The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

Workshop on "Physics for Renewable Energy"
October 17 - 29, 2005

301/1679-18

"The Role of Biomass for Sustainable Growth"

P. Foscolo
University of L'Aquila
Italy

RENEWABLE ENERGY SOURCES

THE ROLE OF BIOMASS FOR A SUSTAINABLE GROWTH

Pier Ugo FOSCOLO

PROF. OF CHEMICAL REACTION ENGINEERING

UNIVERSITY OF L'AQUILA

CHEMICAL ENGINEERING DEPARTMENT
MONTELUCO – ROIO
67100 L'AQUILA, ITALY
Phone: +39 0862 434214 **Fax: +39 0862 434203**
Email: foscolo@ing.univaq.it

Biomass gasification and fluid-dynamics of fluidized bed reactors are actively cultivated in the CRE laboratory at UNIVAQ since more than 25 years, at the level of theoretical and experimental research investigations, including industrial contracts.

Research Group

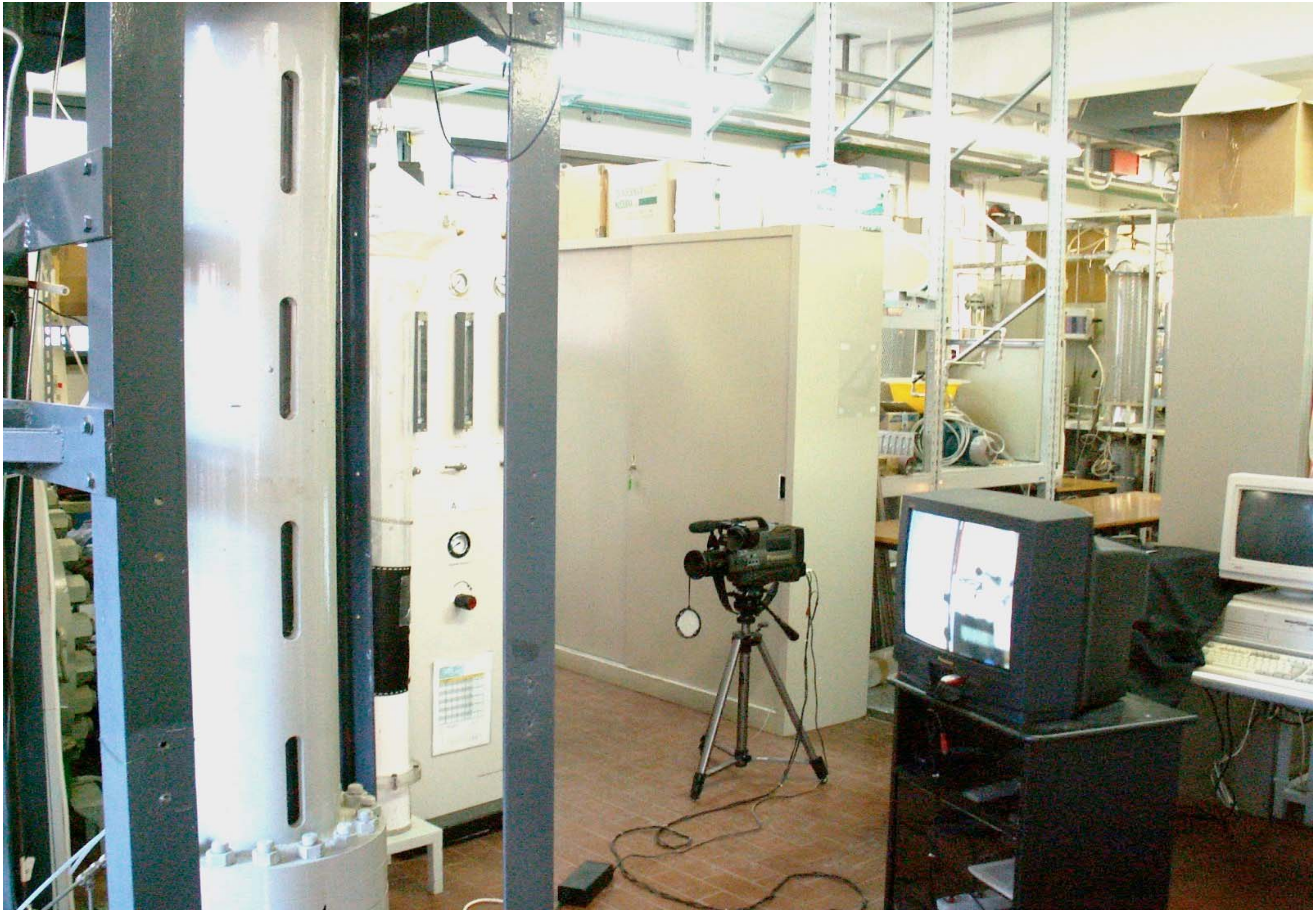
Prof. Pier Ugo Foscolo, full professor in Chemical Reaction Engineering, author of more than 70 papers in International Scientific Journals and as many Conference presentations;

Prof. Larry Gibilaro, previously employed (as full professor) at University College London. His outstanding experience in *Fluidization-Dynamics* has been recently condensed in a book published by Butterworth-Heinemann;

Prof. Antonio Germanà, part-time professor of Chemical and Process Plant Design. He has a long standing academic and professional experience in plant design, construction and commissioning;

Dr Ing. Nader Jand, assistant professor in Chemical Engineering, with outstanding doctoral and post-doctoral experience in biomass gasification both, at experimental and model developing level;

Post doctoral researchers, PhD students and technical staff



Fluidized bed biomass gasifiers at pilot scale have been designed and operated in collaboration with ENEA, the Italian national agency for new technologies, the energy and the environment:

- **European contract JOR3-CT95-0037 "Production of hydrogen-rich gas by biomass gasification: application to small-scale, fuel cell electricity generation". Study of the feasibility of the integrated plant.**

- **European contract JOR3-CT97-0196 "Hydrogen-rich gas from biomass steam gasification". A 500 kWth pilot unit has been built based on a dual, internally circulating fluidized bed gasifier, able to produce a fuel gas with high calorific value (almost negligible nitrogen content). A Nickel-Olivine catalyst has been developed, to be utilised in the gasifier bed inventory for tar cracking and reforming, and to enhance the hydrogen content in the product gas.**

•European contract ENK5-CT2000-00314 and Italian programme FISR 2004 "Biomass-gasification and fuel-cell coupling via high-temperature gas clean-up for decentralised electricity generation with improved efficiency". The project is in progress. The hot gas cleaning section of the Trisaia pilot plant has been completed; the fuel gas will be fed to a molten carbonate fuel cell (MCFC) provided by the company ANSALDO Fuel Cell SpA. The research activities include further studies on the catalyst reactivity, integrated system simulation and CFD modelling of the gasifier.

•International cooperation programme with the Liaoning Research Centre (LIER) in China, financed by the Italian Foreign Ministry "Gasification of agro-industrial refuses to produce electricity". We developed the design of a 1 MW(th) fluidized bed gasifier (air gasification, low heating value fuel gas) and took part in the plant start-up in China.

Further international activities:

- **organization of the third Fluid-Particle Interactions Conference in Davos (Switzerland), 1993;**

- **co-ordination of TEMPUS Tacis Project JEP-10096 in Chemical Engineering education, involving Italy, United Kingdom and Kazakhstan;**

- **student exchange programmes (ERASMUS) with different academic Institutions throughout Europe;**

- **evaluation of research projects in the field of "biomass" for the 5th and 6th European Framework Programmes.**

B
I
O
M
A
S
S

- **the best manner for solar energy storage!**
- **an abundant and distributed source of energy and chemicals;**
- **the biomass production – power generation cycle is characterized by near-zero contribution to the accumulation of green-house gases;**
- **a renewable source for a sustainable growth.**

FOR A GLOBAL AND WIDESPREAD BREAKTHROUGH OF RENEWABLES (AND BIOMASS AMONG THESE) DIFFERENT SCENARIOS IN THE WORLD ECONOMY NEED TO BE ESTABLISHED

IS THIS A REMOTE HYPOTHESIS?

Physical and chemical properties of biomass (example)			
Type	Almond shells		
Status	Raw	Dry	Dry-ash-free (daf)
Moisture (wt%)	7.90	-	-
Ash (wt%)	1.16	1.26	-
Volatile matter (wt%)	72.45	78.66	79.67
Carbon (wt%)	46.65	50.65	51.30
Hydrogen (wt%)	5.55	6.03	6.10
Oxygen (wt%)	38.74	42.06	42.60
LHV (kJ/kg)	18350		
Cellulose (wt%)	29		
Hemicellulose (wt%)	28		
Lignin (wt%)	35		
Density (kg/m^3)	1200		

B I O – R E S I D U E S

• waste-biomass has the potential to provide as much as 330 GW of electric power world-wide, if utilized efficiently;

• in Mediterranean countries (because of climate), in Eastern EU countries (because of extensive utilization of land for food crops), and in intensely populated industrial areas, energy crops and virgin biomass are scarce, and costly because of alternative uses;

• when by-products of agro-industrial processes or MSW (RDF) are utilized as feedstock, the problem and the cost of disposal are reduced, and this contributes positively to the economic balance of the conversion process to energy or chemicals.

AN INTERESTING NICHE MARKET!

Physical and chemical properties of biomass (example)			
Type	Olive waste from oil production		
Status	Raw	Dry	Dry-ash-free (daf)
Moisture (wt%)	8.90	-	-
Ash (wt%)	7.74	8.5	-
Volatile matter (wt%)	67.78	74.40	81.31
Carbon (wt%)	43.93	48.22	52.70
Hydrogen (wt%)	6.00	6.59	7.20
Oxygen (wt%)	31.76	34.86	38.10
Nitrogen (wt%)	1.33	1.46	1.60
Sulphur (wt%)	0.05	0.06	0.07
Chlorine	0.34	0.34	0.37
LHV (kJ/kg)		18500	
Bulk density (kg/m^3)	659		

Physical and chemical properties of biomass (example)			
Type	Rice husk		
Status	Raw	Dry	Dry-ash-free (daf)
Moisture (wt%)	6.96	-	-
Ash (wt%)	14.71	15.8	-
Volatile matter (wt%)	66.69	71.71	85.17
Carbon (wt%)	36.25	38.96	46.27
Hydrogen (wt%)	4.75	5.11	6.07
Oxygen (wt%)	35.32	37.96	45.08
Nitrogen (wt%)	2.02	2.17	2.58
Sulphur (wt%)	0.13	0.14	0.17
Chlorine	-	-	-
LHV (kJ/kg)	13544		17290
Bulk density (kg/m^3)	161		

HIGH-TEMPERATURE GASIFICATION

A thermal and reactive conversion process, aimed at efficient production of a clean gas keeping the chemical energy of the original solid fuel;

by-products: char, ash, tar.

- **the closest to industrial exploitation from among the available conversion options for efficient power generation;**
- **it can be well integrated with MCFC or SOFC (which accept syn-gas), and FC + turbine or gas turbine + steam turbine combined cycles;**
- **net electric efficiencies > 40% (pressurized gasification);**
- **availability of an energy (hydrogen-rich) and/or chemicals carrier gas for a variety of utilities and applications.**

Combustion (incineration) exploits directly the thermal energy of the solid fuel, with a lower efficiency and a considerably greater amount of gas to be treated and cleaned.

Thermally induced biomass decomposition occurs over the temperature range 250 ÷ 500°C, and the primary pyrolysis products are:

organic vapours, char and ash.

At the gasification temperature (> 800°C):

Organic Vapours → (cracking, steam reforming) → CO, CO_2, H_2, H_2O; light hydrocarbons (mainly CH_4)

Organic Vapours → (polymerisation) → high molecular weight organics (tar)

Char + H_2O, CO_2 → CO, H_2

Overall, an endothermic reaction process

The global reactive process occurring in a biomass gasifier can be characterized as follows:

$$C_{a_C} H_{a_H} O_{a_O} N_{a_N} + x_1 H_2 O_{(l)} + x_2 H_2 O_{(g)} + x_3 \left(O_2 + \gamma N_2\right) \Rightarrow z_1 H_2 +$$

$$z_2 CO + z_3 CO_2 + z_4 CH_4 + z_5 N_2 + z_6 NH_3 + z_7 H_2 O_{(g)} + z_8 C_{10} H_8 + z_9 C_{(s)}$$

the g-atoms of carbon, hydrogen, oxygen and nitrogen in the biomass raw formula are given by the fuel elemental analysis,

x_1 is given by the fuel humidity,

(x_1+x_2) is fixed by the steam/biomass ratio, SBR,

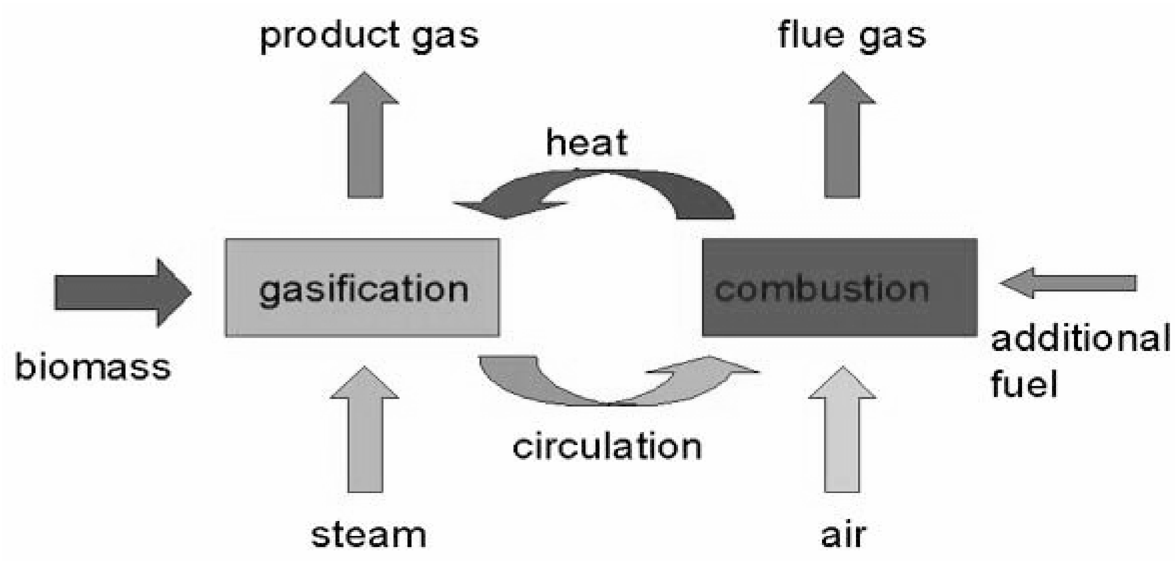
x_3 by the value of the equivalence ratio, ER,

γ is chosen according to the nature of the gasification agent (air, enriched air or pure oxygen).

The list of chemical species on the RHS of the above equation has been restricted to the most significant ones.

