, Runge-Kutta method T=1000K, P=1013hPa.

CHEMICAL EQUILIBRIUM – PYROLYSIS OF SOLID FUELS

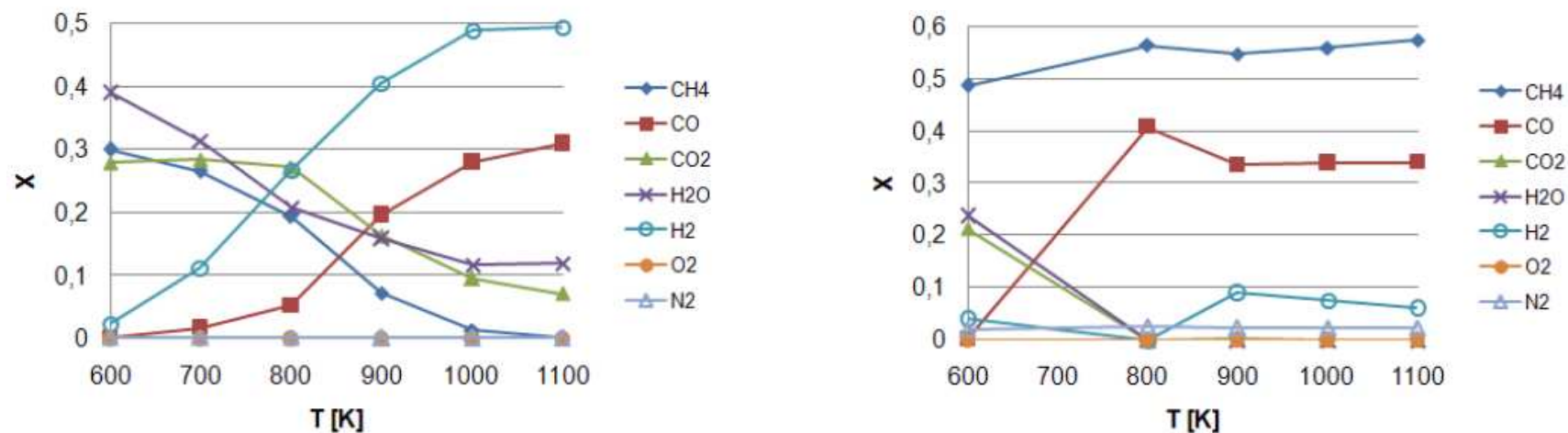


Fig. 2. Pyrolysis of solid fuels: a) pine sheed shells, b) carbon, $P=1013\text{hPa}$.

Table. The comparison of the results from the equilibrium state with the numerical analysis results from the FLUENT; combustion of pyrolitic gas released from pine sheed shells: a) rich mixture, 190-equations model, 57 components, $T_{\text{pyrolyzy}} = 900\text{K}$,

b) lean mixture, 5-and 6-equations model, $T_{\text{pyrolyzy}} = 600\text{K}$.

model	methane	stan równowagowy	model	5-równaniowy	stan równowagowy	5-równaniowy + H ₂	stan równowagowy
T[K]	1171,37		T[K]	1450.05		1469.46	
CH ₄	$2,675 \times 10^{-4}$	$6,010 \times 10^{-5}$	CH ₄	6.250×10^{-9}	3.178×10^{-30}	4.522×10^{-9}	4.773×10^{-30}
O ₂	$1,689 \times 10^{-16}$	$1,083 \times 10^{-17}$	O ₂	1.285×10^{-1}	1.206×10^{-1}	1.269×10^{-1}	1.067×10^{-1}
CO ₂	$8,944 \times 10^{-2}$	$8,267 \times 10^{-2}$	CO ₂	7.299×10^{-2}	1.136×10^{-1}	7.300×10^{-2}	7.315×10^{-2}
CO	$2,394 \times 10^{-1}$	$2,428 \times 10^{-1}$	CO	7.234×10^{-5}	5.601×10^{-7}	6.804×10^{-5}	7.956×10^{-7}
H ₂ O	$1,773 \times 10^{-1}$	$1,645 \times 10^{-1}$	H ₂ O	1.245×10^{-1}	8.123×10^{-2}	1.277×10^{-1}	1.278×10^{-1}
N ₂	$1,369 \times 10^{-1}$	$1,386 \times 10^{-1}$	N ₂	6.723×10^{-1}	6.845×10^{-1}	6.723×10^{-6}	6.923×10^{-1}
H ₂	$3,567 \times 10^{-1}$	$3,713 \times 10^{-1}$	H ₂	-	2.836×10^{-8}	0	4.637×10^{-7}
			NO	5.735×10^{-8}	-	8.013×10^{-8}	-
			He	1.588×10^{-3}	-	4.149×10^{-6}	-

BIOMASS GASIFICATION – results from the equilibrium state analysis

T,K	CH ₄	CO	CO ₂	H ₂ O	H ₂	N ₂	C ₂ H ₂	C ₂ H ₄	C ₂ H ₆
623	14.61	0.02	20.29	56.53	2.12	4.44	0	0	0
723	9.33	7.15	17.06	53.22	9.93	3.32	0	0	0
823	4.41	4.74	31.51	35.53	21.87	1.92	0	0	0
923	0.69	8.87	17.19	31.91	38.31	3.04	0	0	0
1023	0.09	14.92	11.77	31.31	38.43	2.47	0	0	0
1123	0.01	13.18	13.49	30.58	40.29	2.45	0	0	0
1223	0	16.66	9.83	34.10	36.94	2.47	0	0	0
1323	0	18.60	7.80	36.39	34.74	2.47	0	0	0

Fig. Gasification of wood chips, air gasification.

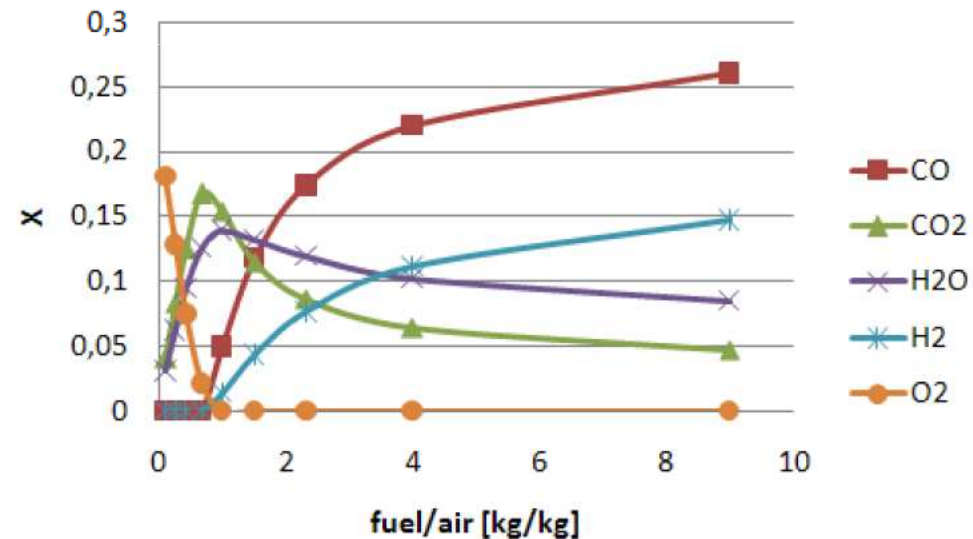
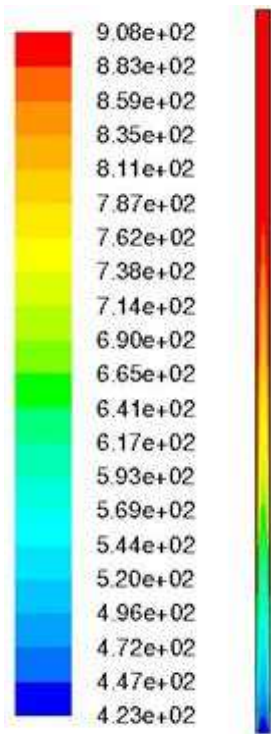


Fig. Combustion of syngas with different fuel to air ratio, T=1537K

MODELLING OF COMBUSTION OF SINGLE COAL PARTICLE

NUMERICAL SIMULATIONS - FLUENT Heating chanel



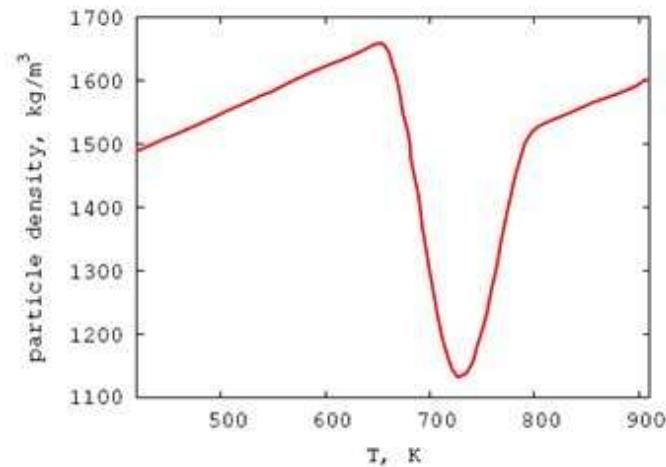
Rys. Temperatute of air

Initial conditions

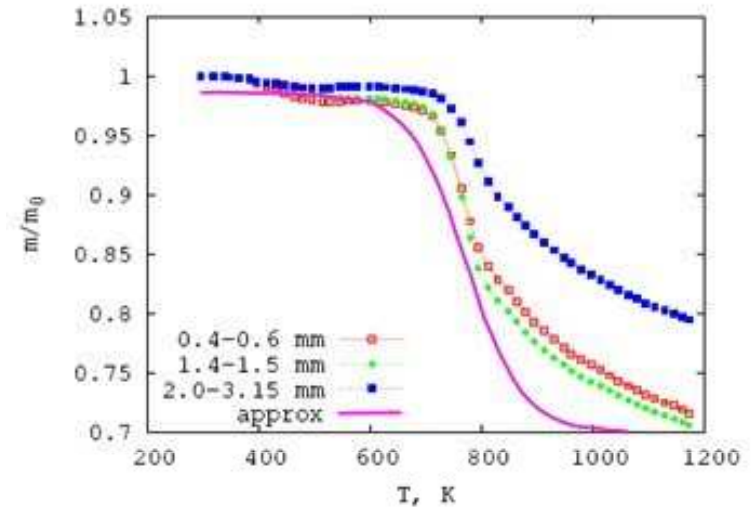
$$T_{\text{fuel}} = 373\text{K}$$

$$T_{\text{air}} = 473\text{K}$$

Experimental data (IChPW Zabrze)



