

*Benelux PHOENICS User Meeting – Eindhoven, May 24th 2005*

# **Simulation of high temperature raw materials processing using CFD**

*- education and research*

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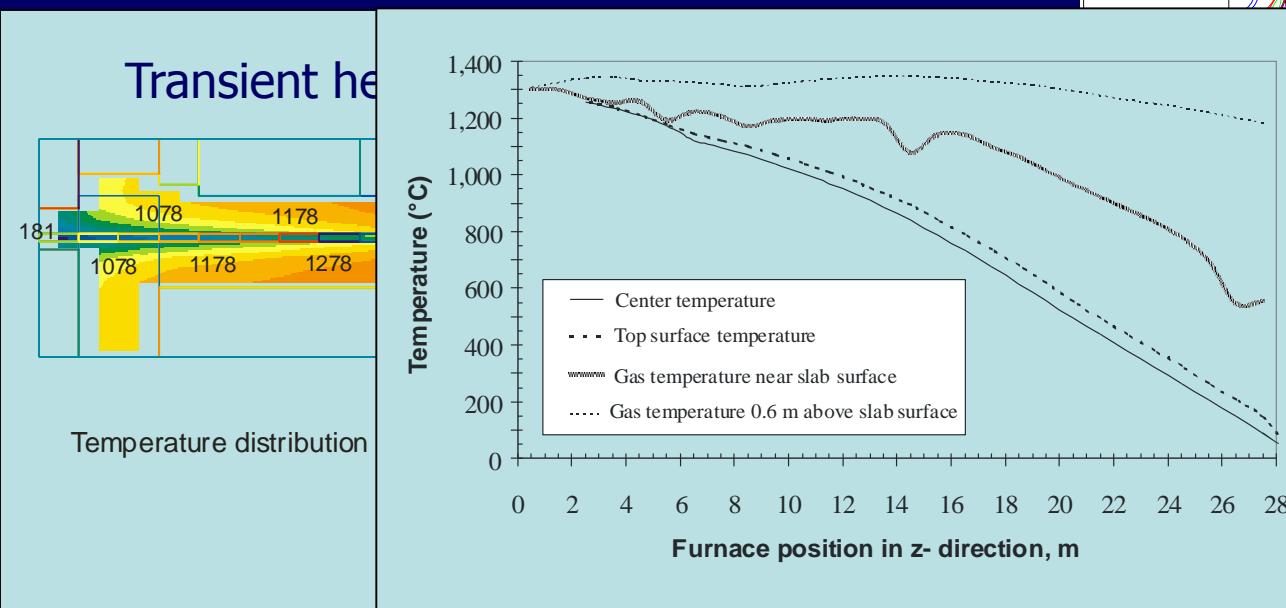
# Overview

- Introduction
- Examples of using CFD for raw materials processing
  - Simulation of hazardous waste combustion
  - Simulation of transient heating of dredging impellers
- Summary

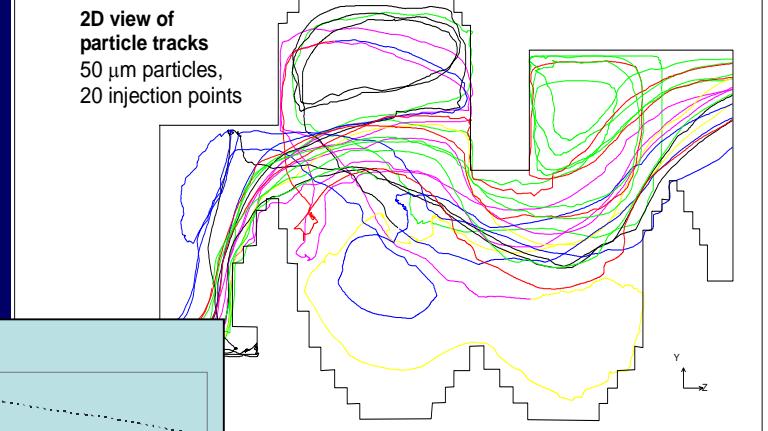
# Introduction

- History of using PHOENICS
  - Simulation of off-gas cooling in waste-heat boilers for copper flash smelting process. (1992 – 1997 HUT)
  - Simulation of gas flow and slab heating of steel reheat furnace. (1997 – 2000, HUT and TU Delft)
  - Flow and combustion modeling of hazardous waste incineration in rotary kilns. (1999 – 2004, TU Delft)
  - Predicting the fuel combustion and transient heating process of metal components. (2003 – 2004, TU Delft)