How to supply the energy needed by the gasification process:

- **addition of air/oxygen-enriched air/oxygen, to burn part of the solid fuel;**
- **circulation of reactor bed inventory between separate gasification and combustion zones (solid particles act as an heat carrier);**
- **circulation of bed inventory + an additional, exothermic reaction which helps furnishing the necessary thermal energy: solid circulation allows the regeneration of the reactant.**



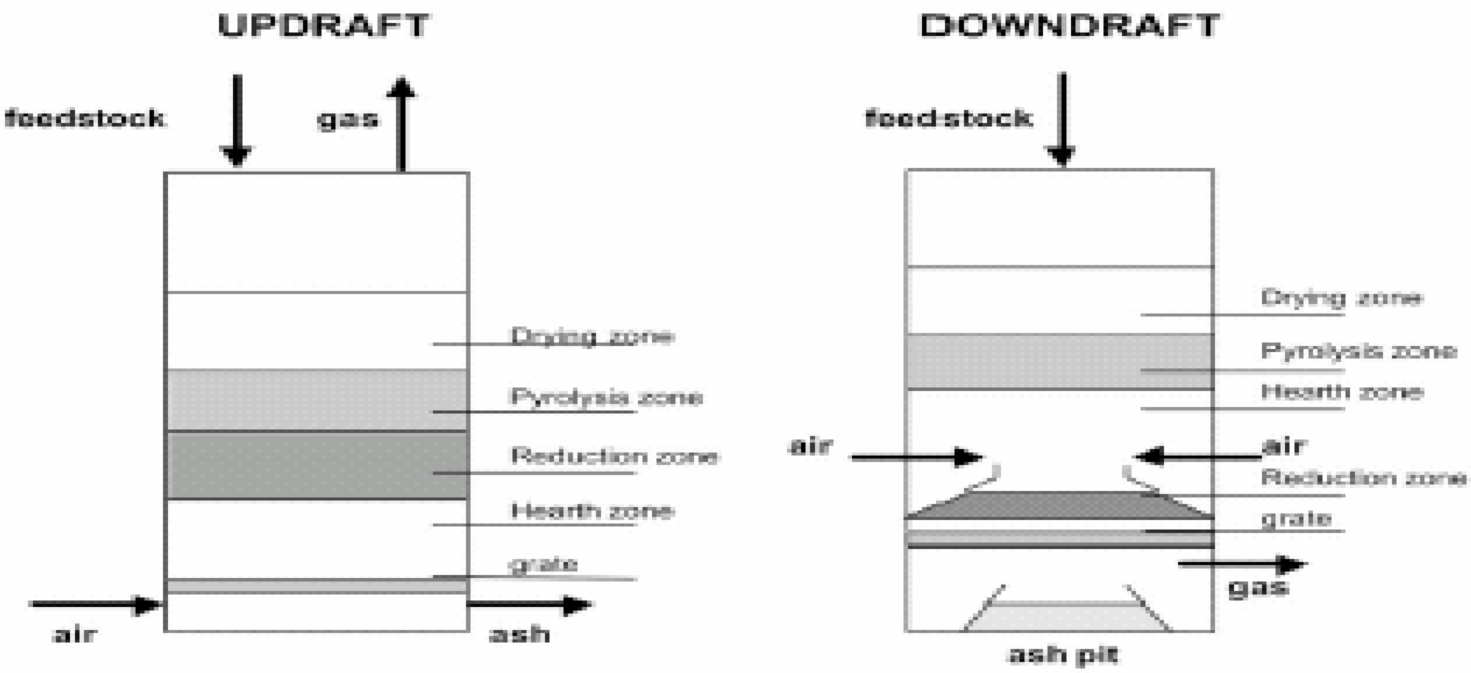
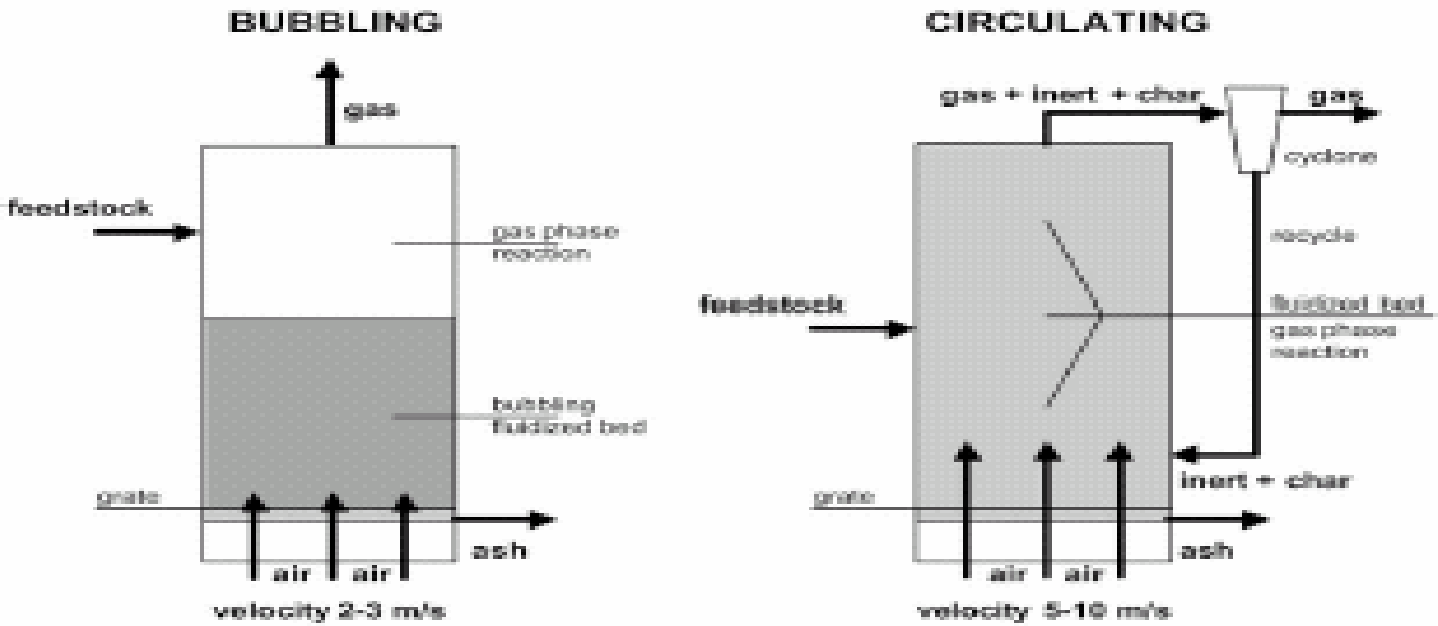


Fig. 5. Fixed bed gasifiers (Quaak et al., 1999).



FLUIDIZED BED GASIFIERS

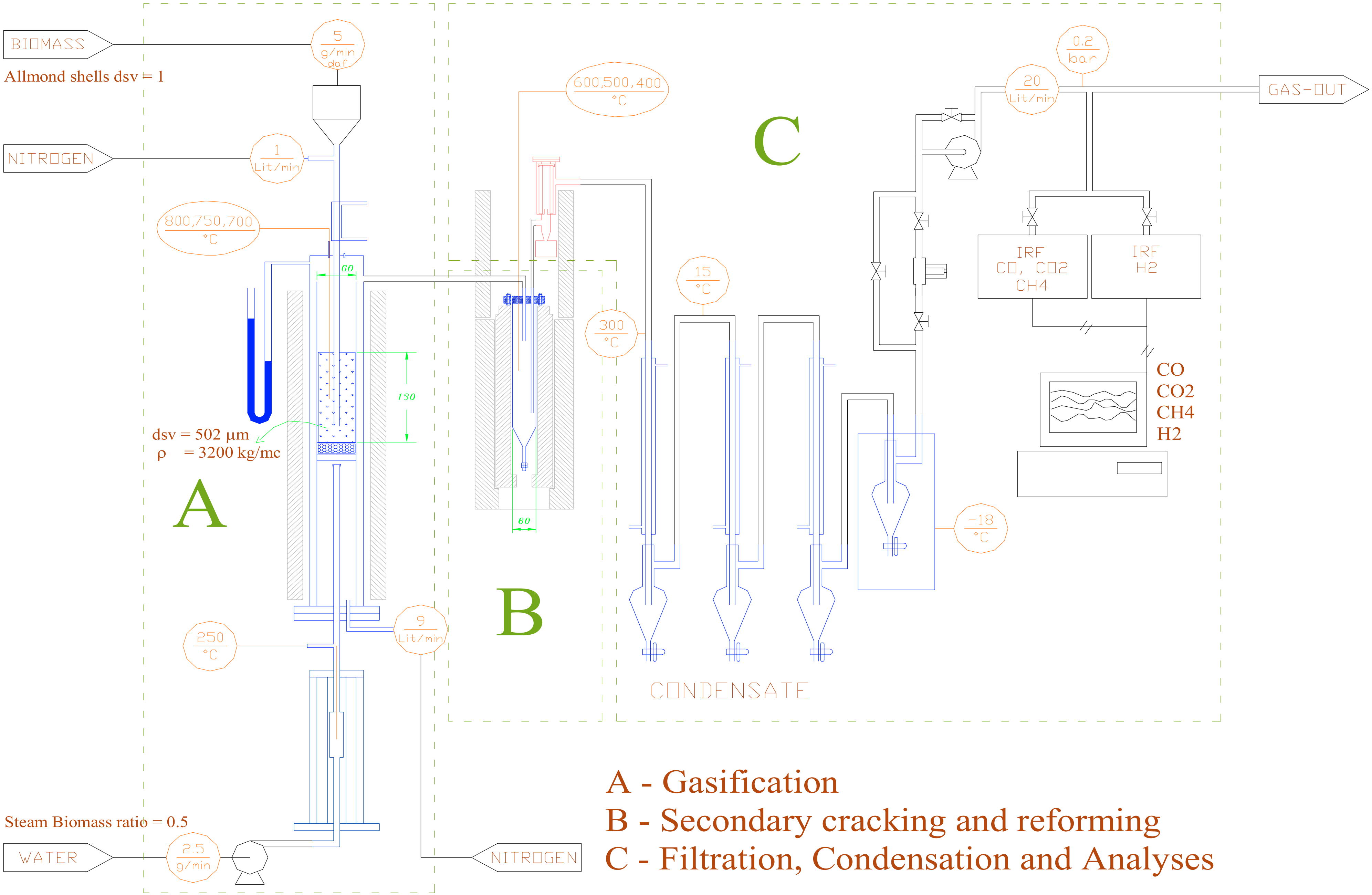
Advantages:

- very good mixing of the bed inventory;
- temperature homogeneity;
- high heat-up rates of the feedstock particles;
- possibility to add a catalyst to enhance yield of permanent gases;
- internal circulation of the bed inventory to help mixing of particles of different densities;
- external circulation of the bed inventory (fast fluidized beds).

Disadvantages:

- entrainment of fine particles (char, ash) by the product gas;
- feedstock of controlled size, very smooth feeding rates;
- careful design and operation.

Laboratory, fluidized bed steam gasification facility



A - Gasification

B - Secondary cracking and reforming

C - Filtration, Condensation and Analyses

Catalytic steam gasification tests with almond shells

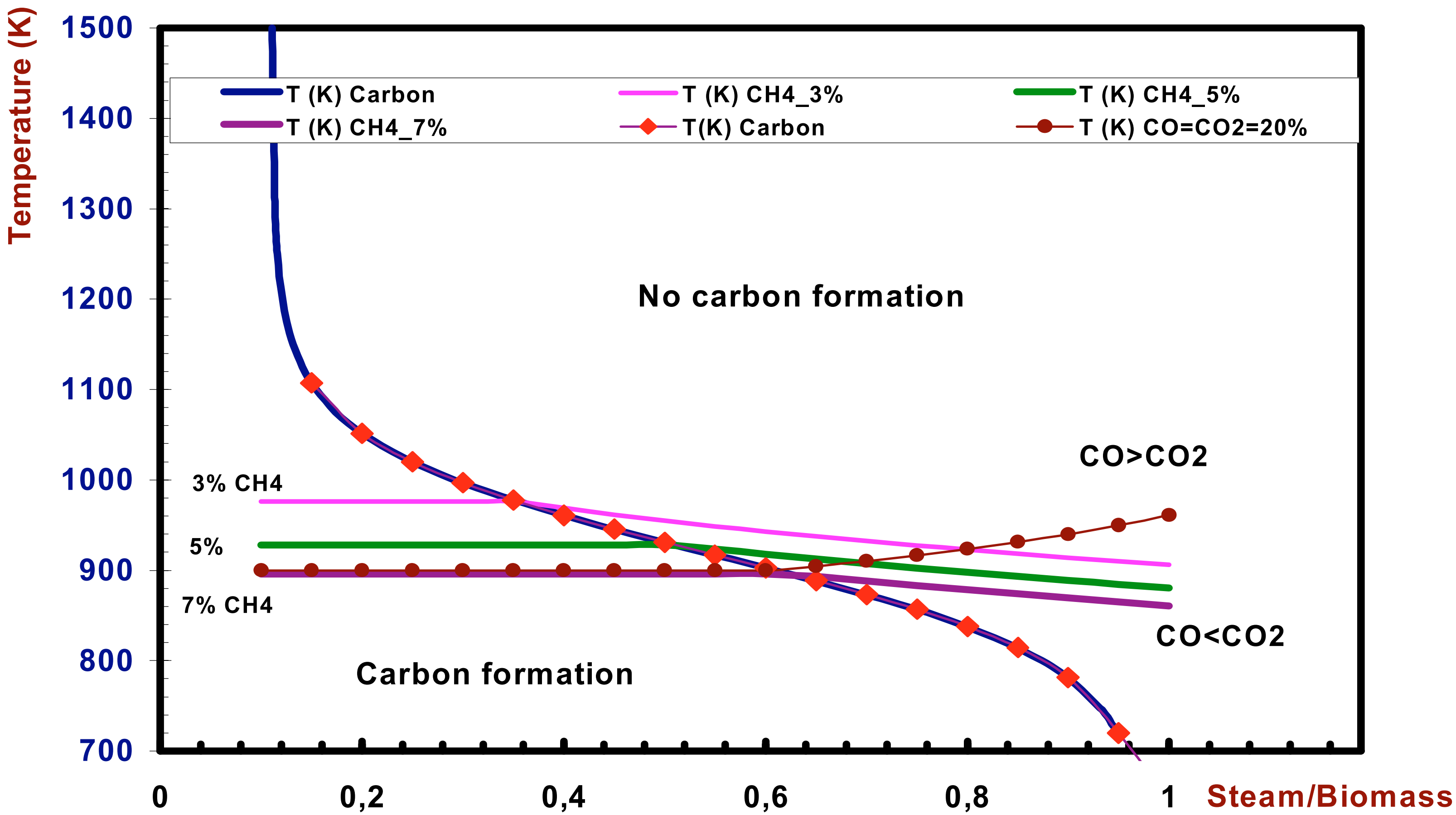
T_Gasifier, °C	**820(*)**	**820**	**820**	**750**	**700**
Gas residence time, s	**1,16**	**1,17**	**1,2**	**1,24**	**1,2**
Steam_tot/Biomass_dry	**1**	**1**	**0,5**	**0,5**	**0,5**
Water conversion	**0,49**	**0,45**	**0,59**	**0,43**	**0,26**
Net-gas, Nlit / g daf	**1,92**	**1,72**	**1,68**	**1,22**	**0,90**
Tar yield, g/Nm^3	**0,45**	**0,52**	**0,15**	**1,84**	**17,06**
H2	**51,2%**	**50,0%**	**48,2%**	**43,3%**	**37,7%**
CO	**23,6%**	**23,4%**	**29,6%**	**29,9%**	**29,1%**
CO2	**21,1%**	**21,7%**	**17,8%**	**19,4%**	**26,4%**
CH4	**4,2%**	**5,0%**	**4,4%**	**7,4%**	**6,9%**
*** Note: Fresh Catalyst**					

Prediction of products composition from a gasification process:

- **the thermodynamic approach**

  Gibbs free energy minimisation models

  (Li, Grace et al., Biomass & Bioenergy, 2004)



- **the chemical kinetics approach**

  sophysticated, comprehensive models

  (Di Blasi, AIChE Journal, 2002)

The series reactor method

(Meissner et al., 1969; Modell and Reid, 1974)

the Gibbs free energy of a system, G, at constant temperature and pressure will always be reduced when anyone reaction is allowed to proceed toward equilibrium.

In a iterative procedure, if each reaction is allowed to proceed to equilibrium "sequentially", G converges on a minimum value that corresponds to the equilibrium condition for the simultaneous reactions.

The procedure is repeated until the extent of reaction in each reactor has passed below some predetermined minimum value.