Rys. Coal density



Rys. Particle mass

MODELLING OF COMBUSTION OF SINGLE COAL PARTICLE

Case 01

- Heating
- Standard devolatilization model

Case 02

- Heating
- Mass and density changes (UDF)



$$d_2 = 70 \times 10^{-6} \text{ m}$$

$$d_3 = 140 \times 10^{-6} \text{ m}$$

$$d_4 = 180 \times 10^{-6} \text{ m}$$

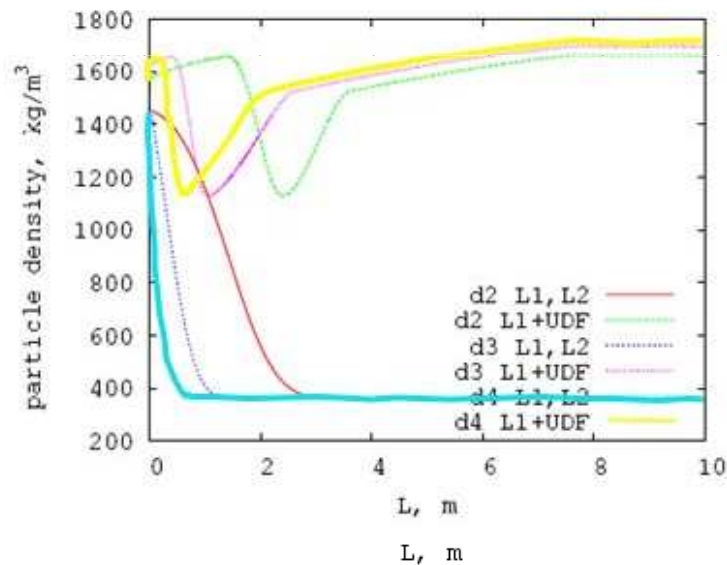


Fig. Particle density – case 01 i case 02

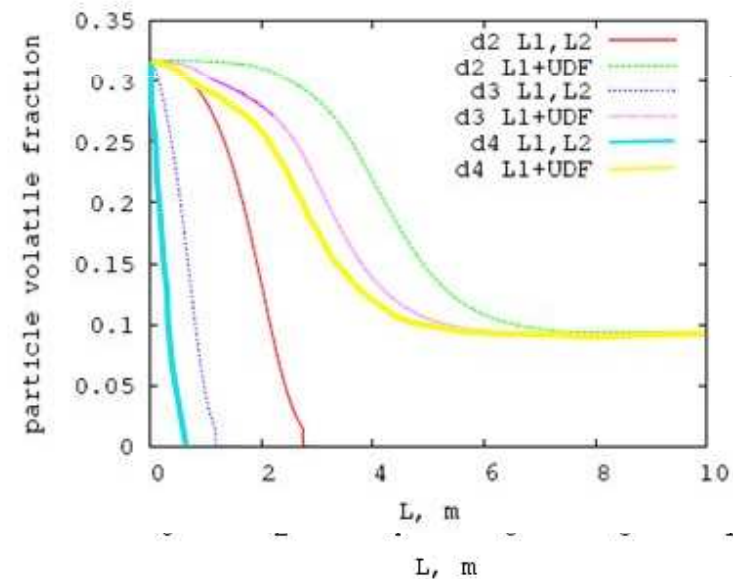
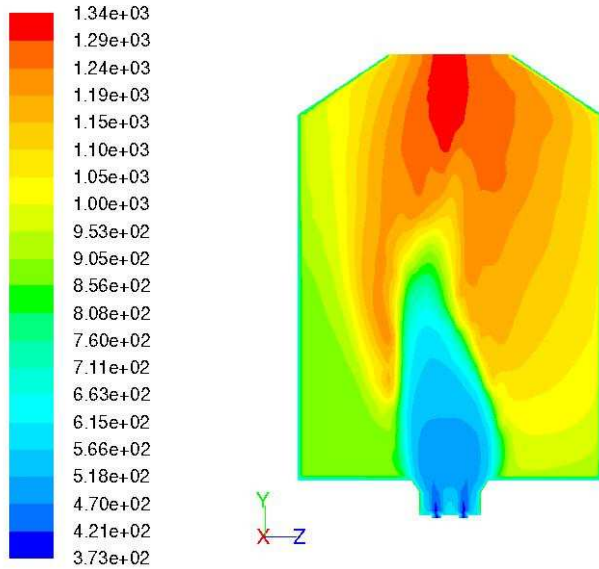
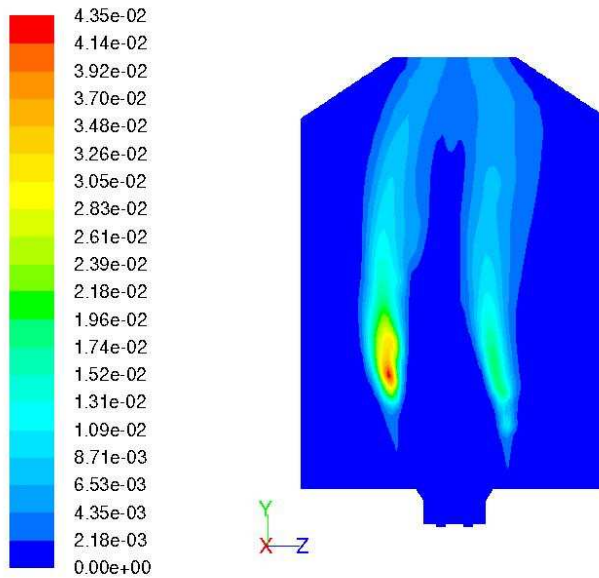
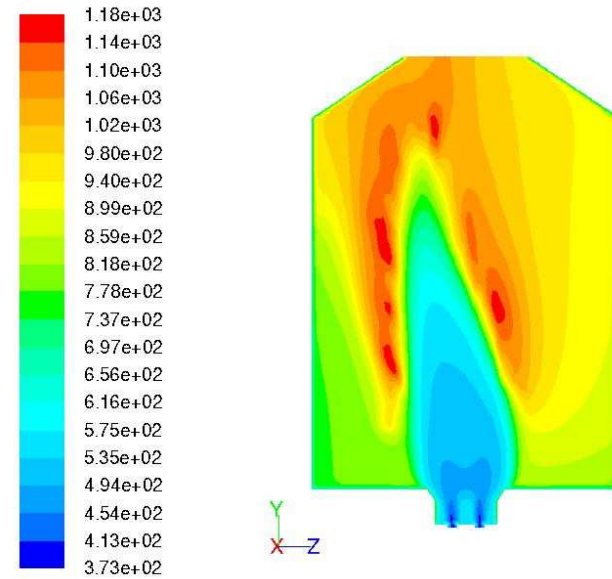


Fig. Particle volatile fraction – case 01 i case 02

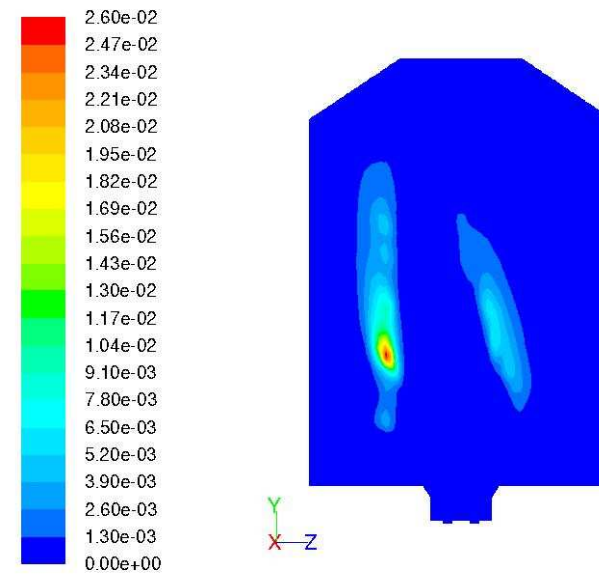
Numerical simulation 3D – coal combustion



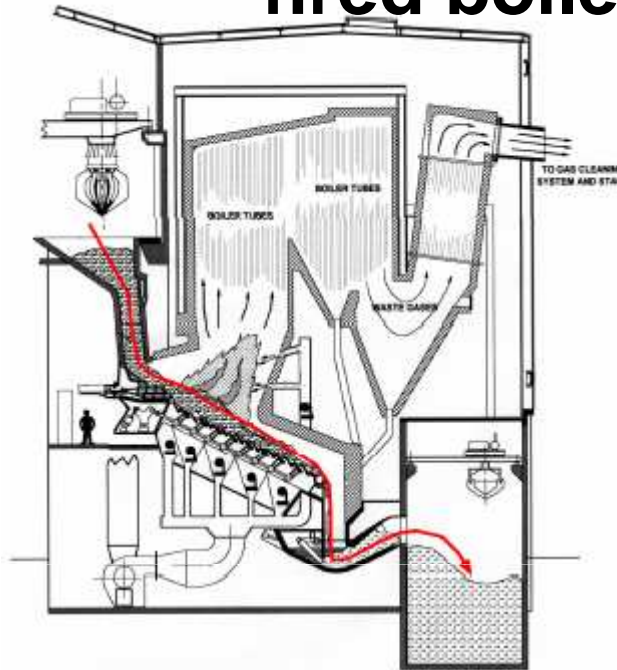
Rys. Temperature field;
left – standard model,
right – UDF (variable density)



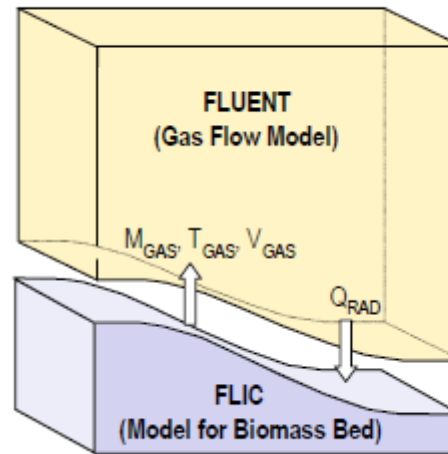
Rys. CO mole fraction;
left – standard model,
right – UDF (variable density)



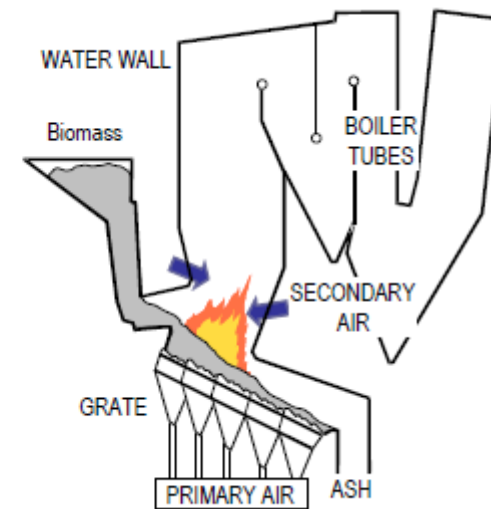
Syngas combustion in a stoker-fired boiler



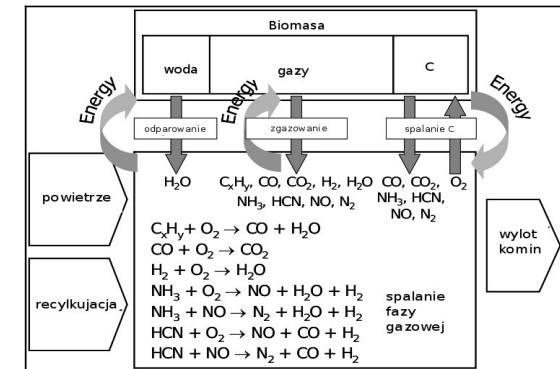
Burning or gasifying bed



Fluent/FLIC* model integration for biomass bed/gas phase interaction



- ❑ **The objective** – simultaneous simulation of waste combustion and gas flow field considering their heat and mass interaction
- ❑ **Calculation procedure:** Iterative calculation of FLIC and FLUENT
 - ✓ FLIC->FLUENT: Gas properties leaving the bed as input conditions of the inlet
 - ✓ FLUENT->FLIC: Radiation profile along the bed as boundary condition on the top of the bed
 - ✓ Convergence criterion: changes in radiation or in the gas temperature
 - ✓ Gas phase combustion calculation – GRI-MECH full or reduced model



* Bed Modelling Programme for Waste Incinerator – Sheffield University (J.Swithenbank team)

Syngas combustion in a stoker-fired boiler

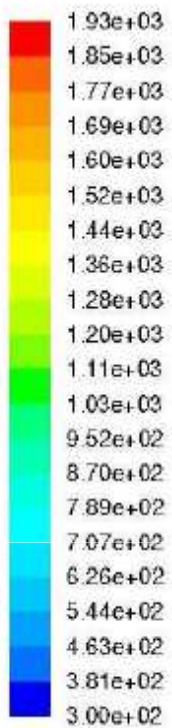


Fig. Temperature field, reduced Grimech

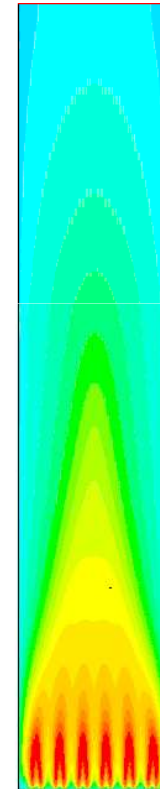
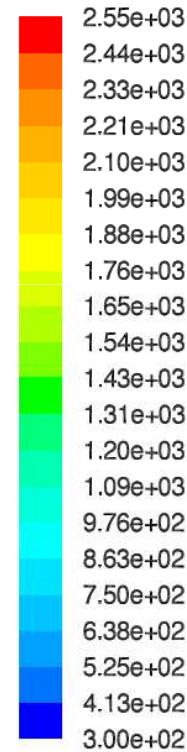
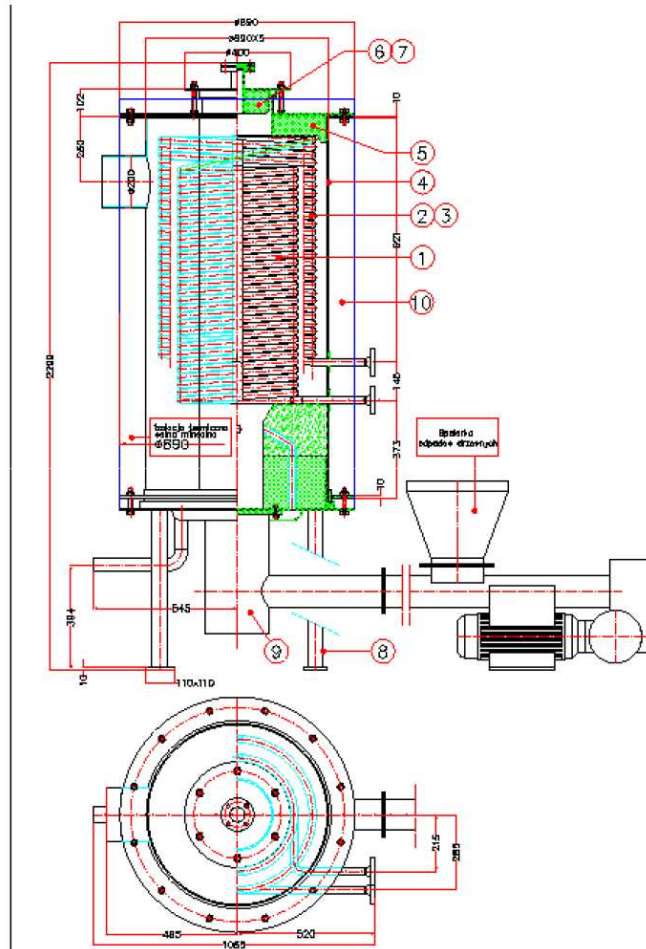


Fig. Temperature field, reduced syngas combustion model

Small biomass fired boiler

Experimental stand



Biomass combustion in a small scale boiler 25kW

Basic assumptions:

- rate of wood pyrolysis in a function
 1. the difference between the present pyrolysis stage and the equilibrium one
 2. the pyrolysis rate constant (experiments)
- equilibrium pyrolytic gas composition (mixture Gibbs chemical potential)
- different gas combustion models:
 1. Saxena-Wiliams 35 eqns
 2. Grimech 150 eqns
 3. Pressumed PDF 2 eqns (mixture fraction and mixture fraction variance)

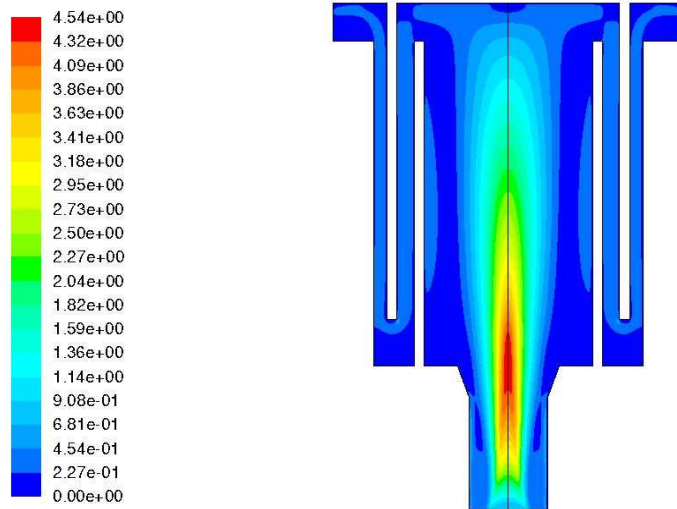


Fig. Velocity field

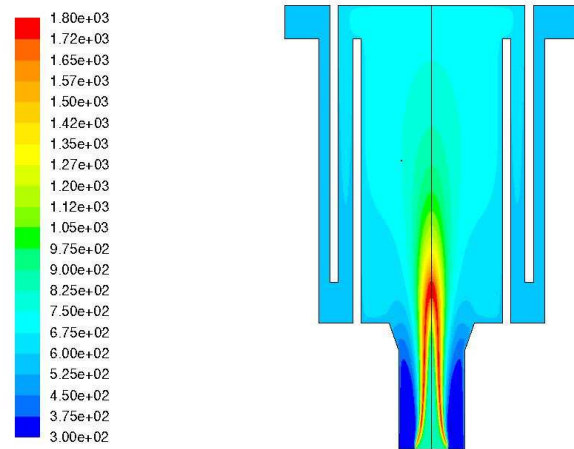


Fig. Temperature field

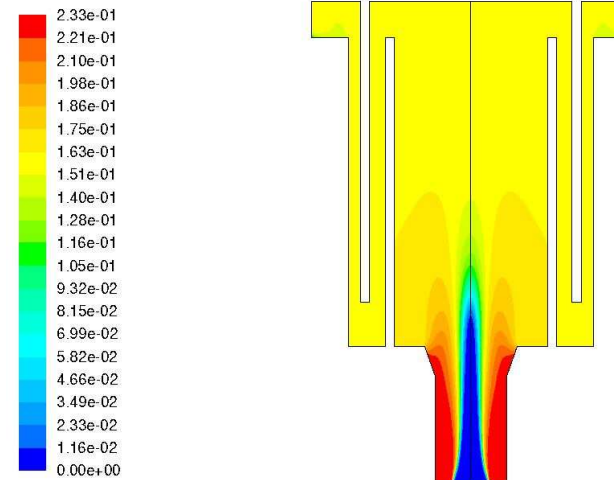


Fig. Mass fraction of O₂

OD - CALCULATION OF HEAT TRANSFER IN BIOMASS BIOLER

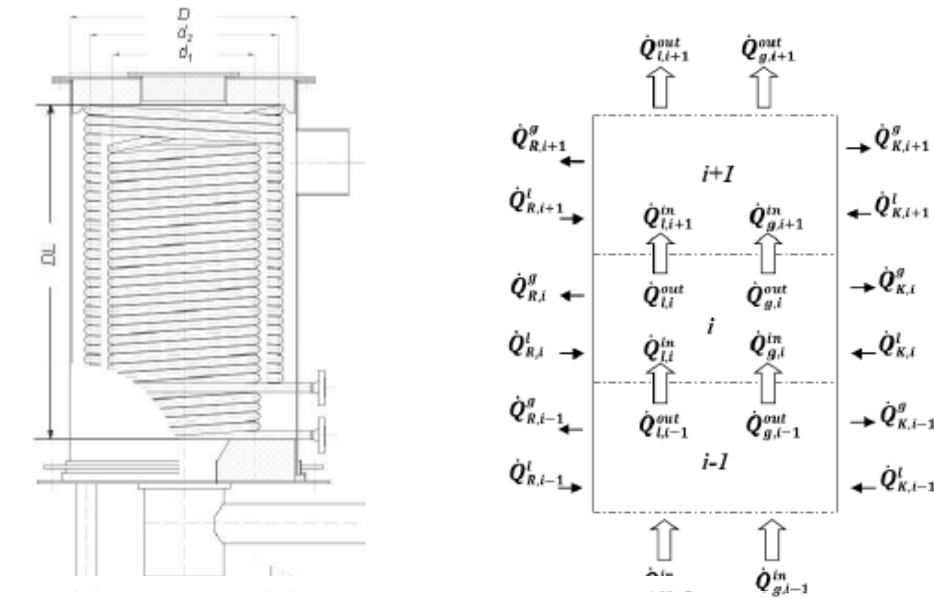


Fig. A) Bioler zoning,
B) single zone heat balance

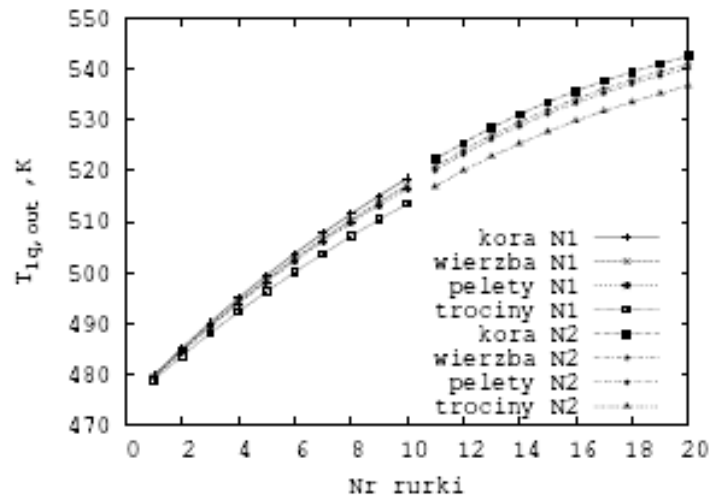


Fig. Oil output temperature for different types of fuels

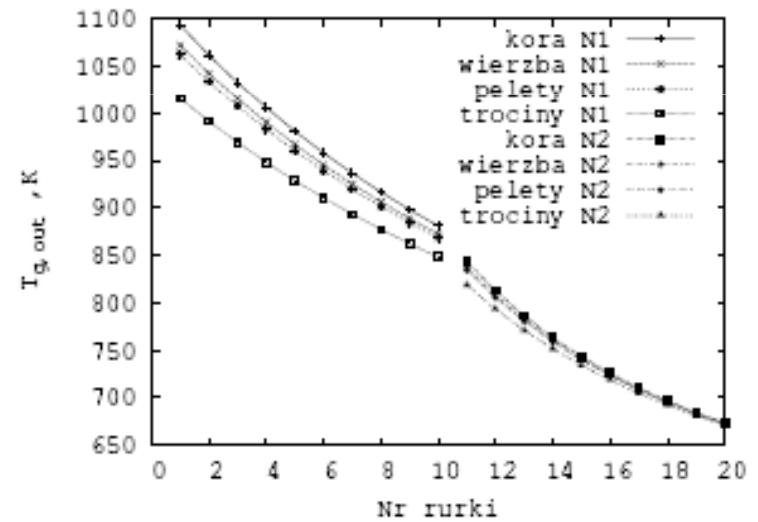
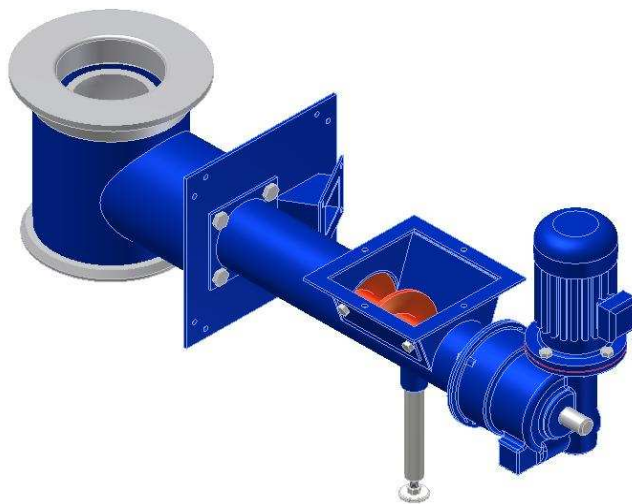
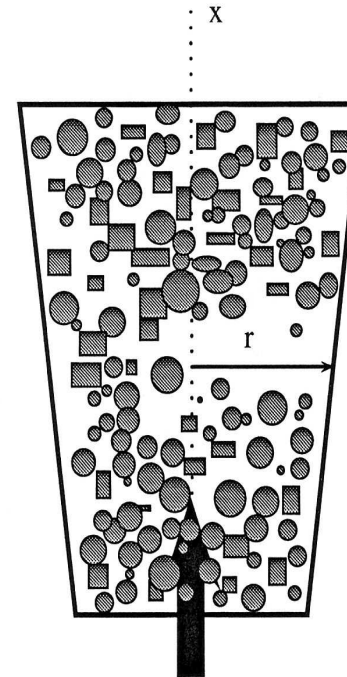