The series reactor method is applied to the air/steam gasification of pure cellulose, $(C_6H_{10}O_5)_x$;

Assumptions:

- **thermodynamic data for cellulose are predicted from literature by a group-estimation method (Janz, 1967)**
- **the input species are air, steam and cellulose, in fixed ratios**
- **it is assumed that hydrogen, carbon monoxide and dioxide, methane, naphthalene, and graphitic carbon appear in the evolution of the system toward equilibrium, through a set of independent stechiometric relationships**

$$\left(C_6H_{10}O_5\right)_x \quad = \quad 5xCO + 5xH_2 + xC_{(s)} \qquad (1)$$

$$CO + H_2O \quad = \quad CO_2 + H_2 \qquad (2)$$

$$CO + 3H_2 \quad = \quad CH_4 + H_2O \qquad (3)$$

$$CH_4 \quad = \quad C_{(s)} + 2H_2 \qquad (4)$$

$$C_{10}H_8 + 10H_2O \quad = \quad 10CO + 14H_2 \qquad (5)$$

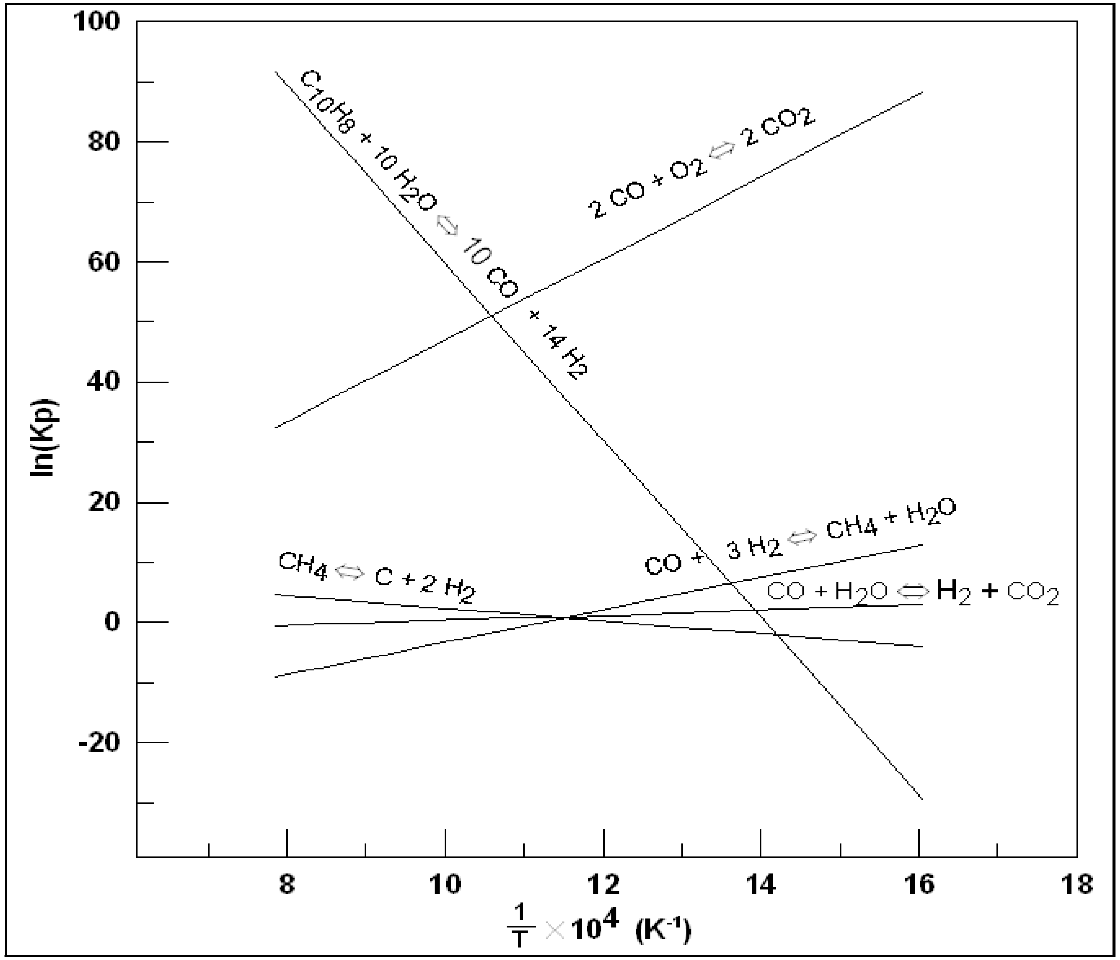
$$2CO + O_2 \quad = \quad 2CO_2 \qquad (6)$$

Generalisation of eq. 5:

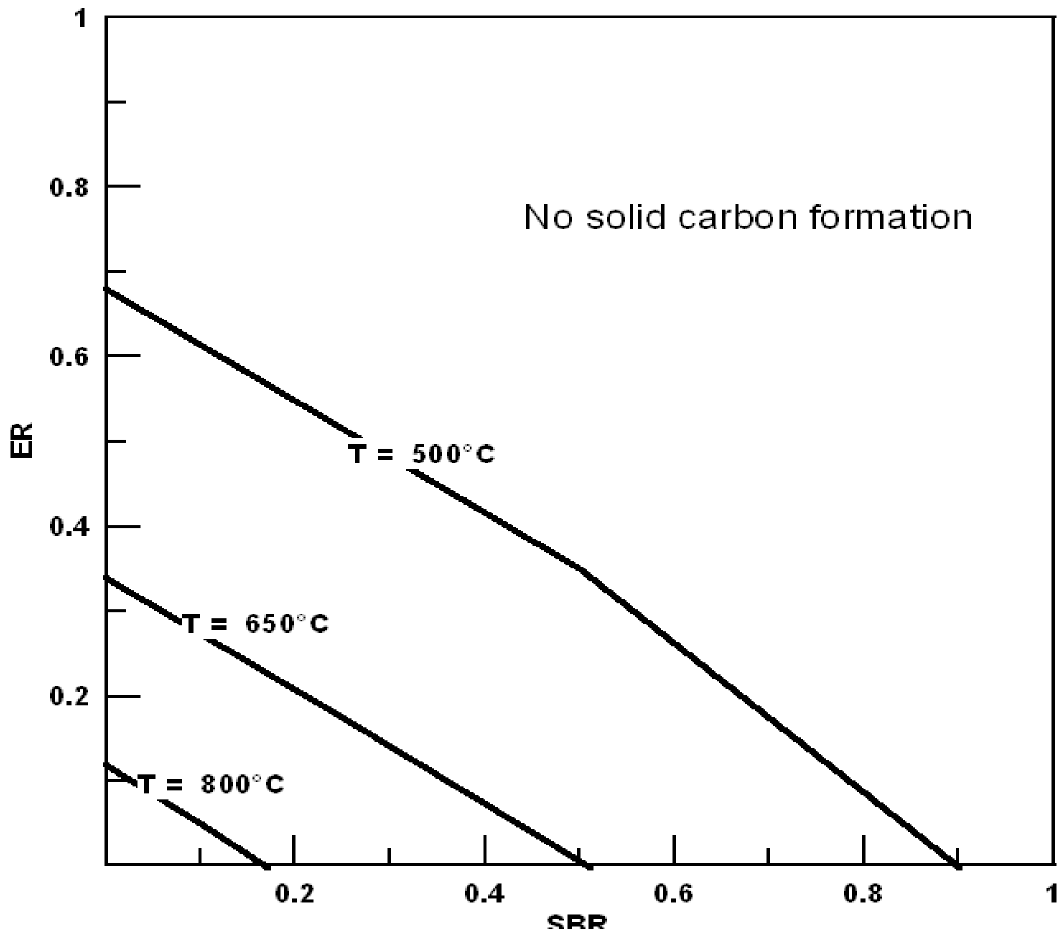
$$C_nH_x + nH_2O \quad = \quad nCO + \left(n + x/2\right)H_2$$

Linear combination of eqs 2, 3 and 4 (Boudouard reaction) :

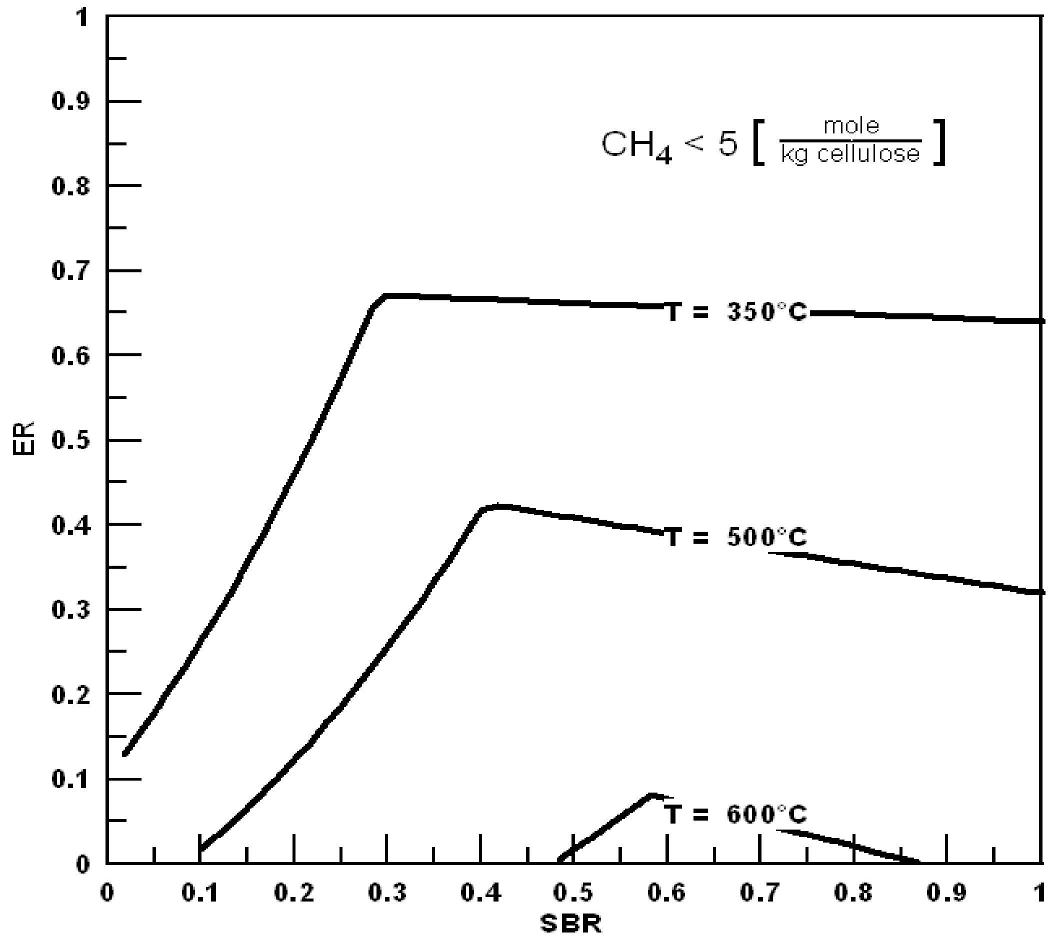
$$2CO \quad = \quad C_{(s)} + CO_2$$



Equilibrium constants for stoichiometric relations 1-6, as a function of temperature



Gasification of cellulose: influence of temperature, SBR and ER on the presence at equilibrium of a solid phase containing carbon.



Gasification of cellulose:

influence of temperature, SBR and ER on the methane yield at equilibrium.

The mole fraction of naphthalene (tar) his found to be insignificant over the whole temperature range:

at high temperature, the equilibrium constant associated with eq. 5 becomes very high,

at low temperature, the mole fractions of steam, carbon monoxide and hydrogen are such to result in a negligible presence of naphthalene, in spite of a rapidly decreasing K_P.

This result is quite general (it is not linked to the choice of naphthalene to represent tar, nor to the ratios among H, C and O in cellulose): the primary products of pyrolysis are very unstable, tending to result in a solid phase of essentially carbon, and a gaseous phase of small molecules (permanent gases), which becomes predominant at high temperature.

This is why rapid quench and separation of the vapour phase is strongly recommended for "flash pyrolysis" processes, aimed at the production of bio-oils.

In real systems, $C_{(s)}$ may be assumed to represent all the carbon that is not converted into gaseous fuels; a more complete picture, distinguishing between char and tar compounds, appears not feasible at this level of description.

The G minimisation method

(Zeleznik & Gordon, 1968; Ma & Shipmen, 1972)

does not require knowledge of an independent set of chemical reactions. For a system at constant temperature and pressure:

$$dG = \sum_{i=1}^{c} \mu_i \, dn_i = 0$$

$$\sum_{i=1}^{c} n_i \, a_{ik} - A_k = 0 \qquad (k = 1,2,\ldots,m)$$

Using the Lagrangian method of undetermined multipliers, the resulting equations become (for a gaseous phase system):

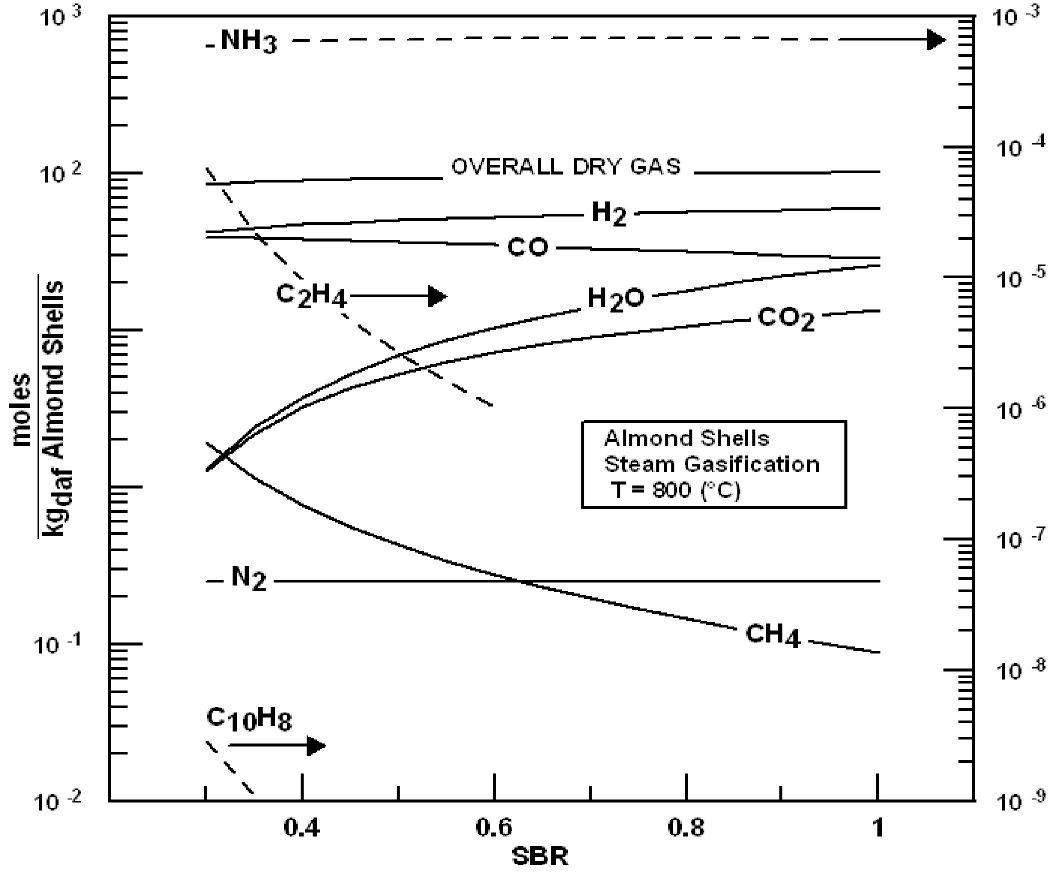
$$\Delta G_{f_i}^{0} + RT \ln(y_i \, P) + \sum_{k=1}^{m} \pi_k \, a_{ik} = 0 \qquad (i = 1,2,\ldots,c)$$

$$\sum_{i=1}^{c} y_i \, a_{ik} = \frac{A_k}{n} \qquad (k = 1,2,\ldots,m)$$

The numerical procedure proposed by Smith and Missen (1982) to solve the above equations for single-phase systems has been coded in MATHCAD11®.

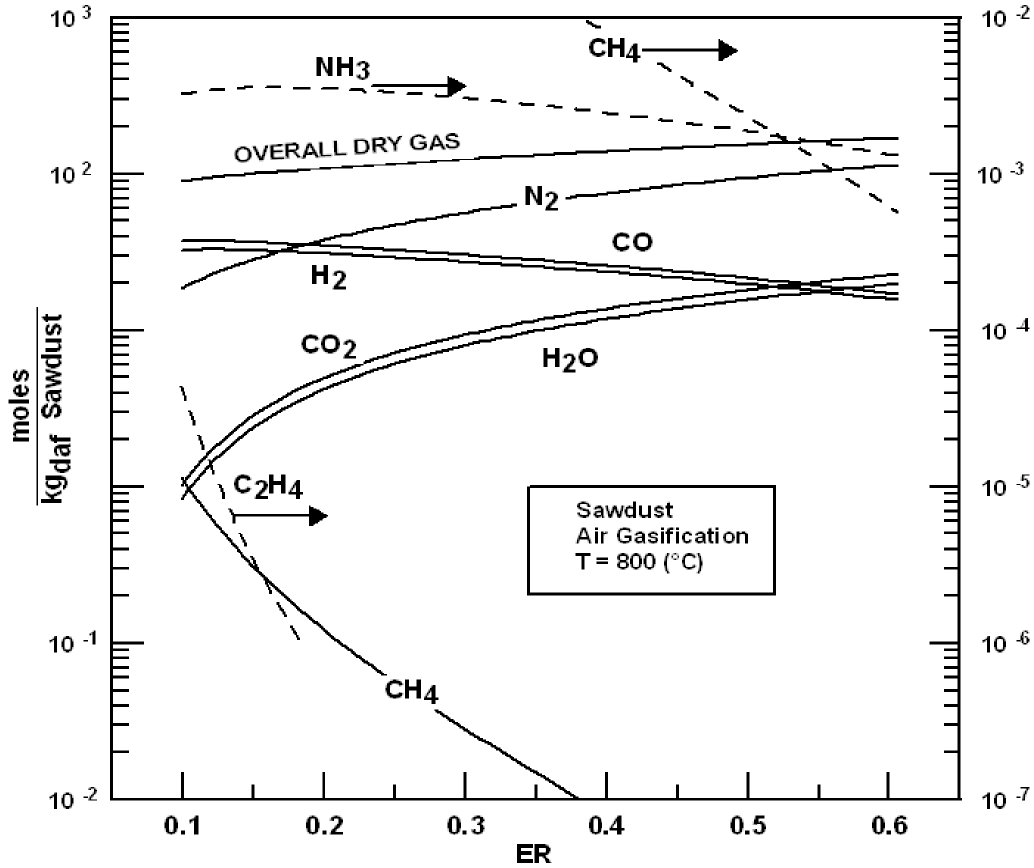
It has been applied to the gaseous phase obtained as a result of steam gasification of almond shells and air gasification of sawdust

	Almond shells	Sawdust
Moisture (wt %)	7.9	6.33
Ash (wt % dry)	1.26	1.86
Elemental Analysis (wt % daf)		
Carbon	51.7	48.2
Hydrogen	6.1	6.4
Oxygen	41.4	45.9
Nitrogen	0.76	0.23
LHV (kJ/kg daf)	18306	18467



Steam gasification of almond shells at 800°C:

yield of different gaseous species as a function of SBR.