Fig. Exhaust gas temperature for different types of biomass

Pellets burner



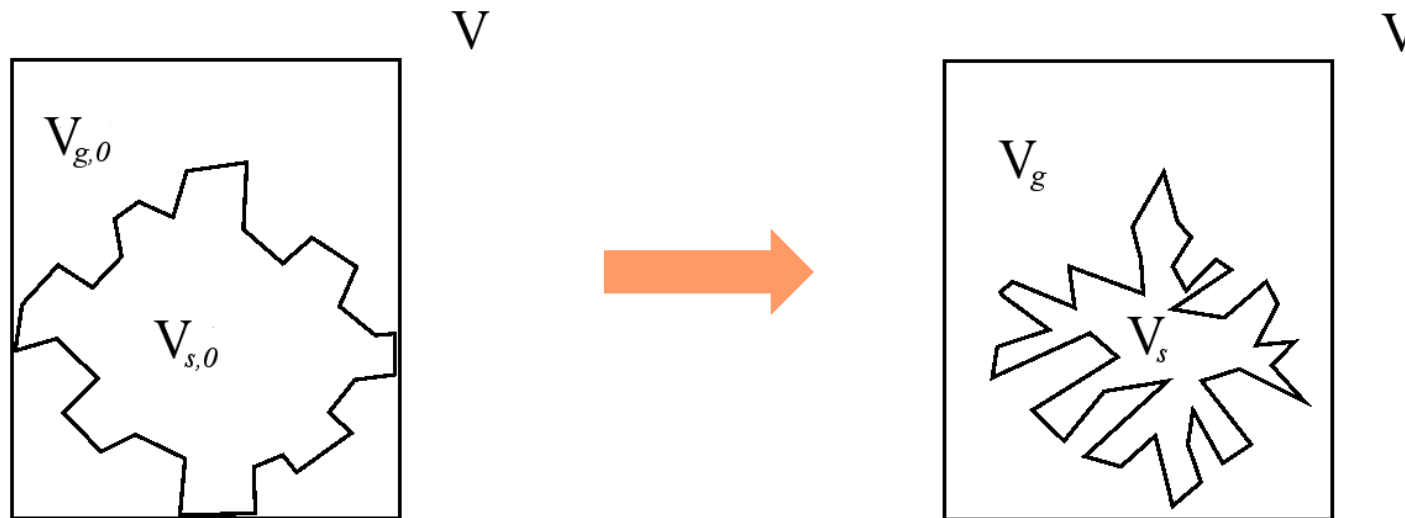
Retort pellets burner



Scheme of pellets burner

Modelling of devolatilisation in a retort burner

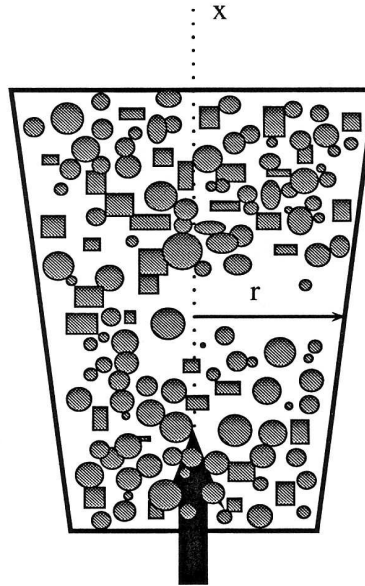
Physico-chemical processes



- moisture evaporation
- fuel pyrolysis (devolatilisation)
- combustion of gases from pyrolysis
- combustion of char

Mathematical model

Fig. Model scheme.



Solid phase

$$(s1) \quad \frac{\partial \varepsilon_s \rho_s}{\partial t} + \frac{1}{A} \frac{\partial \varepsilon_s \rho_s v_s A}{\partial x} = -W_\pi$$

Gas phase

$$\frac{\partial \varepsilon_g \rho_g}{\partial t} + \frac{\partial \varepsilon_g \rho_g v_g}{\partial x} = W_\pi \quad (g1)$$

$$\frac{\partial \varepsilon_g \rho_g v_g}{\partial t} + \frac{\partial \varepsilon_g \rho_g v_g^2}{\partial x} = -\frac{\partial \varepsilon_g p_g}{\partial x} - \frac{\mu_g \varepsilon_g v_g}{k} \quad (g2)$$

$$(s3) \quad \frac{\partial \varepsilon_s \rho_s u_s}{\partial t} = -\frac{\partial \varepsilon_s q_s}{\partial x} - W_\pi Q_\pi - a\alpha(T_s - T_g)$$

$$\frac{\partial \varepsilon_g \rho_g u_g}{\partial t} + \frac{\partial \varepsilon_g \rho_g v_g u_g}{\partial x} = -\varepsilon_g p_g \frac{\partial v_g}{\partial x} + W_\pi Q_\pi + a\alpha(T_s - T_g) \quad (g3)$$

Mathematical model – closing equations

Solid phase

$$\rho_s = \rho_s(T_s)$$

$$u_s = u_s(T_s)$$

$$q_s = -\lambda_s \frac{\partial T_s}{\partial x}$$

Gas phase

$$\rho_g = \rho_g(T_g, p_g)$$

$$u_g = u_g(T_g, p_g)$$

$$k = k(\varepsilon_g, d)$$

$$W_\pi = W_\pi\left(T_s, \frac{\partial T_s}{\partial t}\right)$$

$$a = a(\varepsilon_s, d)$$

$$\alpha = \alpha(v_g, \mu_g, \lambda_g, d)$$

$$\varepsilon_g + \varepsilon_s = 1$$

Simplified model – solid phase

$$\rho_s \frac{d\varepsilon_s}{dx} + \varepsilon_s \frac{d\rho_s}{dT} \frac{dT}{dx} = -\frac{W_\pi A}{\dot{V}}$$

$$\varepsilon_s \rho_s \frac{du_s}{dT} \frac{dT}{dx} + \frac{A}{\dot{V}} \frac{dq}{dx} = \frac{W_\pi Q_\pi A}{\dot{V}}$$

$$q = -\lambda_s \frac{\partial T}{\partial x}$$

$$k = A_r e^{\left(-\frac{E_a}{RT}\right)}$$

$$\rho_s(T) = \begin{cases} 650 & \text{for } T = 100^\circ\text{C} \\ 500 & \text{for } T = 1000^\circ\text{C} \end{cases}$$

$$c_{p,s}(T) = 0.1031 + 0.003867 T$$

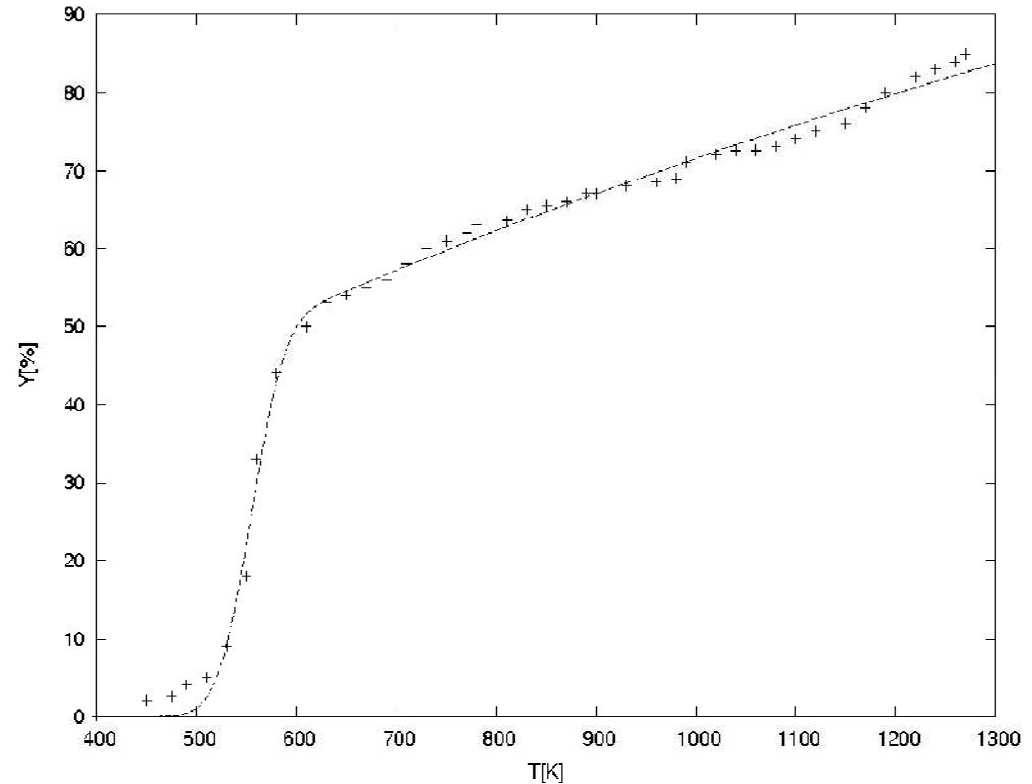


Fig. Experimental data for devolatilisation of pine cones,
A. Demirbas, *Prog Energy Combust Sc* 30, 2004.

$$Z_e = 1 - w(T)$$

$$w(T) = \frac{d\sqrt{T} - a}{2} \left(1 + \operatorname{erf} \left(\frac{T - b}{\sqrt{2c}} \right) \right), \quad T \in \langle 400, 1300 \rangle \text{K}$$

Simplified model – results

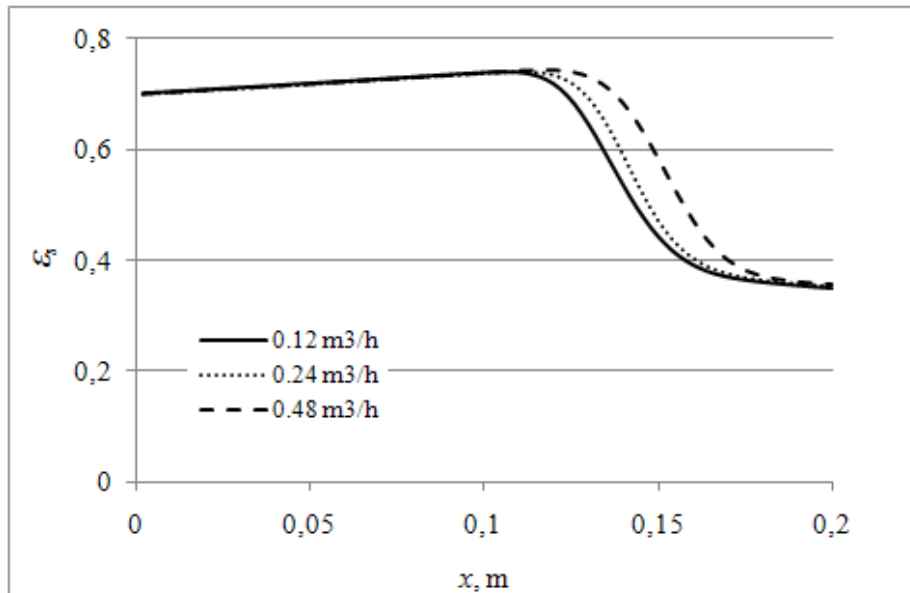


Fig. Change of volume fraction of fuel along the burner for various volumetric flowrate.

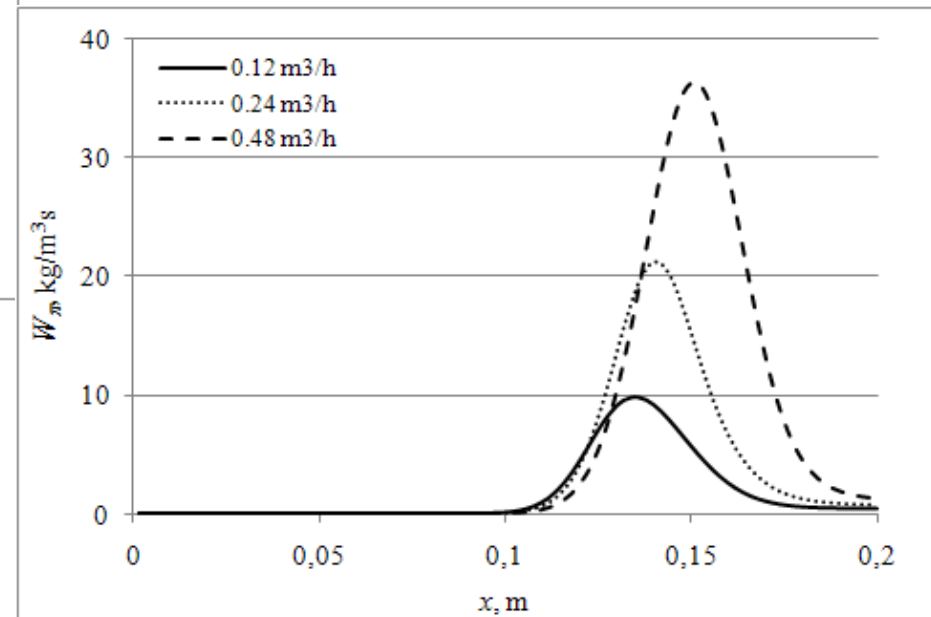
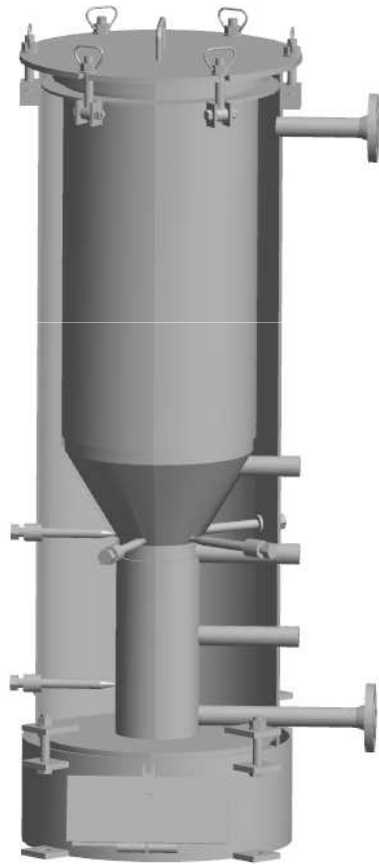


Fig. Distribution of pyrolytic gas generation along the burner for various volumetric flowrate.

Experimental investigation of biomass gasification (first steps)



- The main body of gasifier is made from a carbon steel pipe. In the central part of gasifier the cone with refractory cement is located.
- The cone is inclined at 60° to the horizontal to provide smooth gravitational movement of the wood to the combustion zone.
- The air is supplied to the gasification zone through the three nozzles, which are situated near the bottom of the cone.
- Biomass is supplied through the hatch located at the top of gasifier.





Problems with tars ...



... and throat and grate contraction

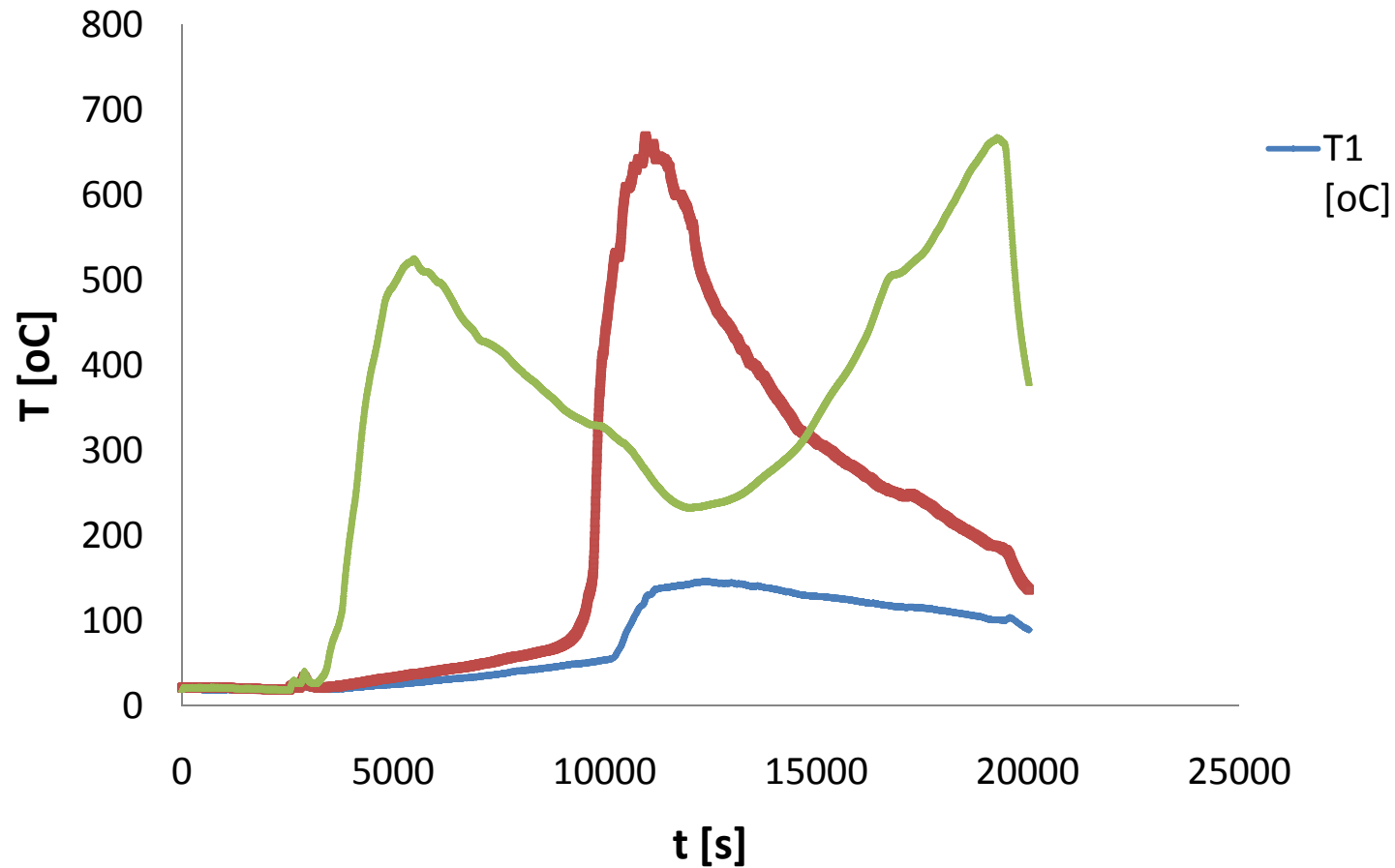


Fig. Temperature field inside reactor.

CFD Studies on biomass pyrolysis

biomass \longrightarrow *char + volatiles*

Change of solid phase

$$\Delta m_s = -k(m_s - m_r)\Delta t$$

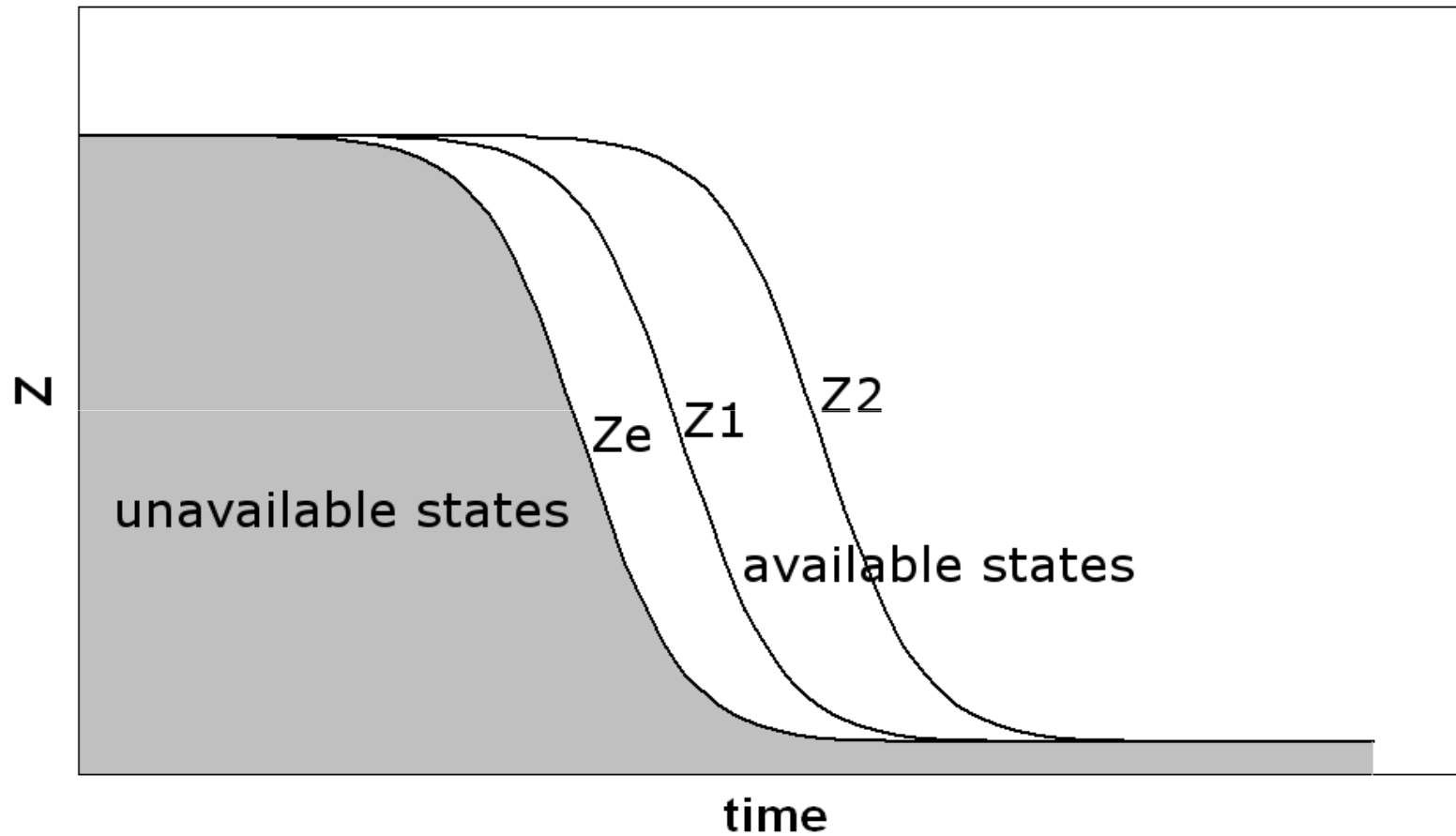
The rate of pyrolysis

$$Z = \frac{m_s}{m_{s,0}},$$

The change of pyrolysis rate

$$\frac{dZ}{dt} = -k(Z - Z_e)$$

The rate of pyrolysis



Conservation law of the mass, momentum, energy

$$\frac{\partial \varepsilon_g \rho_g}{\partial t} + \nabla(\varepsilon_g \rho_g v_g) = S_m$$