Air gasification of sawdust at 800°C:

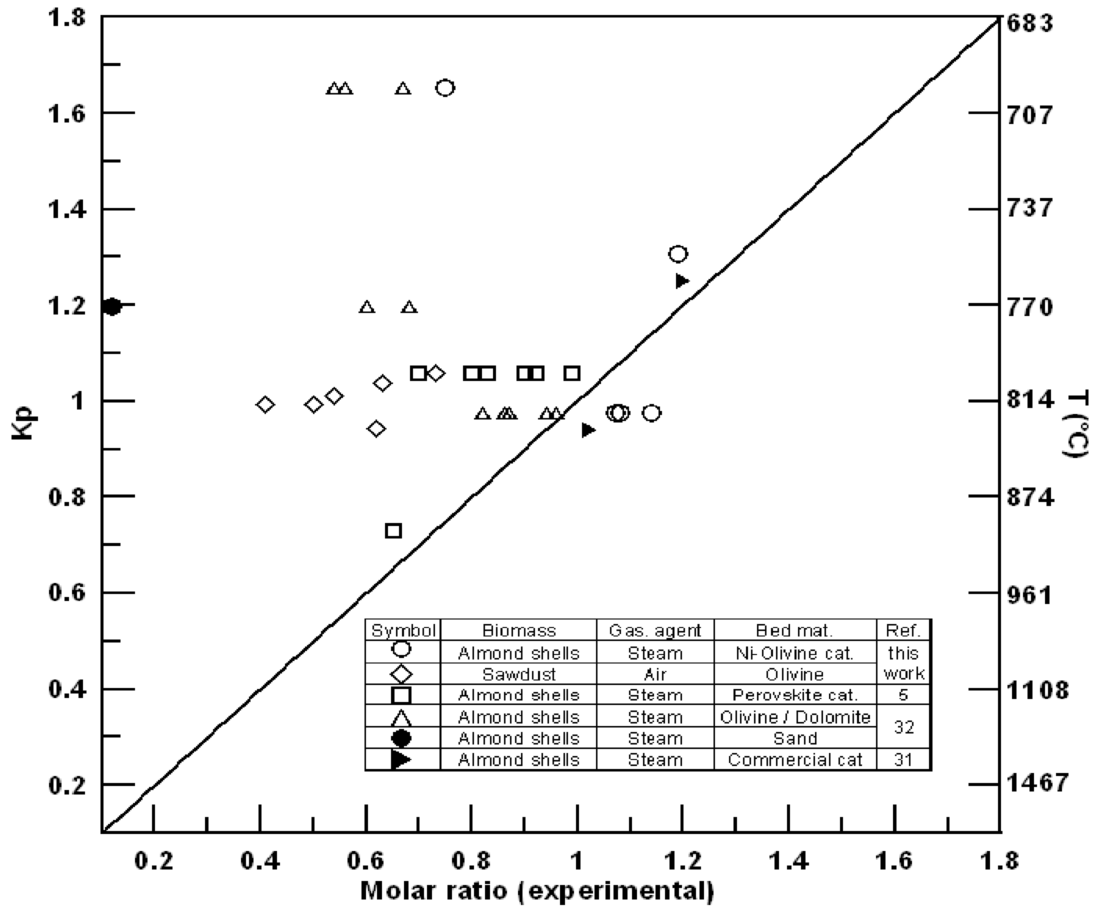
yield of different gaseous species as a function of ER.

Comparison of theoretical thermodynamic data with the results of experimental tests performed utilizing

- **the same laboratory facility;**
- **the same operating procedures.**

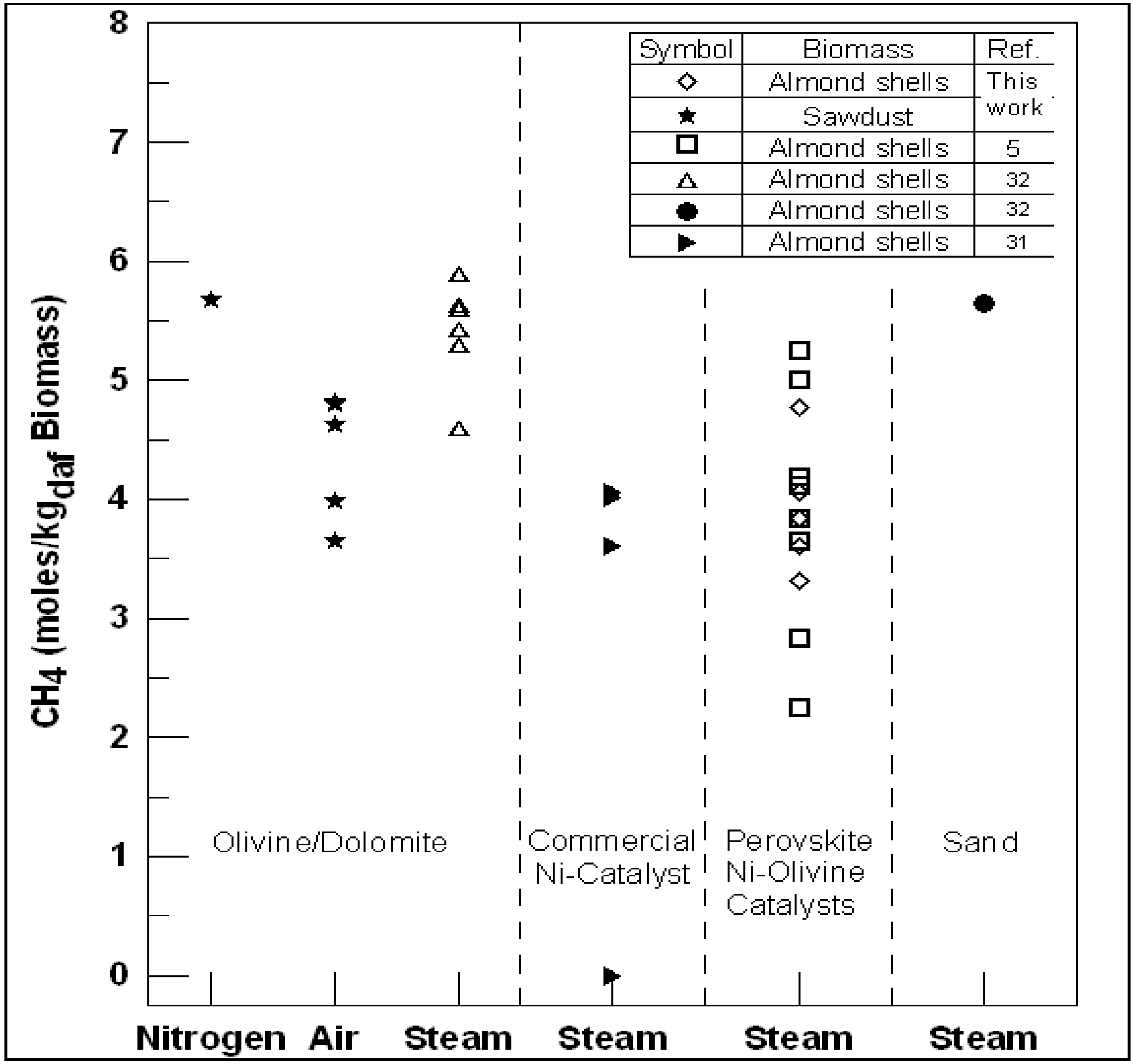
Obvious kinetic arguments can be invoked to justify the residual presence of those compounds that are predicted to be absent, nevertheless these can not explain why they have appeared in the first place.

On the other hand, the thermodynamic analysis highlights effects linked to the non-isothermal gasification process experienced by fuel particles, while they are heated from ambient conditions to about 900°C. The final products retain a memory of this thermal history: devolatilization is a fast process, occurring during the particle heating up phase, whereas subsequent heterogeneous reactions involving charcoal are much slower.



Water gas shift reaction:

experimental vs equilibrium values of the molar concentration ratio at different operating conditions.



Methane yield per kg daf biomass at different operating conditions.

A semi-empirical calculation procedure

CHEMCAD® software routine for chemical reactors

modification of the elemental balance restraining conditions for carbon and hydrogen in the equilibrium calculations:

$$A_C = A_{C0}\,X_C - n_{CH_4dev}\left(1 - X_{CH_4}\right)$$

$$A_H = A_{H0} - 4\,n_{CH_4dev}\left(1 - X_{CH_4}\right)$$

A_{C0} and A_{H0} are the true values of carbon and hydrogen g-atoms in the system, and A_C and A_H are the corrected quantities to utilize in the equilibrium calculations.

$$n_{CH4dev} = 5.5; \qquad 0.8 \le X_C \le 0.9; \qquad 0 \le X_{CH4} \le 0.33$$

A fictitious inert gaseous compound is introduced, having the function of restoring methane contribution in the calculation of the total moles and gas molar fractions:

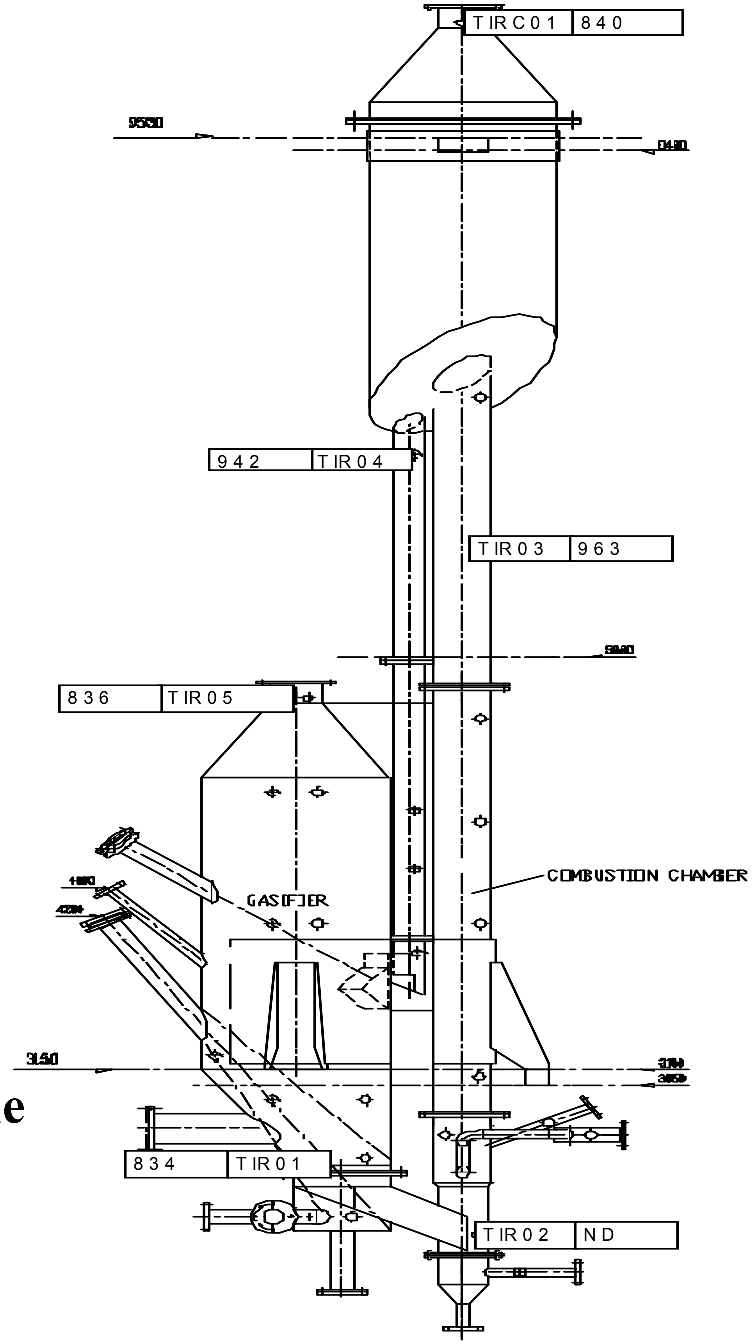
$$n_{Ig} = n_{CH_4dev}\left(1 - X_{CH_4}\right)$$

	Plant results [33]	Calculation tool	Straightforward equilibrium
Gas yield Nm^3dry/kg daf	2.04	2.10	2.64
H_2 vol. %	11.9	11.9	24.5
CO vol. %	14.2	15.4	28.7
CO_2 vol. %	16.4	15.7	6.6
CH_4 vol. %	4.0	6.5	0.01
C2 vol. %	1.45	0.0	0.0
C6+ vol. %	0.03	0.0	0.0
N_2 vol. %	51.4	50.5	40.3
NH_3 vol. %	n.d.	0.001	0.002
H_2O vol% wet	12.4	12.0	5.9
Char + Tar g C/kg daf	69.2 [1]	74.7	0

Prediction of the performance of the 500kWth fast fluidized bed biomass gasifier operated by ECN (Netherlands Energy Research Foundation)

Air gasification at T=851°C (Kersten et al., 2003); X_C=0.85; X_{CH4}=0.

Bed inventory	Olivine		Ni-olivine	
Temperature	850 °C		838 °C	
	Plant results[34]	Calc. tool	Plant results[34]	Calc. tool
Gas yield Nm^3 dry/kg dry	0.95	1.13	0.99	1.20
H_2 vol. %	38.9	47.7	43.9	52.7
CO vol. %	29.1	19.4	27.2	20.2
CO_2 vol. %	17.5	21.9	18.8	20.2
CH_4 vol. %	11.4	10.7	8.3	6.9
C2 vol. %	2.0	0	1.3	0.0
N_2 vol. %	n.d.	0.08	n.d.	0.08
NH_3 vol. %	n.d.	0.0091	n.d.	0.0002
[H_2O in-H_2O out]/[Biomass dry]	0.044	0.077	0.072	0.082



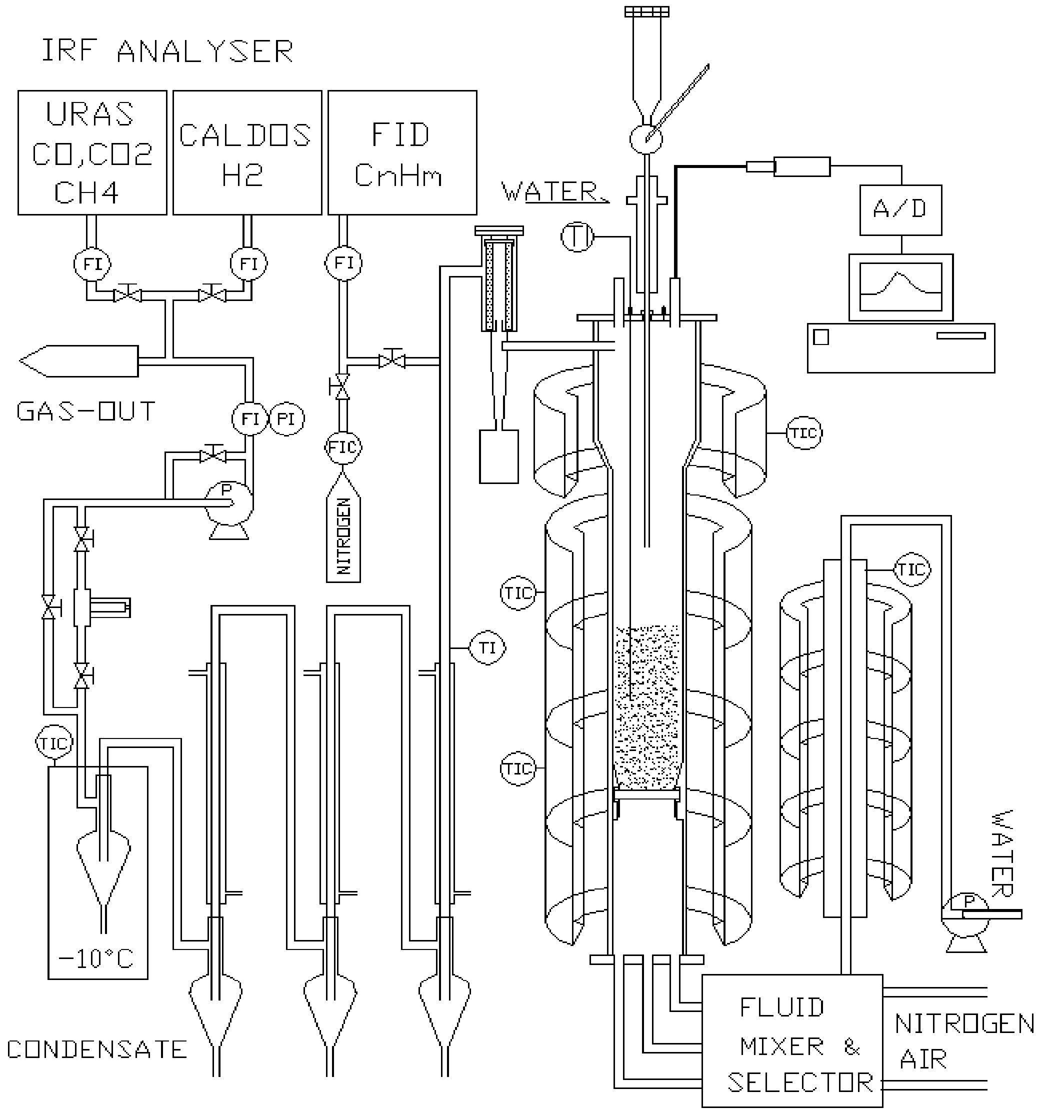
Steam gasification of wood pellets (SBR=0.63) with the 100kWth FICFB gasifier operated by the Technical University of Vienna (Pfeifer et al., 2004)