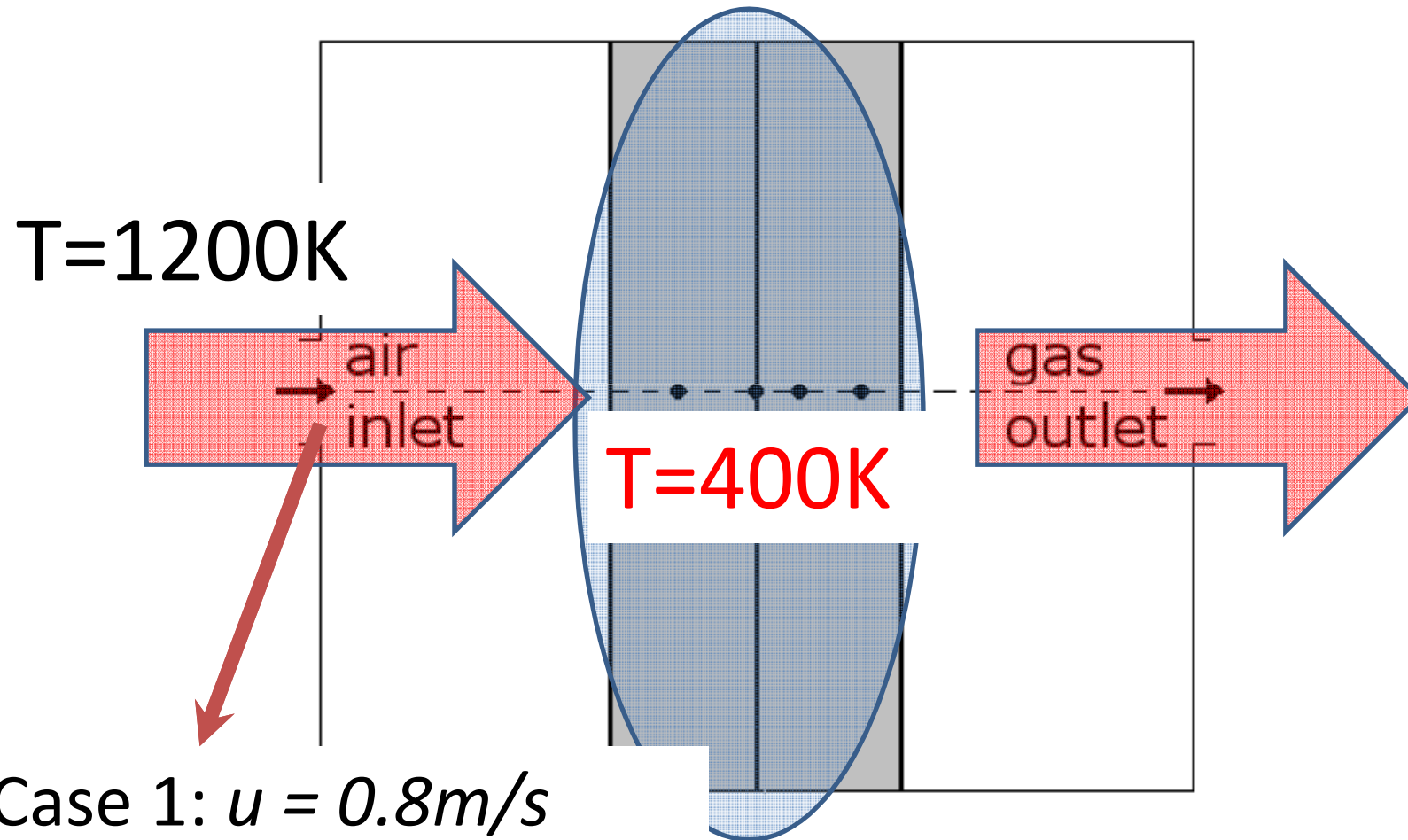
$$\frac{\partial \varepsilon_g \rho_g v_g}{\partial t} + \nabla(\varepsilon_g \rho_g v_g v_g) = -\nabla p + \nabla(\varepsilon_g \mu_g \nabla \mu_g) + S_p$$

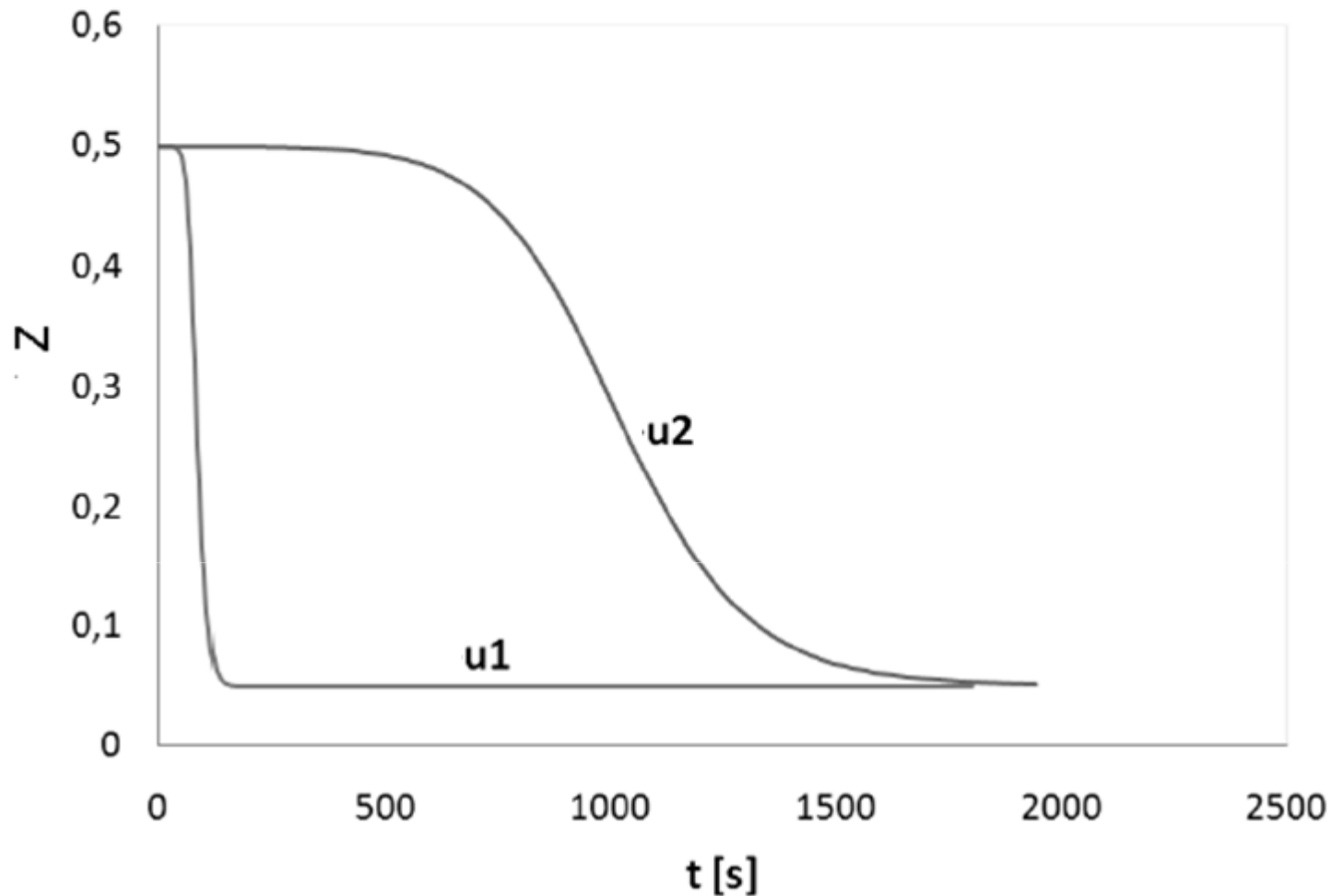
$$\frac{\partial \varepsilon_g \rho_g U_g}{\partial t} + \nabla(\varepsilon_g \rho_g v_g U_g) = -p_g \nabla v_g + \alpha(T_s - T_g) + \nabla(\lambda \nabla T_g) + S_U$$

$$\frac{\partial \varepsilon_s \rho_s}{\partial t} = -S_m$$

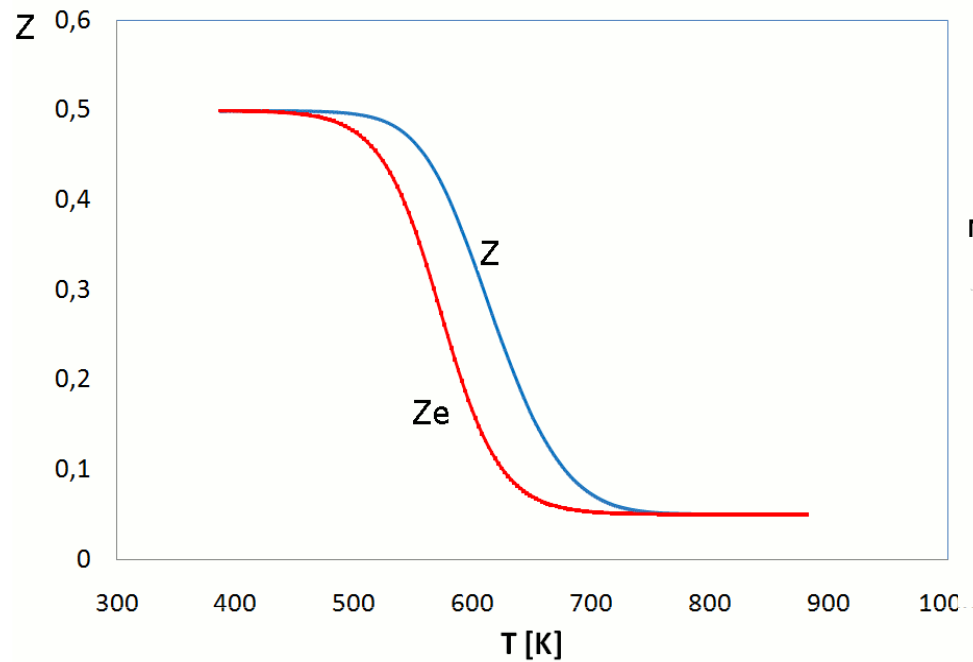
$$\frac{\partial \varepsilon_s \rho_s U_s}{\partial t} + \nabla(\varepsilon_s \rho_s v_s U_s) = -\alpha(T_s - T_g) + \nabla(\lambda \nabla T_s) - S_U$$

Modeling the rate of pyrolysis in function of temperature

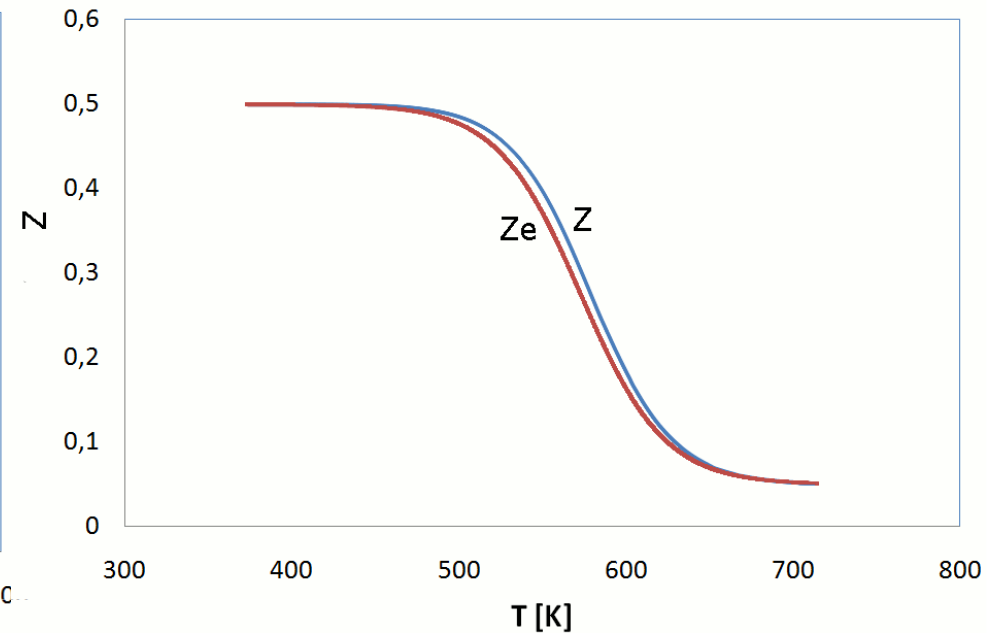




Rate of pyrolysis for two velocities of hot air
 $u_1 = 0.8\text{m/s}$, $u_2 = 0.08\text{m/s}$.