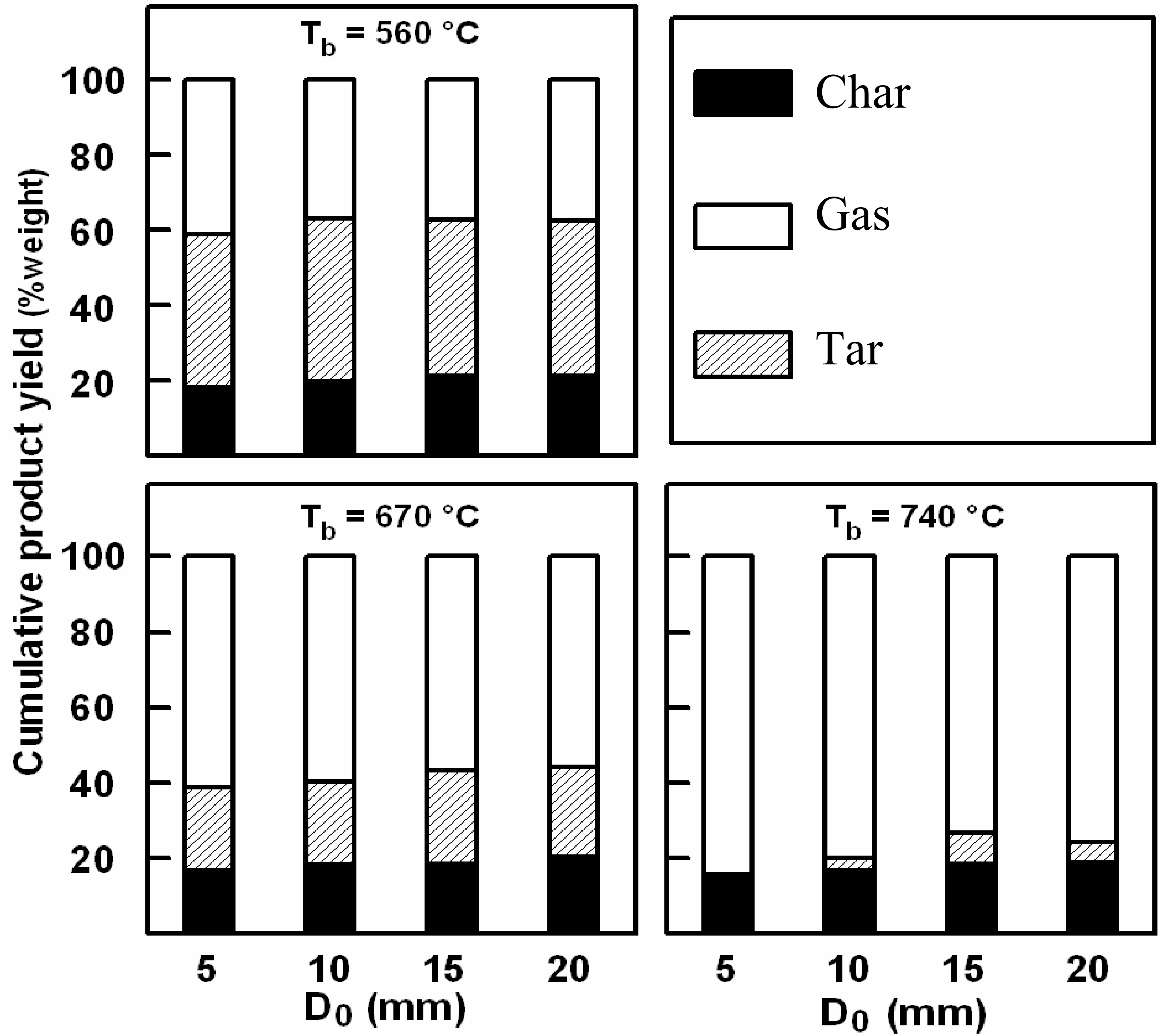
Olivine: X_{CH4}=0. - Ni-olivine: X_{CH4}=1/3

Products composition from biomass devolatilization at high temperature:

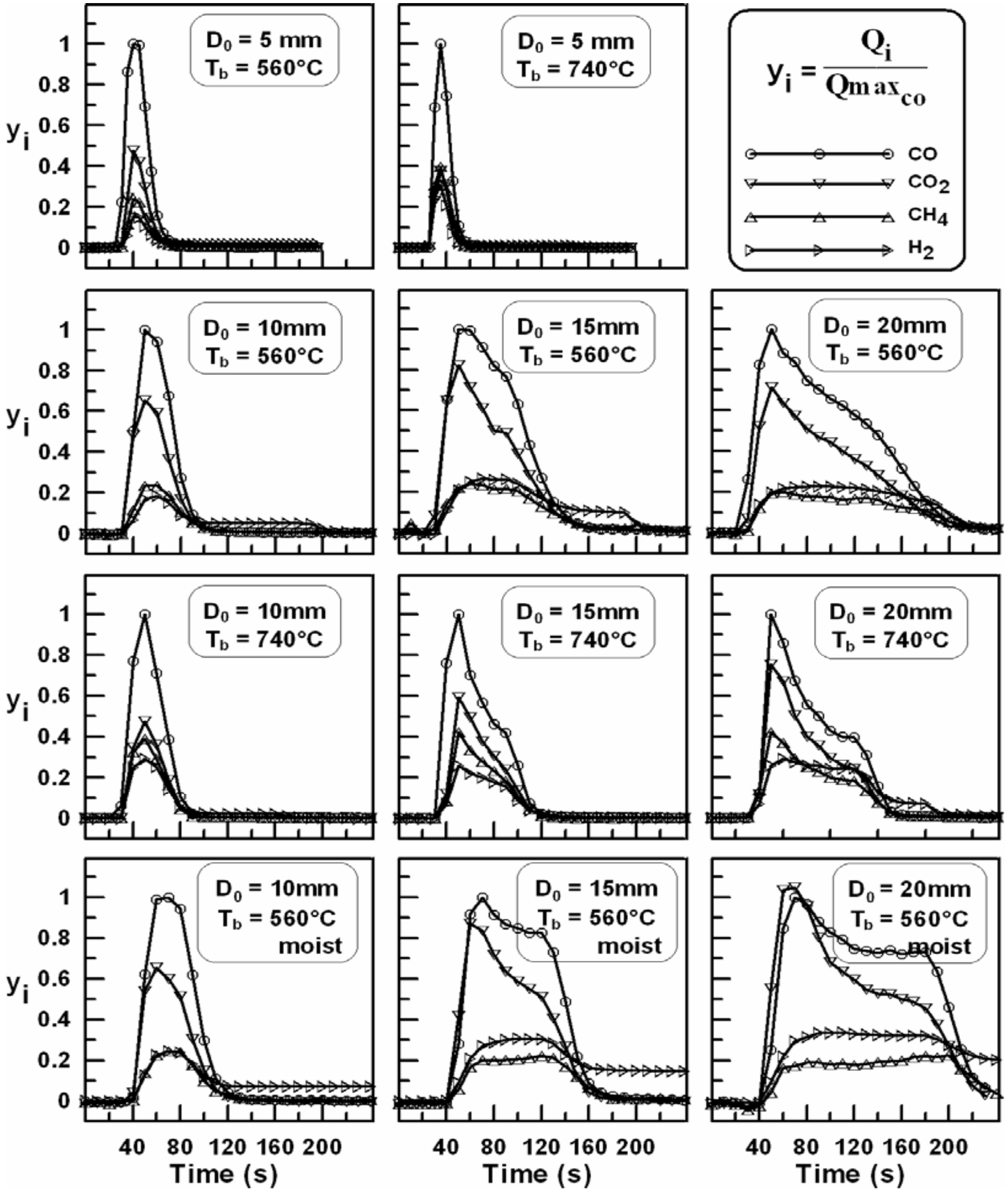
- **an experimental approach (tested with wood spheres of controlled size)**

(Jand and Foscolo, Ind. Eng. Chem. Research, in press)

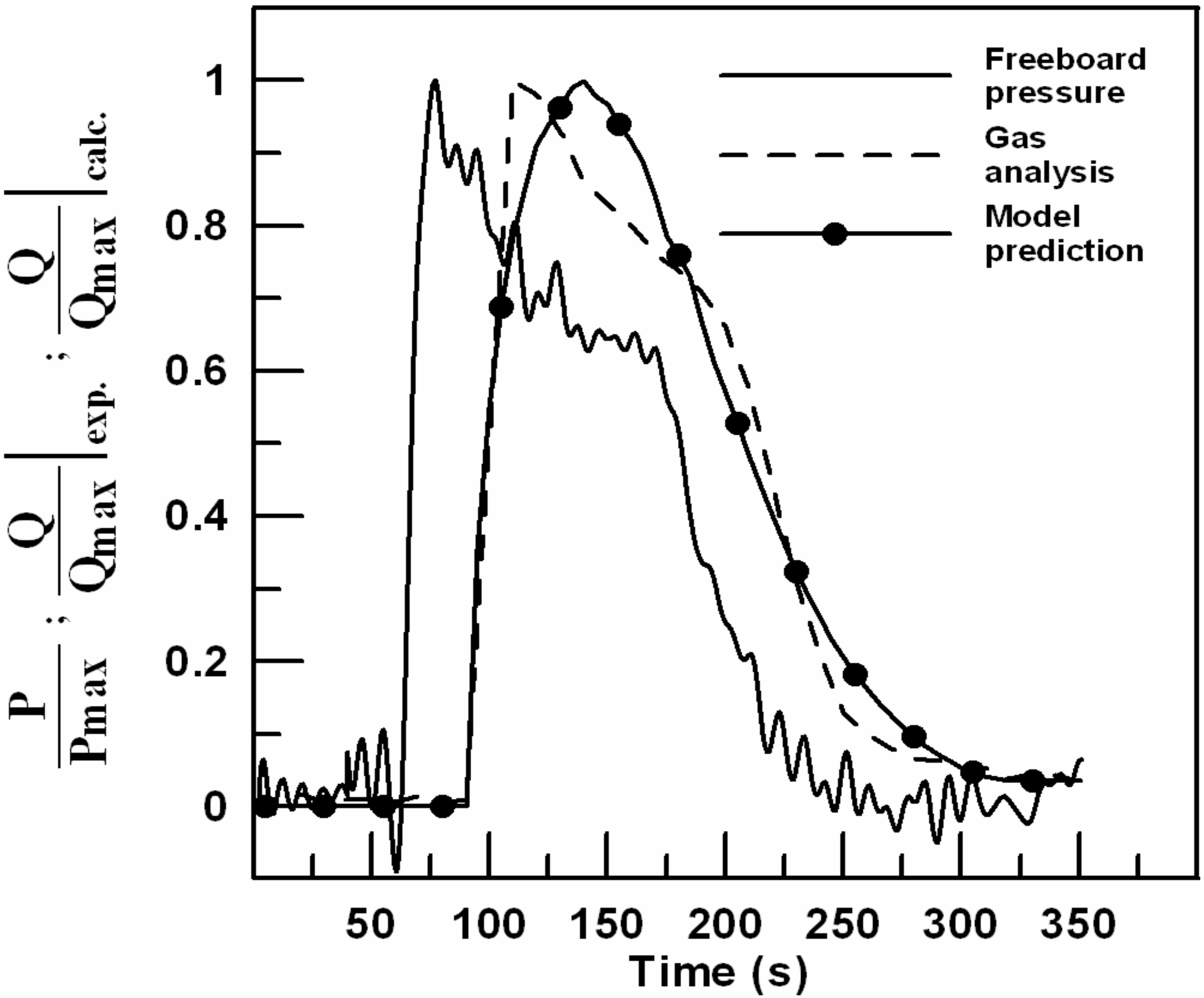




Cumulative product yield (%weight)
Tb = 560 °C
Tb = 670 °C
Tb = 740 °C
100
80
60
40
20
5
10
15
20
D0 (mm)
Char
Gas
Tar



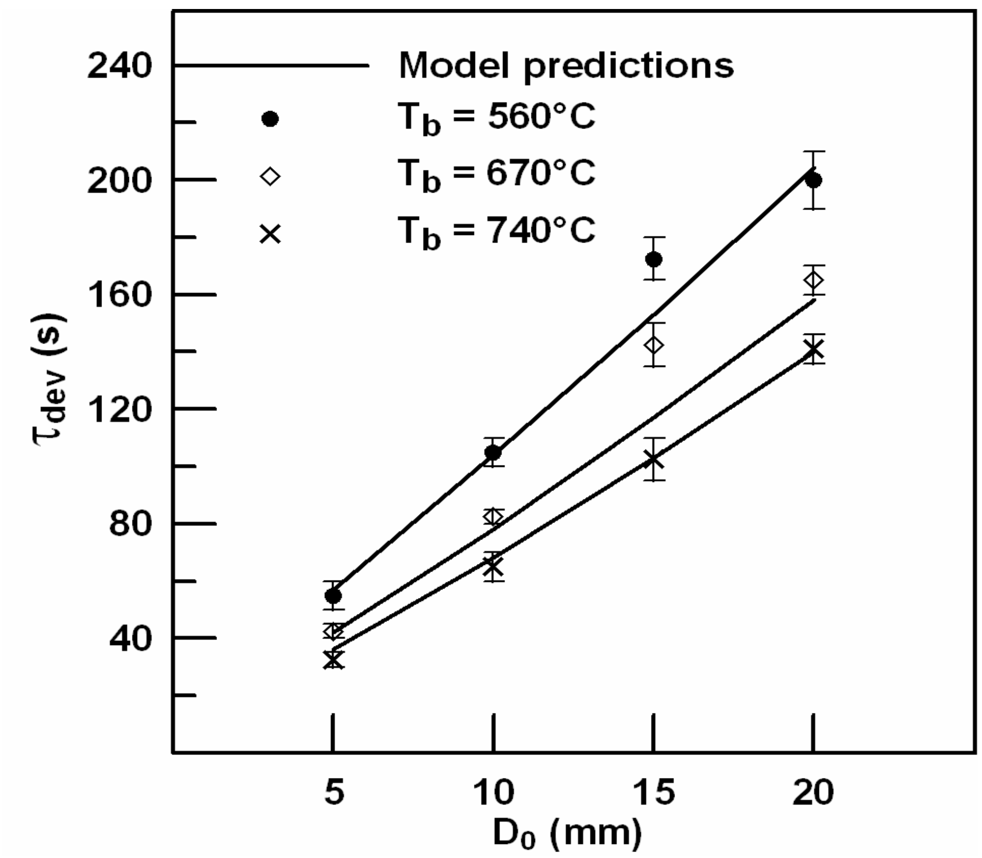
Instantaneous yield of different gases – effect of temperature, wood size, and moisture.



Dwood = 20 mm;   Tbed = 560°C

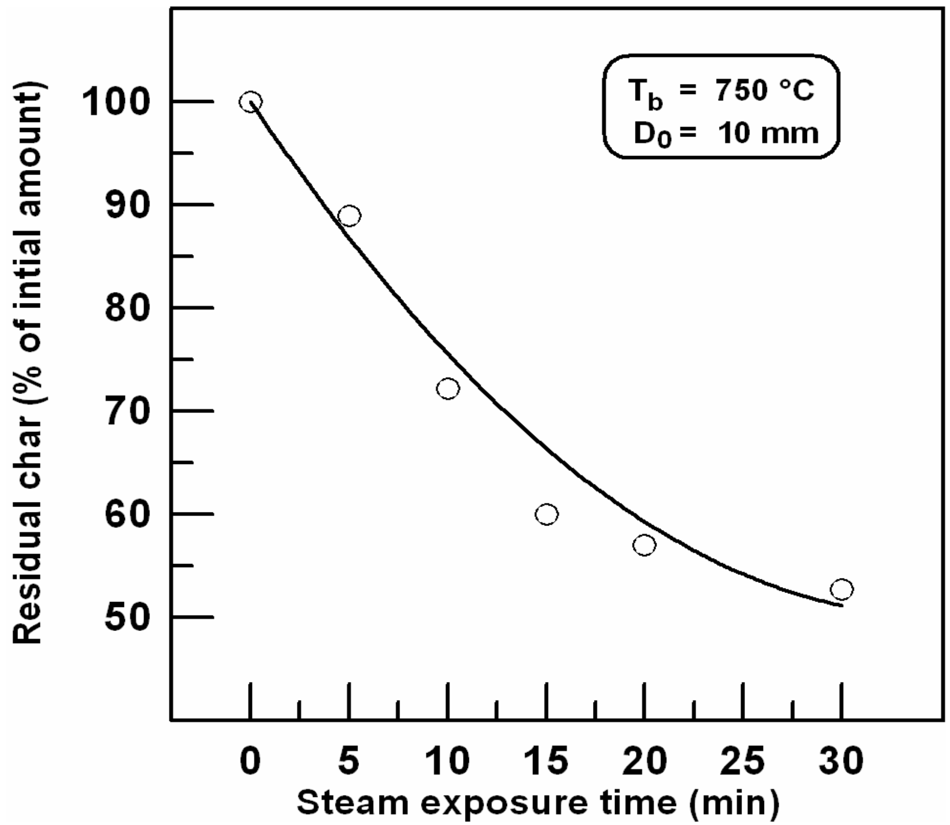
Devolatilization time

Experimental data and model predictions



Char consumption with steam

Experimental data



R&D Projects at pilot scale

- **Direct coupling of biomass gasification and fuel cell**

funded in part by EC (JOR3-CT97-00196 and ENK5-CT2000-00314) and by the Italian Goverment (FISR, GU n° 146, June 24, 2004).

- **Electricity generation from wood scraps and rice husk**

a bilateral project between Italy and China, involving the Liaoning Institute for Energy Resources (LIER), ENEA (Trisaia Research Centre) and the University of L'Aquila.

Overall objectives

- high energy efficiency, even in distributed power generation
- ultra-clean environmental performance
- near-zero greenhouse gas emissions

Specific project objectives

- assembly and operation of an integrated pilot plant
- ancillary research activities focused on key areas to the optimization of the plant performance

Challenges

Construction and operation of an integrated pilot plant that includes 3 major sections:

•500 kWth fast internally circulating fluidized bed (FICFB) gasifier for catalytic biomass (almond shells, wood chips) steam-gasification;

•Hot gas clean-up system for acid compounds removal by adsorption on a basic powder, and ceramic candle fine particle filtration;

•125 kWe Molten Carbonate Fuel Cell (MCFC).

Challenges

Accompanying research tasks:

- Development of a low-cost Ni-olivine catalyst to be included in the bed inventory of the gasifier for Hydrogen enhancement and Tar reduction;

- Operation of a cold model to optimize design and running conditions of the gasification system;

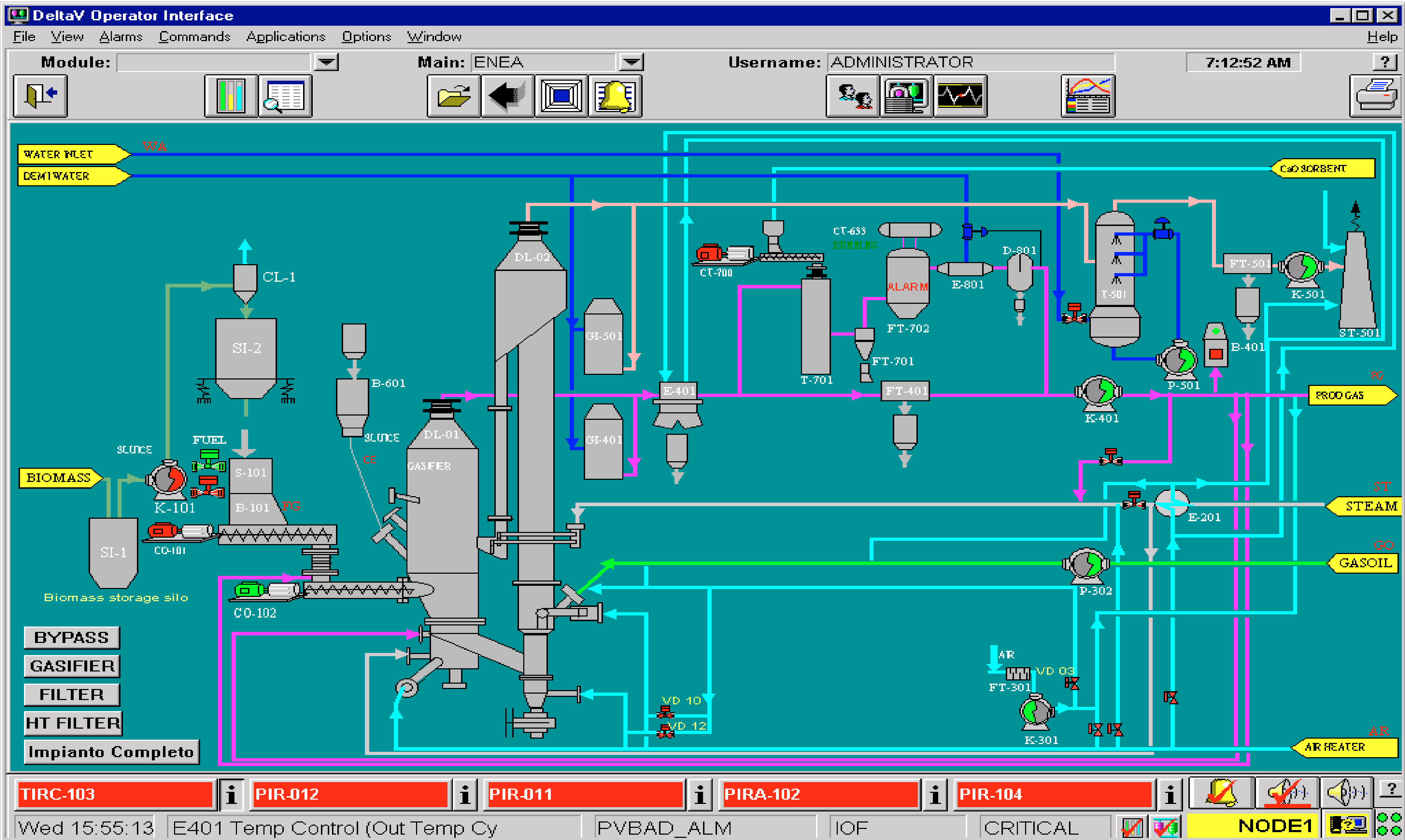
- CFD model of the gasifier, which combines overall reaction kinetics and heat transfer processes with fluidization dynamics;

- Simulation tool of the whole system, implemented on commercial software, to develop optimal operation and control strategies;

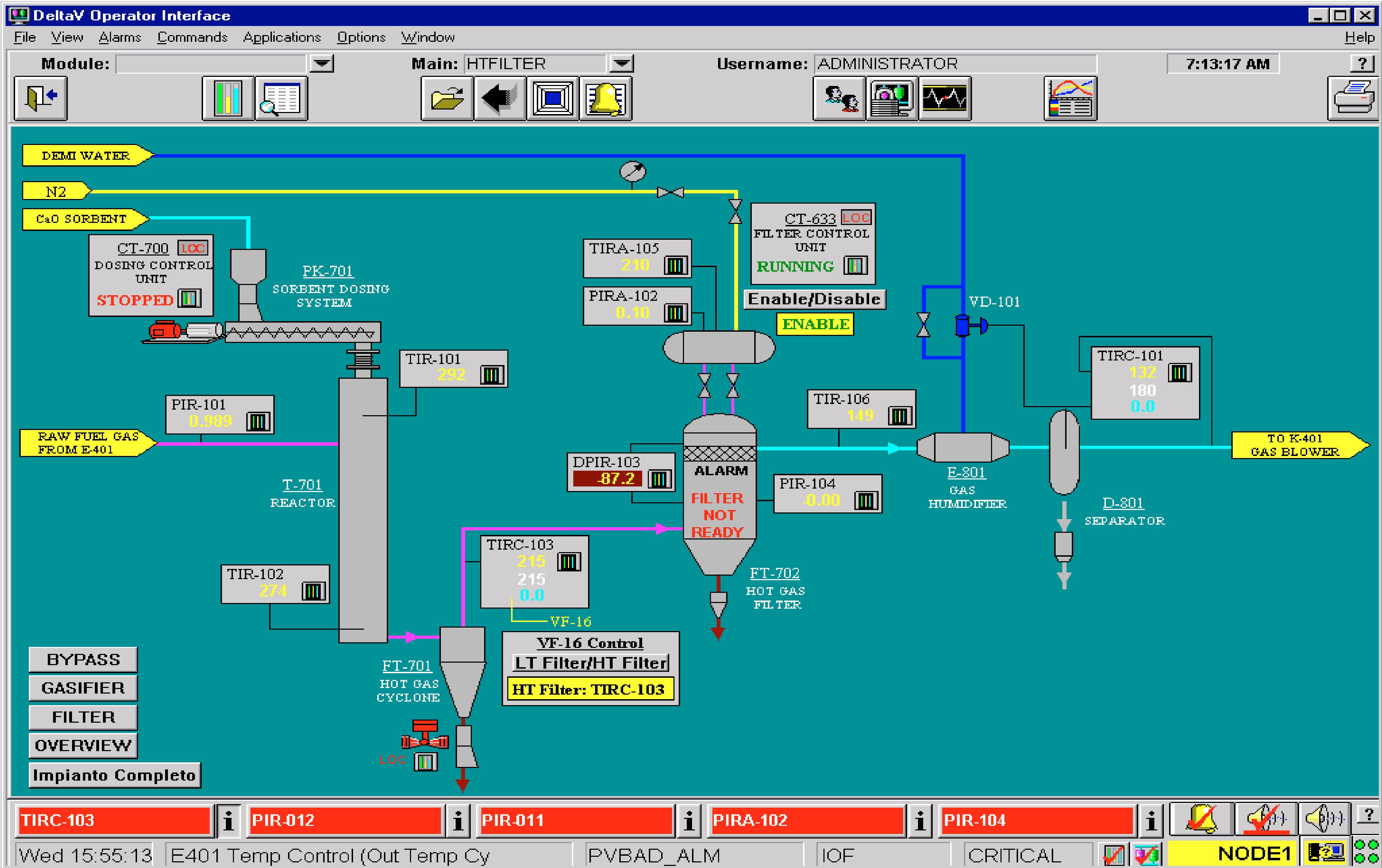
Project structure

Participant Name	Main Functions
University of L'Aquila Italy	Coordination, Pilot plant integration and catalytic gasification studies
Technical University of Vienna Austria	System simulation, catalyst performance in 100 kWth gasifier
University College London United Kingdom	Cold modeling and CFD simulation of the gasifier
University of Strasbourg France	Development, characterization and preparation of Ni-olivine catalyst
Ansaldo Ricerche Srl Genova – Italy	Hot gas clean-up system: acid gas removal
Pall Schumacher GmbH Crailsheim – Germany	Hot gas clean-up system: fine particles filtration
ENEA – Research Agency for New Technology, Energy and Environment – Italy	Pilot plant assembly and operation
Ansaldo Fuel Cells SpA Genova – Italy	MCFC stack design and supply

The Fast Internally Circulating Fluidized Bed (FICFB) Gasifier, developed by Technical University of Vienna.

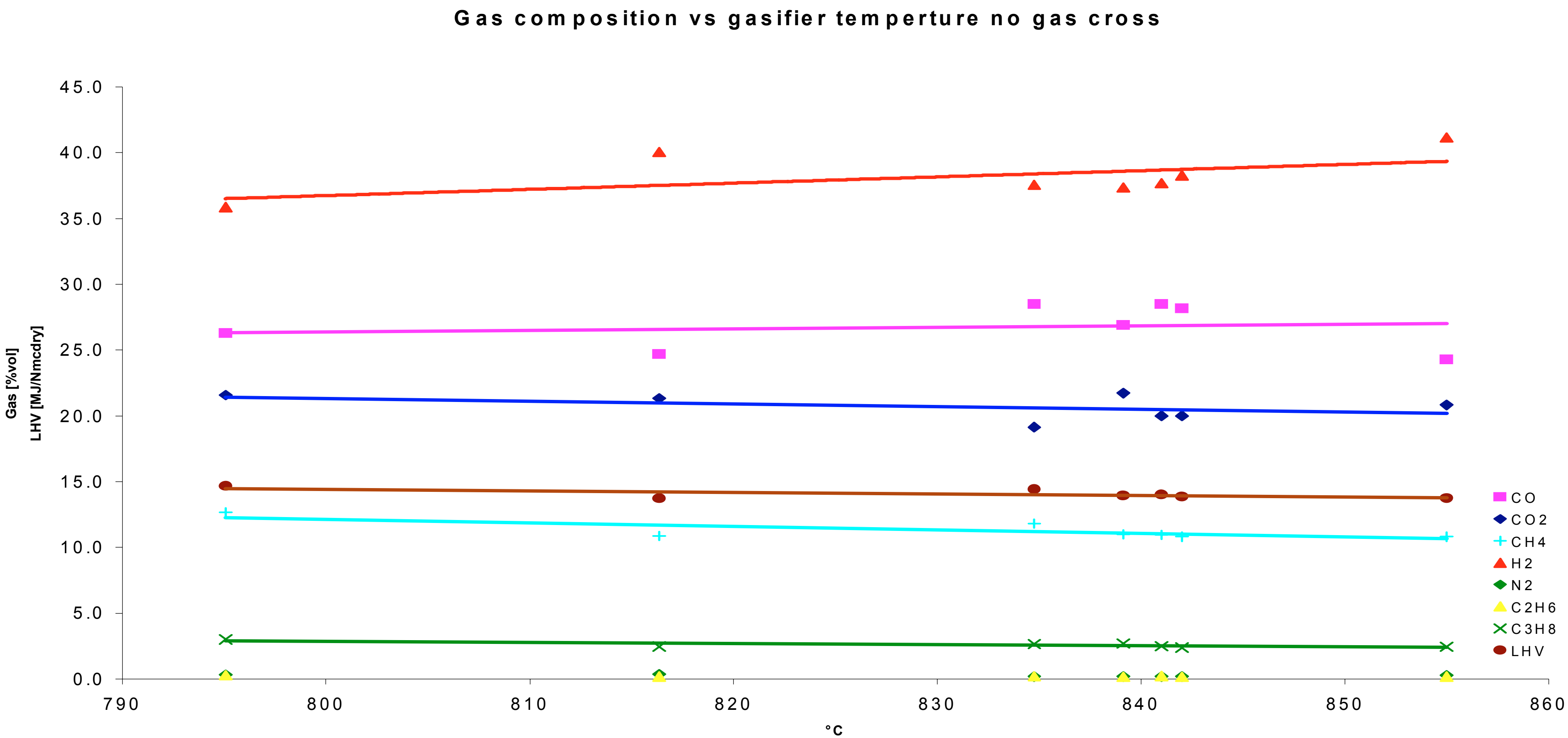


The hot gas clean-up section of the Trisaia integrated plant



The Trisaia pilot plant

Fuel gas quality (Olivine bed inventory)



Dry gas yield: up to 1.4 Nm^3/kg of biomass d.a.f.