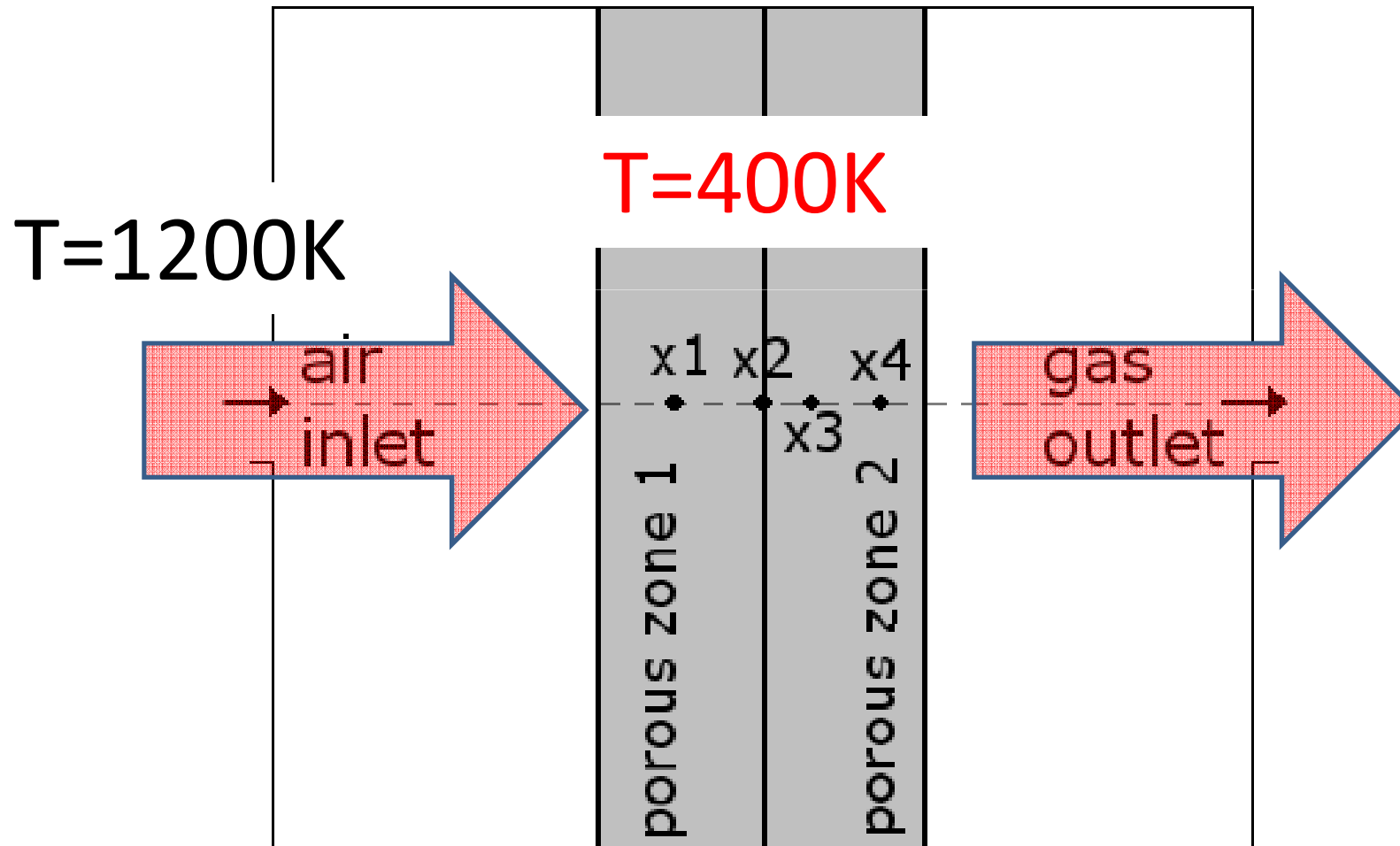
$u_1 = 0.8\text{m/s}$

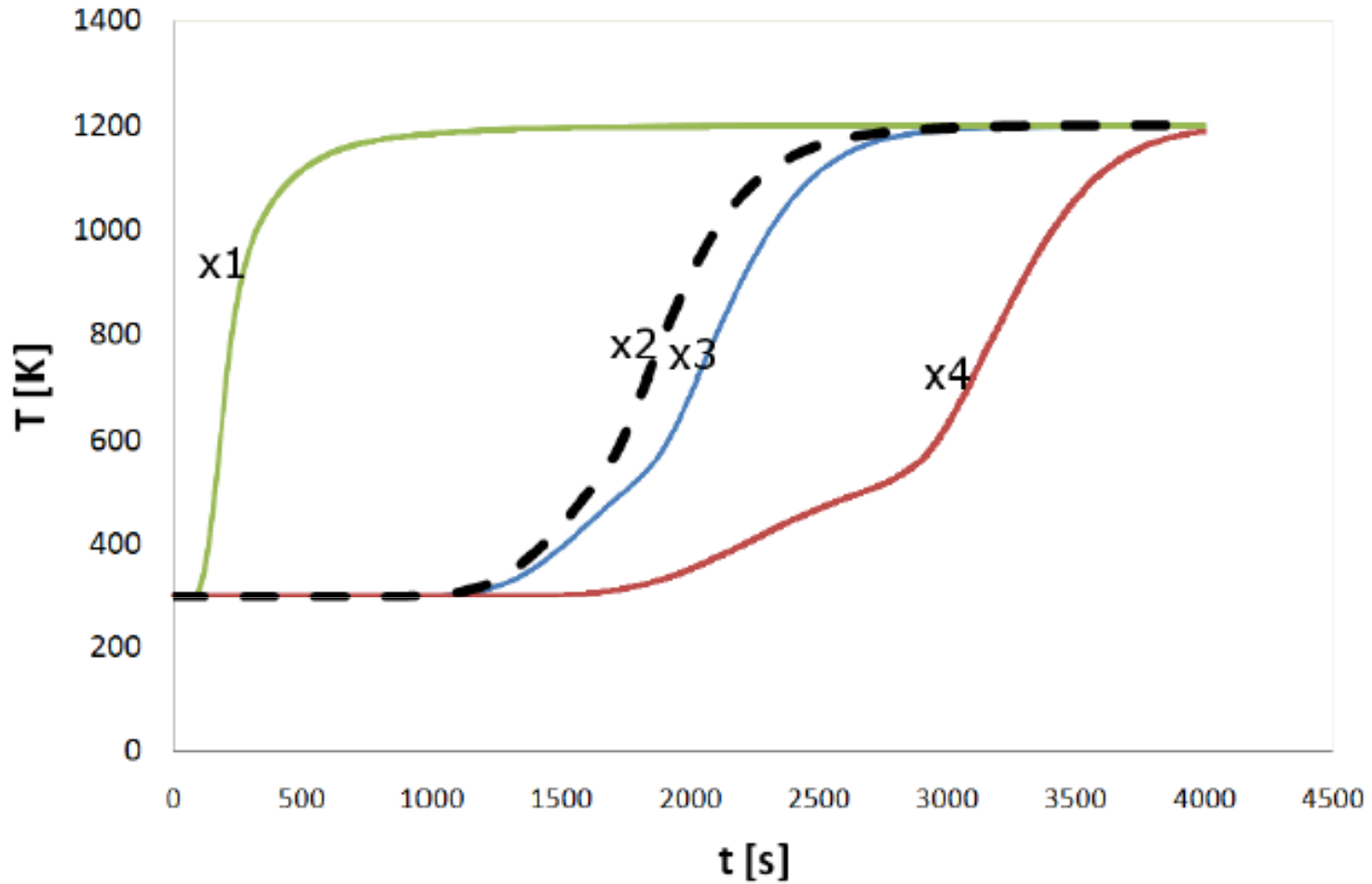


$u_2 = 0.08\text{m/s}$

The pyrolysis rate **Z** and equilibrium rate of pyrolysis **Z_e** in temperature function.