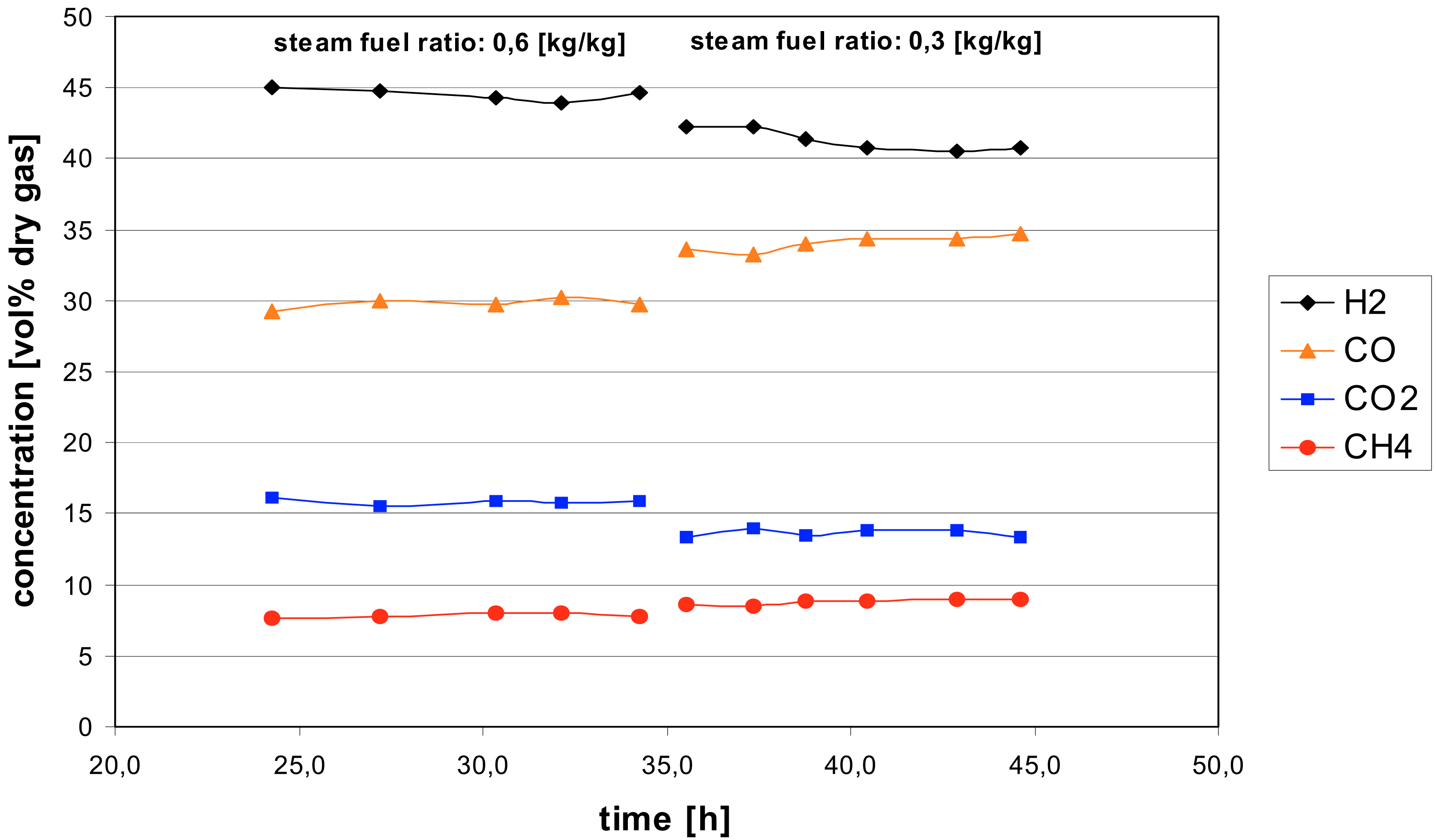
Tar content: 3 – 6 g/Nm^3 dry gas

Gasifier chemical efficiency: up to 72%

Gasifier thermal efficiency: up to 95%

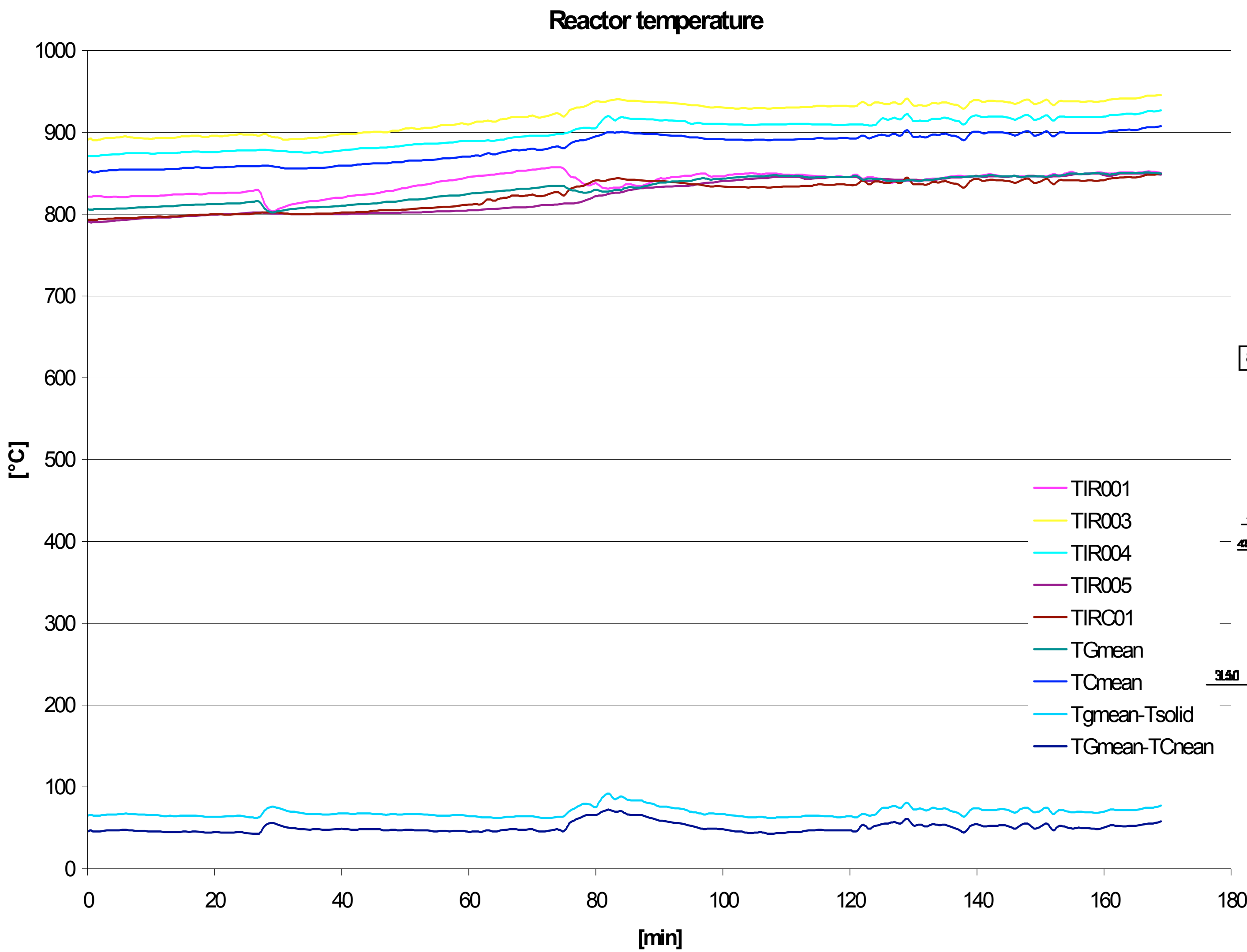
Fuel gas quality with the Ni-Olivine catalyst in the gasifier bed

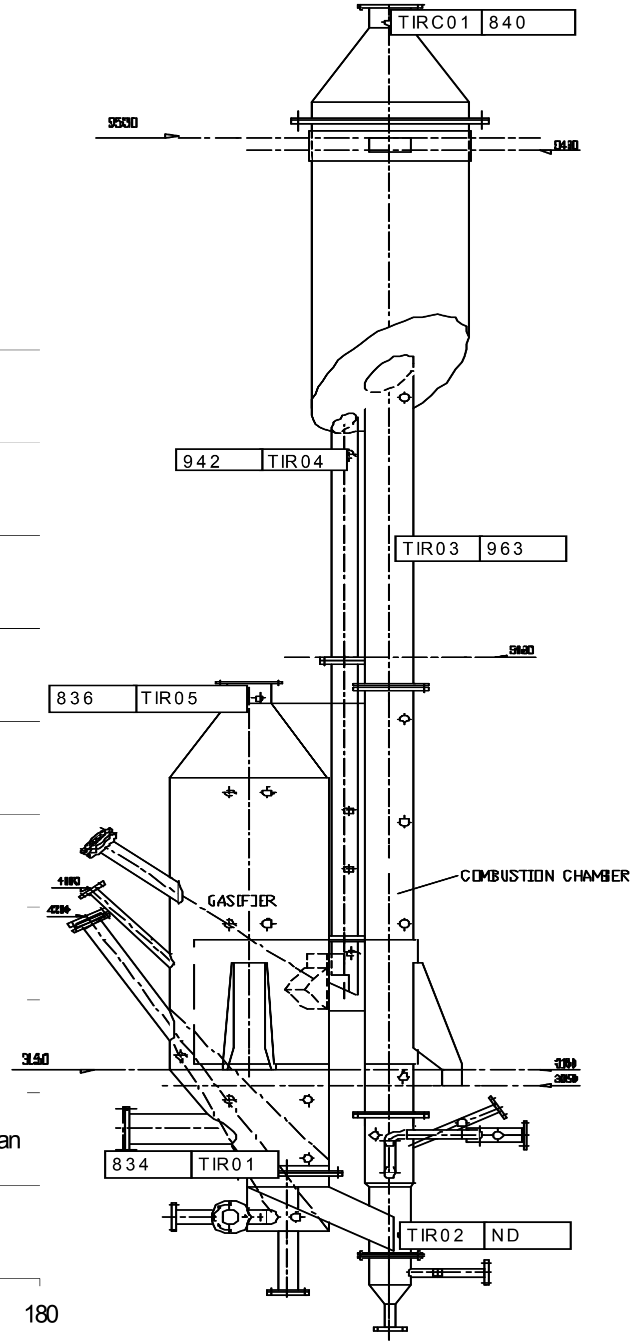
(Kiennemann, Petit, Courson, Foscolo, Rapagnà and Matera, PCT Patent, 2001)



Tar content = 0.5 g/Nm^{3}dry when the bed inventory is 50% Ni-Olivine

Temperature level in gasification and combustion zones

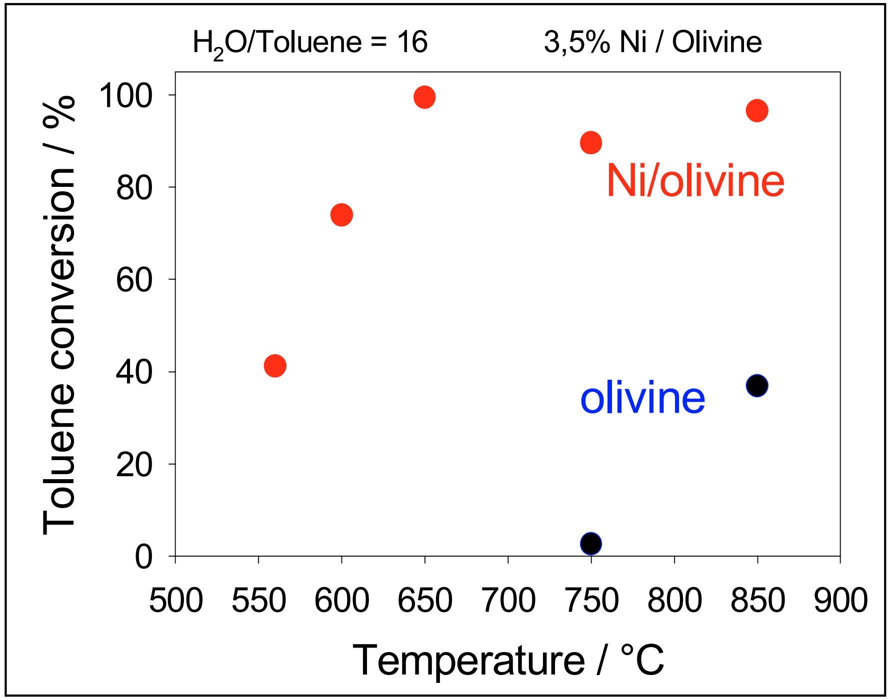




Tar reforming

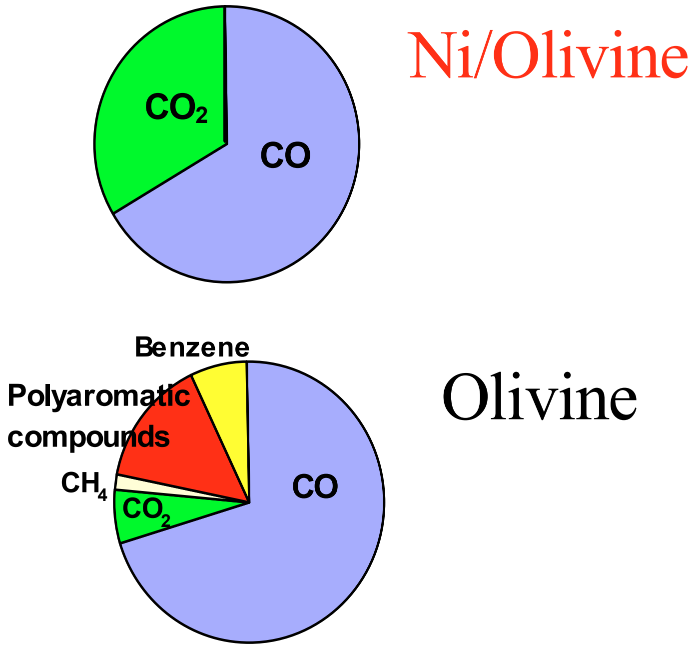
Steam reforming of toluene

$$C_7H_8 + 7H_2O \rightarrow 7CO + 11H_2 \quad \text{and} \quad CO + H_2O \rightleftarrows CO_2 + H_2$$



- high activity of **Ni/Olivine** in toluene reforming at 800°C
- stability (no deactivation) after 7 h on stream

Selectivity 850°C



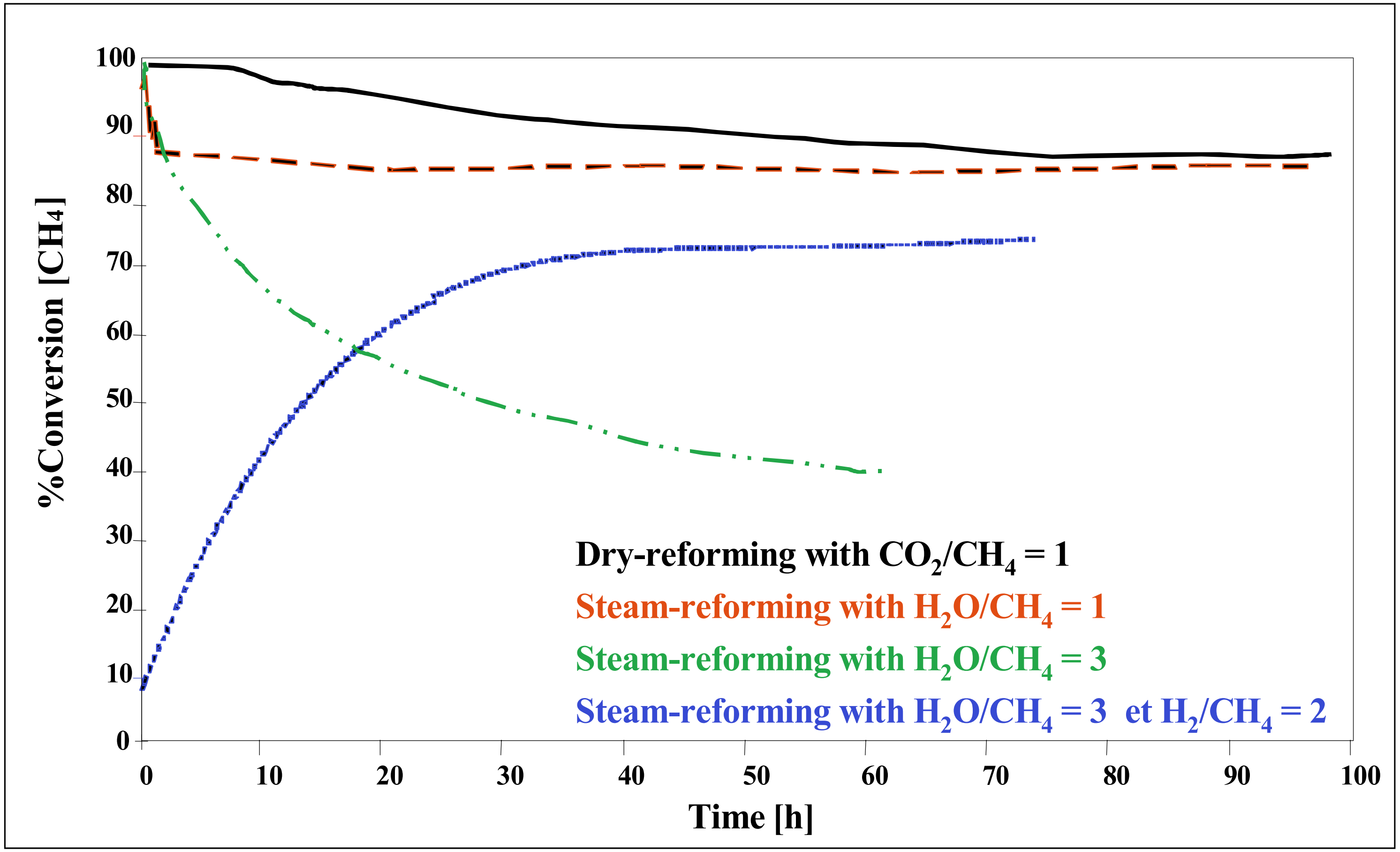
- total toluene conversion to permanent gases CO_2, CO and H_2 with **Ni/Olivine** catalyst

Catalyst optimisation — Ageing

- **Dry- and Steam-reforming of methane**

$$\begin{cases} CH_4 + CO_2 \longrightarrow 2CO + 2H_2 \\ CH_4 + H_2O \longrightarrow CO + 3H_2 \end{cases}$$

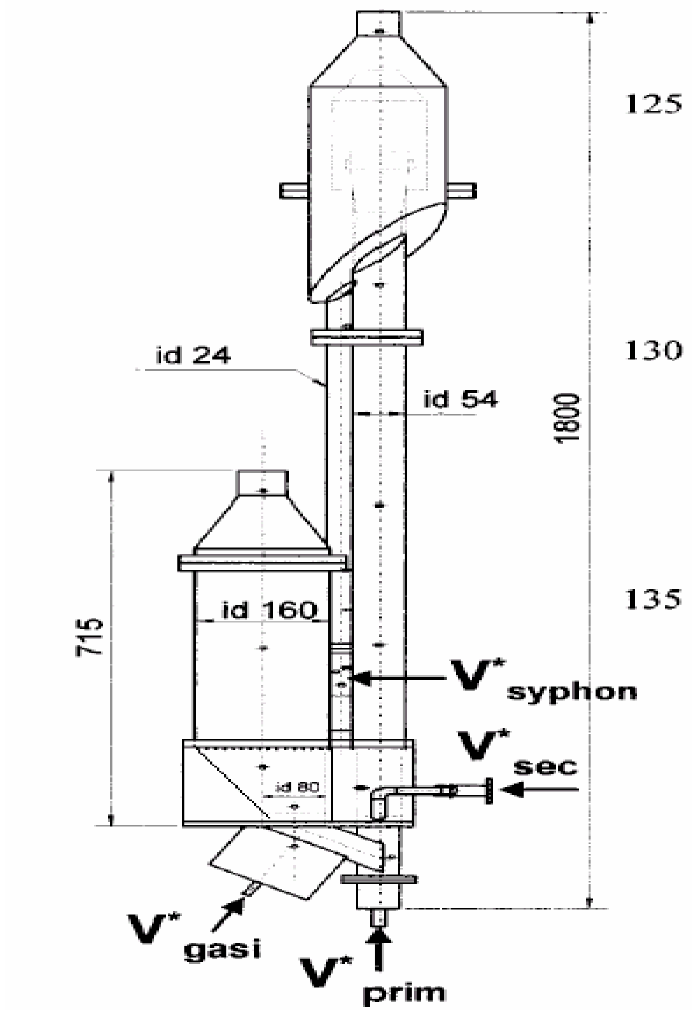
F(total) = 7.5 NL/h/$g_{catalyst}$, F(CH_4) = 0.75 NL/h/$g_{catalyst}$, T = 800 °C



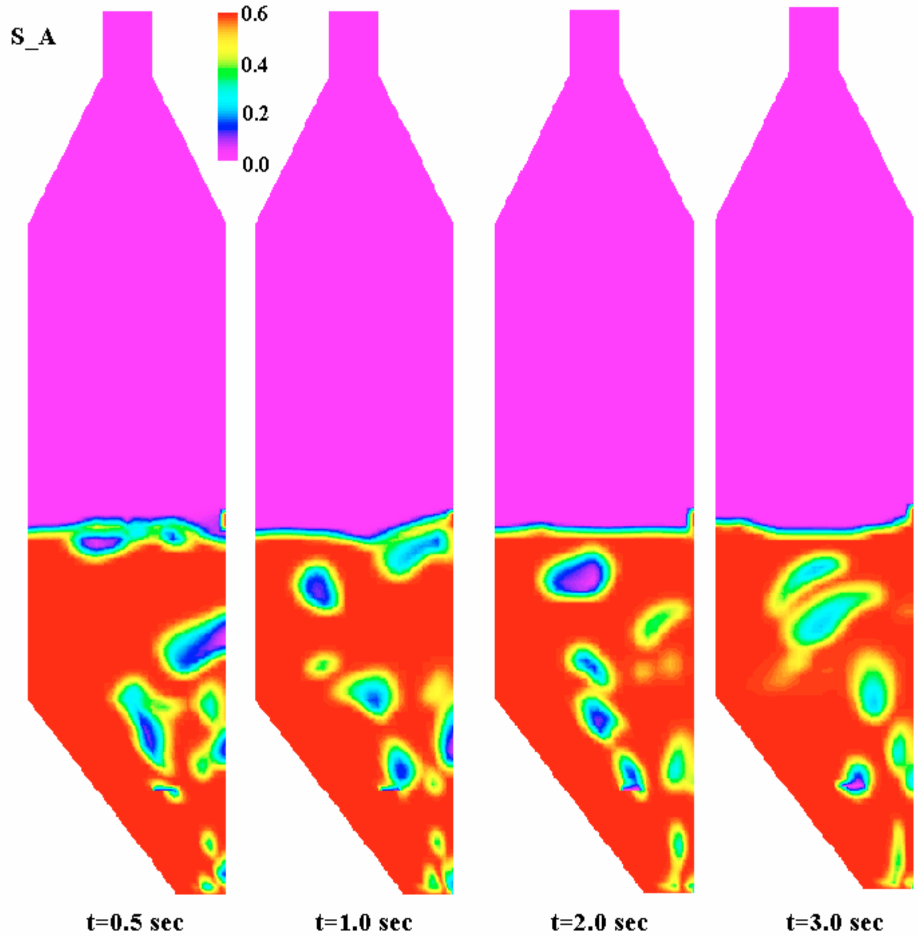
Simulation of the fluidized bed gasifier

(Brandani and Zhang, AIChE Symp. Series, 2004)

Cold Model



CFD



Two gas inlets with solid circulation

Performance of the entrained flow reactor for fuel gas deacidification

(Ansaldo Ricerche srl)

T_{in} [°C]	508
T_{out} [°C]	476
CaO [kg/h]	0.57
Ca/(Cl+S) [molar]	4.3
H_2S_{in} [ppmv]	250
HCl_{in} [ppmv]	105
H_2S_{out} [ppmv]	40
HCl_{out} [ppmv]	36
SR [%]	84
ClR [%]	66

Performance of the ceramic candle filter

(Pall Schumacher Germany GmbH)

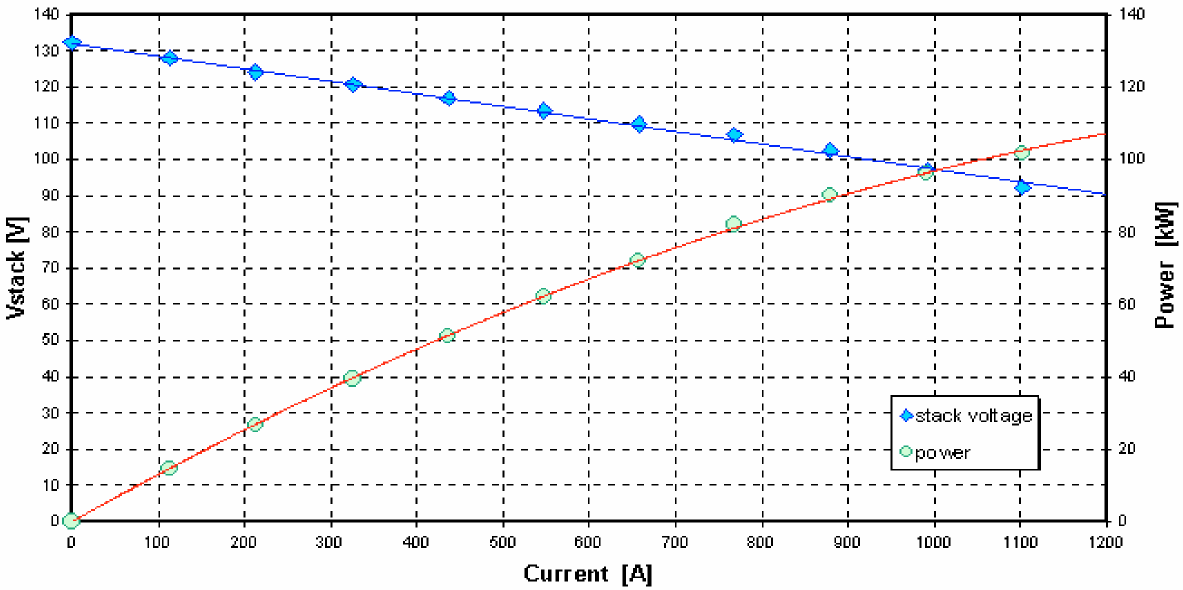
Gas flow rate [Nm^3/h]	**140**
Tin [°C]	**460**
Tout [°C]	**430**
ΔP [mbar]	**12**
N_2 temperature [°C]	**210-220**
$Particulate_{in}$ [g/Nm^3]	**6.4**
$Particulate_{out}$ [mg/Nm^3]	**2.1**

Performance of the 125 kW molten carbonate fuel cell

(Ansaldo Fuel Cell SpA)

(WP8) Simulated Biomass-derived gas - Results

V vs. I curve



simulated mix (*)

ANODE:

H_2	40.4 %MOL
CO_2	24.8 %MOL
STEAM	27.8 %MOL
N_2	7.0 %MOL

CATHODE:

O_2	12.9 %MOL
CO_2	5.0 %MOL
STEAM	13.7 %MOL
N_2	68.4 %MOL

(*) The same planned for the TRISAIA Plant

power

stack voltage = 92.4 V

stack current = 1102 A

100kW has been demonstrated

By courtesy of

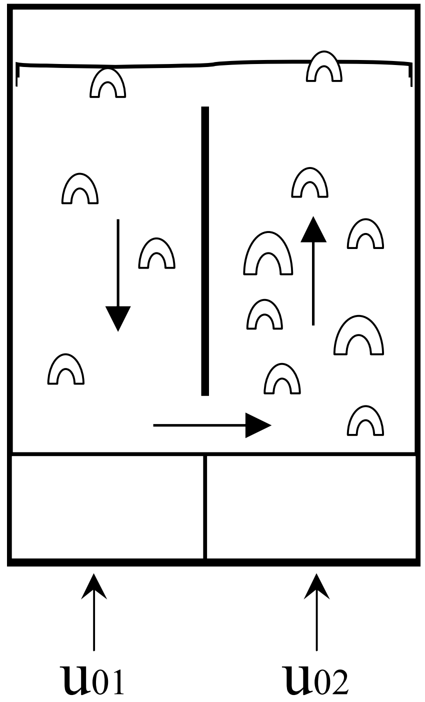
Ansaldo Fuel Cell SpA

GASIFICATION OF WOOD SCRAPS AND RICE HUSK FOR ELECTRICITY PRODUCTION

Project Content

- **Planning, designing, realisation and testing in Italy, in co-operation with Chinese experts from LIER, of a fluidized bed gasification pilot plant of 1 MW(th) coupled with internal combustion engine and power-generator (160 kWe), appropriately modified in order to use gas produced from wastes.**

- **The plant was set up at ENEA's Trisaia Research Centre and then shipped to China and installed at LIER premises in Yingkou.**



The circulation system is made of two granular beds fluidized at different gas velocities, and interconnected by means of an overflow baffle and an orifice. The overall bed inventory should allow a bubbling bed height just above the upper tip of the baffle.

The driving force for solid circulation is provided by the difference in pressure, ΔP, between the two beds, at their bottom level; as it occurs in liquid-like systems, ΔP is in turn linked to the difference in the average density of the particle suspensions on both sides of the baffle, determined by the bubble fraction associated to the respective fluidizing velocity.

Both fluidized beds are contained in the same vessel, so that the gaseous streams coming from both sides of the baffle are mixed together before leaving the reactor.

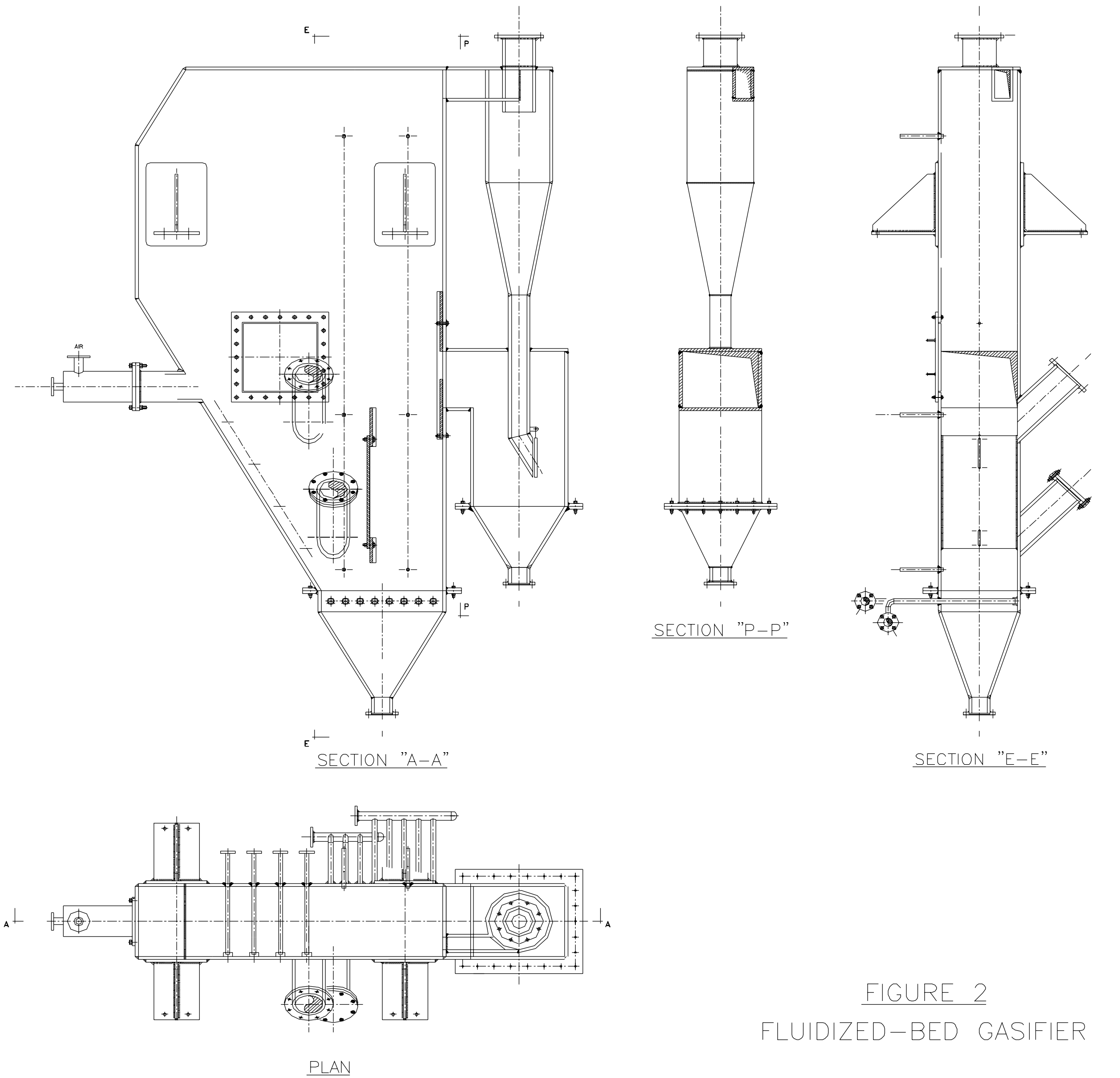


FIGURE 2
FLUIDIZED–BED GASIFIER

Interconnected Fluidized Bed (IFB) Gasifier

The cross section of the slow fluidization chamber is increasing upwards, to take into account the additional gaseous flux coming out of the devolatilizing biomass particles.

The overall amount of solids in the gasifier is controlled by means of a weir, which allows transfer of the overload to an adjacent chamber utilized to withdraw ashes floating on the bed surface and particulate matter separated from the product gas stream by means of a cyclone.

Heavier and bigger solid aggregates are collected below the gas distributor pipes.

Solids accumulated in both chambers are discharged by means of rotary valves.

Cold model testing

Scaling rules are based on the equations of change for fluidization, which define a set of dimensionless numbers: systems characterized by similar values for the corresponding dimensionless quantities, exhibit similar dynamic behaviour.

In addition to the requirement of geometric similarity, which should include also particle average size, shape and size distribution, further fluid dynamic requisites are given by the equality of each one of the following quantities, between the reactor and its cold model:

$$De = \frac{\rho}{\rho_P}$$

$$Ar = \frac{d_P^3 \rho_P \left(\rho_P - \rho\right) g}{\mu^2}$$

$$Fr = \frac{U_0}{\left(g D_R\right)^{1/2}}$$