Influence of porosity and permeability on pyrolysis process

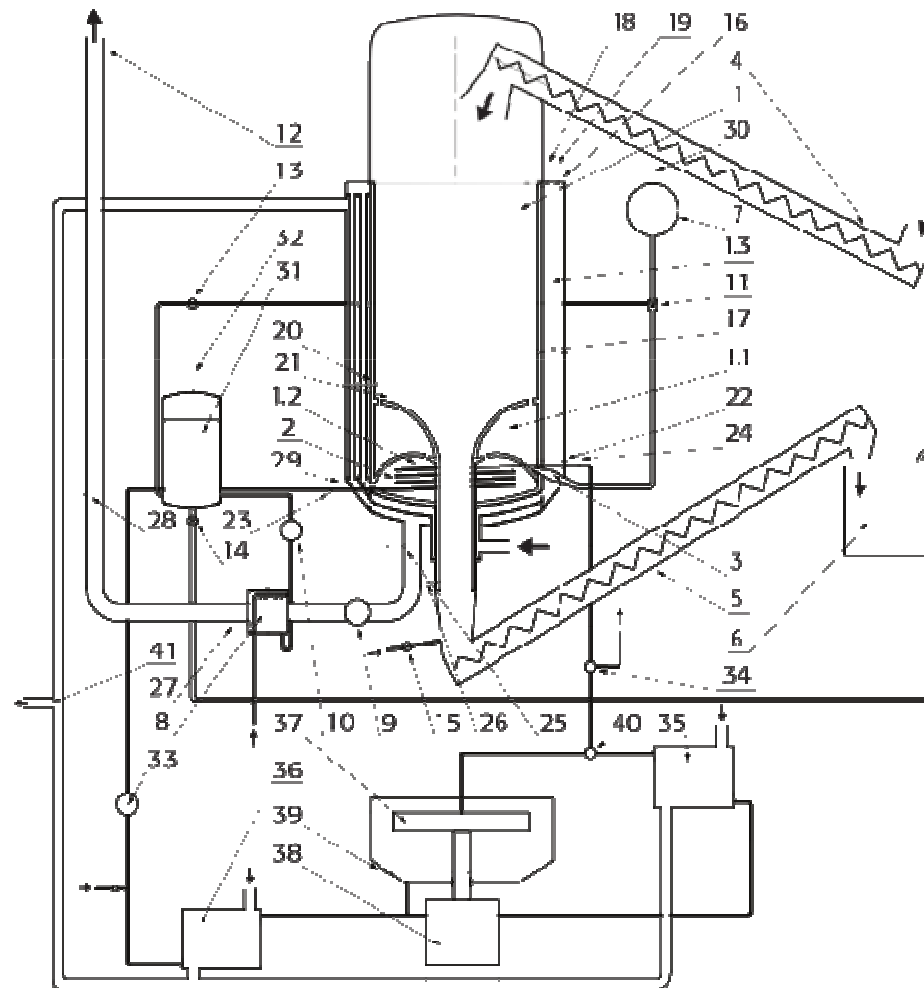




The temperature front of pyrolysis in porous zones

Design of 1 MW gasifier

Schemat Reaktora kogeneracyjnego Xenergo

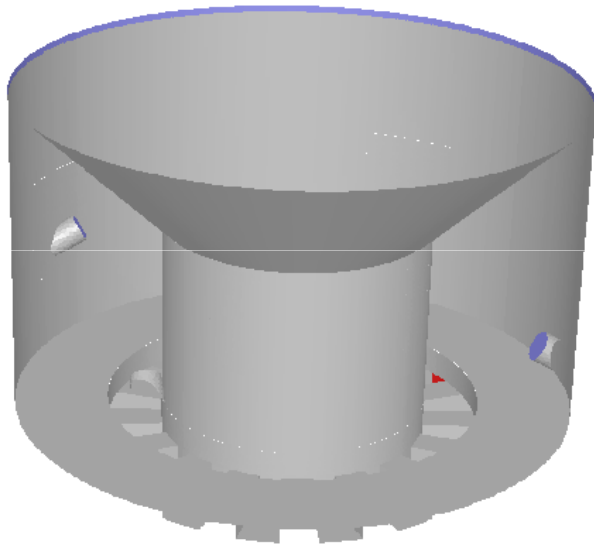


- 1 REAKTOR
- komora proces. gazyfikacji
- 1.1 Komora spalania gazu
- 1.2 Komora wylany cepra
- 1.3 Wysokotemperaturowy płaszcz ochronny
- 2 Wpływnica 5 szt
- 3 Dysza rozpryskowa 4 szt
- 4 Transporter surowca unieruchomionego
- 5 Transporter popiołu
- 6 Zbiornik posiedzi
- 7 Sprężarka 6 bar
- 8 Scrubber 1 szt, czyszcza
- 9 Dm. czołowa wyładowcza
- 10 Pompa wodna
- 11 Filtr 4 szt
- 12 Kłosa
- 13 Zawór wody 2 szt
- 14 Zawór siana
- 15 Regulator przepływu powietrza
- 16 Czujnik poziomu surowca - maksimum - 2 szt.
- 17 Czujnik poziomu surowca - minimum - 2 szt.
- 18 Czujnik temperatury 90 °C - 2 szt
- 19 Czujnik temperatury 95 °C - 2 szt
- 20 Czujnik poziomu popiołu - 2 szt
- 21 Czujnik temperatury gaszenia - 2 szt
- 22 Termopara temperatury spalania gazu - 2 szt
- 23 Czujnik temperatury wody - 2 szt.
- 24 Czujnik temp. wody wysiękowej > 90 °C - 2 szt
- 25 Czujnik temperatury spalin - 2 szt
- 26 Czujnik temperatury popiołu - 2 szt
- 27 Czujnik poziomu wody - 2 szt
- 28 Czujnik temperatury spalin - 2 szt
- 29 Sondy AMRDA 2 szt
- 30 Czujnik ciśnienia powietrza - 2 szt
- 31 Hydrofor
- 32 Czujnik sprężonego powietrza
- 33 Pompa wodna 200 Bar
- 34 Zawór bez ecerstwa
- 35 Skraplacz wym. energii ciepła
- 36 Wymieniacz ciepła
- 37 Turbina
- 38 Prądnica
- 39 Czujnik
- 40 Zawór przelączający
- 41 Uscie ciepłej wody użytkowej

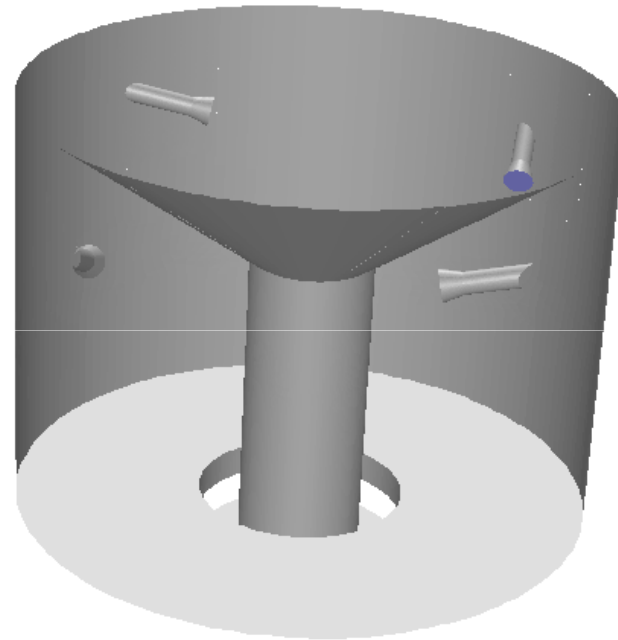
Conditions for gasifier

- Gasification of biomass and wastes
(chloride content <1%)
 - Temperature >850C
 - Residence time of flue gases >2sek.
- Gasification of biomass and wastes
(chloride content >1%)
 - Temperatura >1100C
 - Residence time of flue gases >2sek.

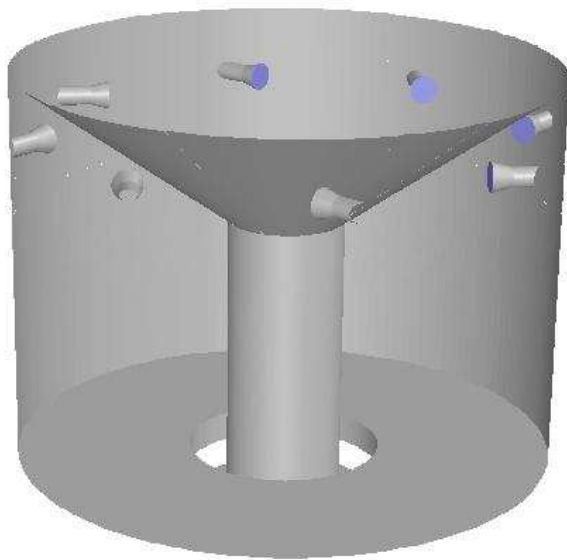
CHECKED CASES



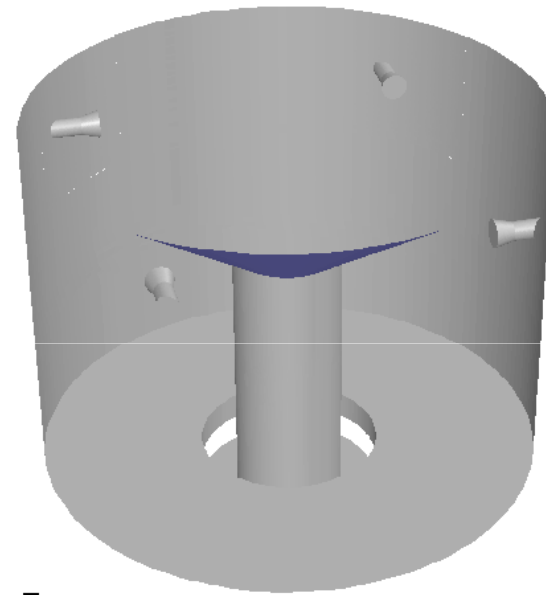
A case



B case



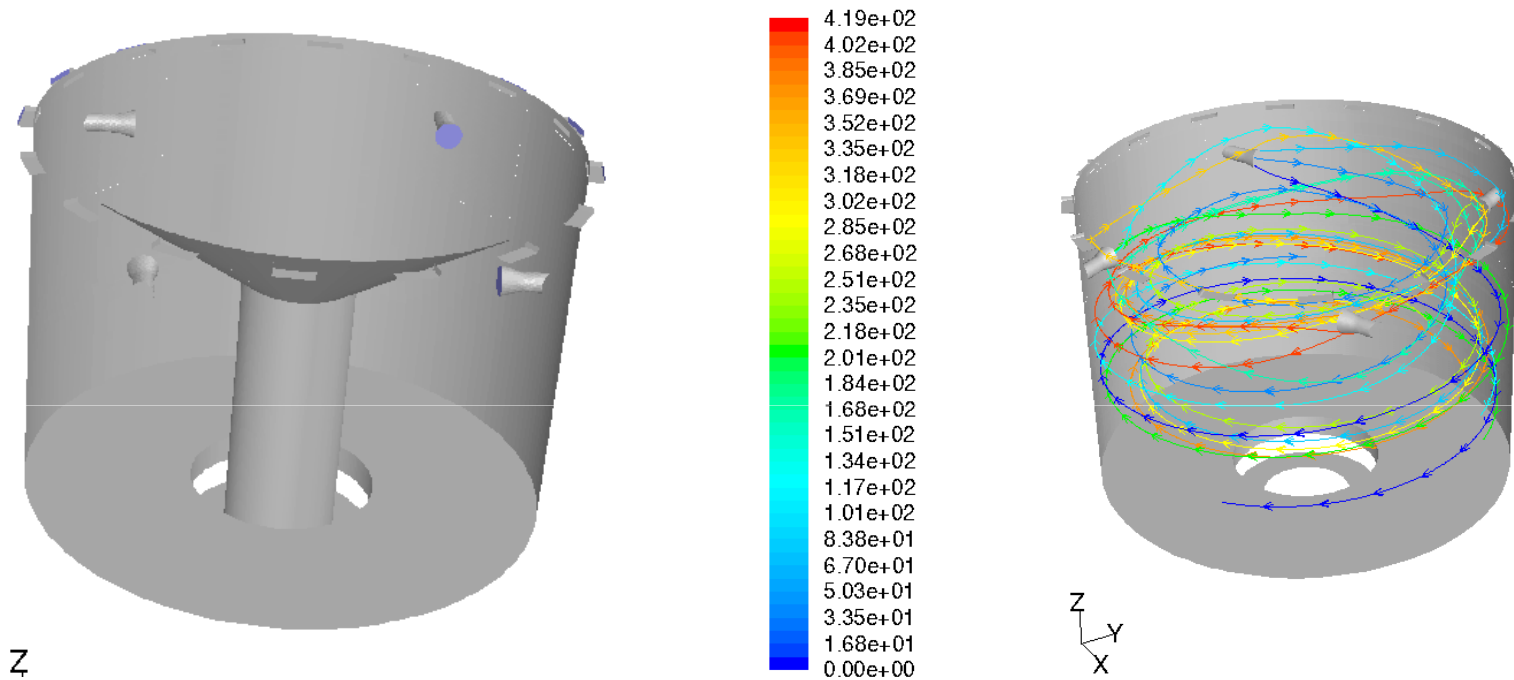
C case



z_r

D case

Final version



Final solution

Pyrolysis in high pressure



Pyrolysis of wood



A) gasproduct



B) Liquid product



C) Char

time=140 min, $T_{\max}=500^{\circ}\text{C}$, $p_{\max}=12.5$ bar,

Misiuk S., Klein M., Kluska J., Kardaś D.

Cotton



A) gas



B) liquid



C) char

time=110 min, $T_{\max}=500^{\circ}\text{C}$, $p_{\max}=20.0\text{bar}$,
A) test palności uzyskanych gazów, B) skropliny, C) karbonizat

Misiuk S., Klein M., Kluska J., Kardaś D.

Wastes



A) gas



B) ciecz



C) ciało stałe

Fot. $t=170$ min, $T_{\max}=495^{\circ}\text{C}$, $p_{\max}=17.0$ bar,
A) Test palności uzyskanych gazów, B) skropliny, C) karbonizat



PROJEKT KLUCZOWY NR POIG.01.01.02-00-016/08
MODELOWE KOMPLEKSY AGROENERGETYCZNE JAKO PRZYKŁAD
KOGENERACJI ROZPROSZONEJ OPARTEJ NA LOKALNYCH I
ODNAWIALNYCH ŹRÓDŁACH ENERGII

THANK YOU