# Introduction: history of using PHOENICS



Off-gas cooling & dust flow in WHBs

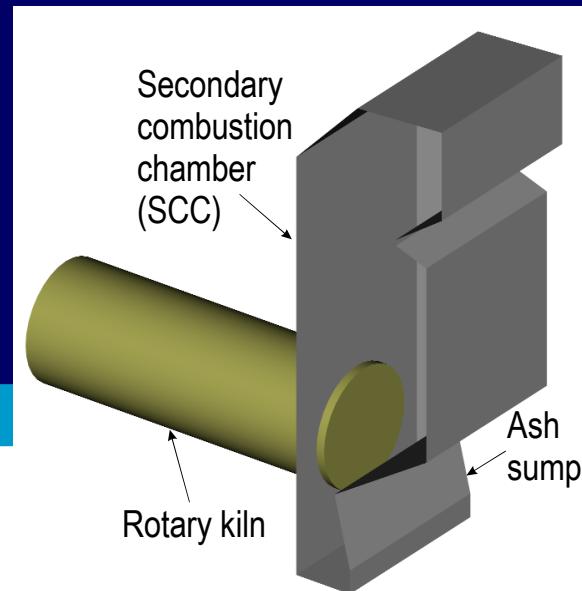


# Introduction

- Use of CFD in Raw Materials Processing at TU Delft
  - PHOENICS:
    - **Education** (1998 -): “transport phenomena in raw materials processing”, Case studies in Computer Practicals.
      - Steel flow in tundish,
      - Off-gas cooling in boilers,
      - Heat loss from furnaces and reactors,
      - Transient cooling of steel slabs
    - **MSc. thesis research:** 5 students
    - **Project research:** modelling of hazardous waste incineration
  - PhD research projects
    - Hot metal flow in an ironmaking blast furnace hearth (**CFX**)
    - Aluminium scrap melting in a rotary furnace (**CFX**)
    - Submerged arc furnace for phosphorus production (**Fluent**)

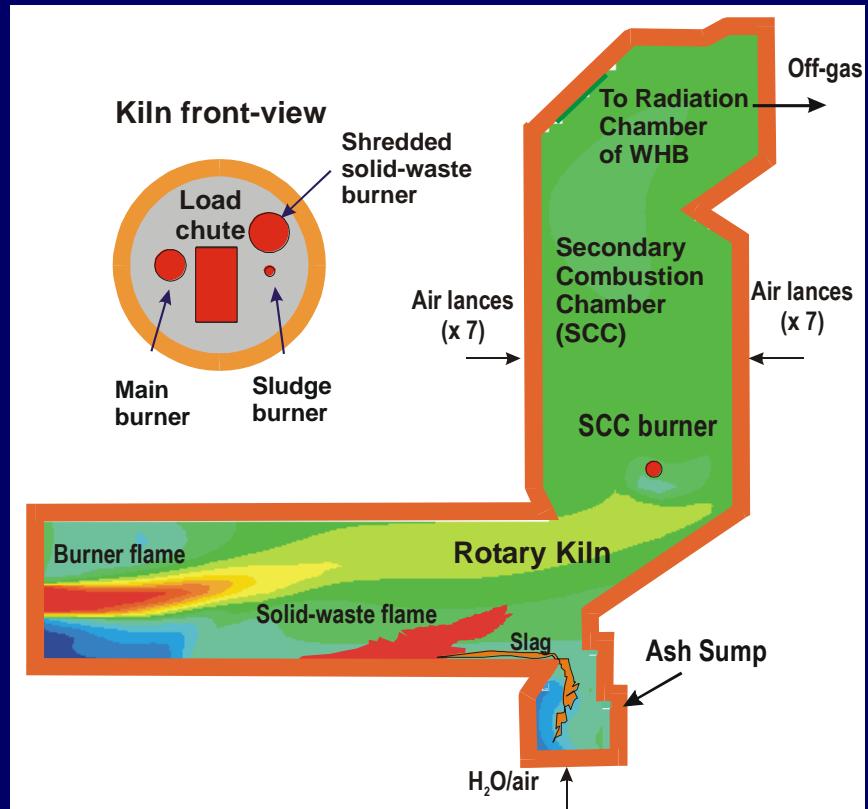
# Example 1: Simulation of hazardous waste combustion in a rotary kiln

- Key Issues and challenges
  - Fuel stream modelling
  - Waste combustion modelling (CFD)
  - Construction of cylindrical kiln and rectangular secondary combustion chamber (SCC)

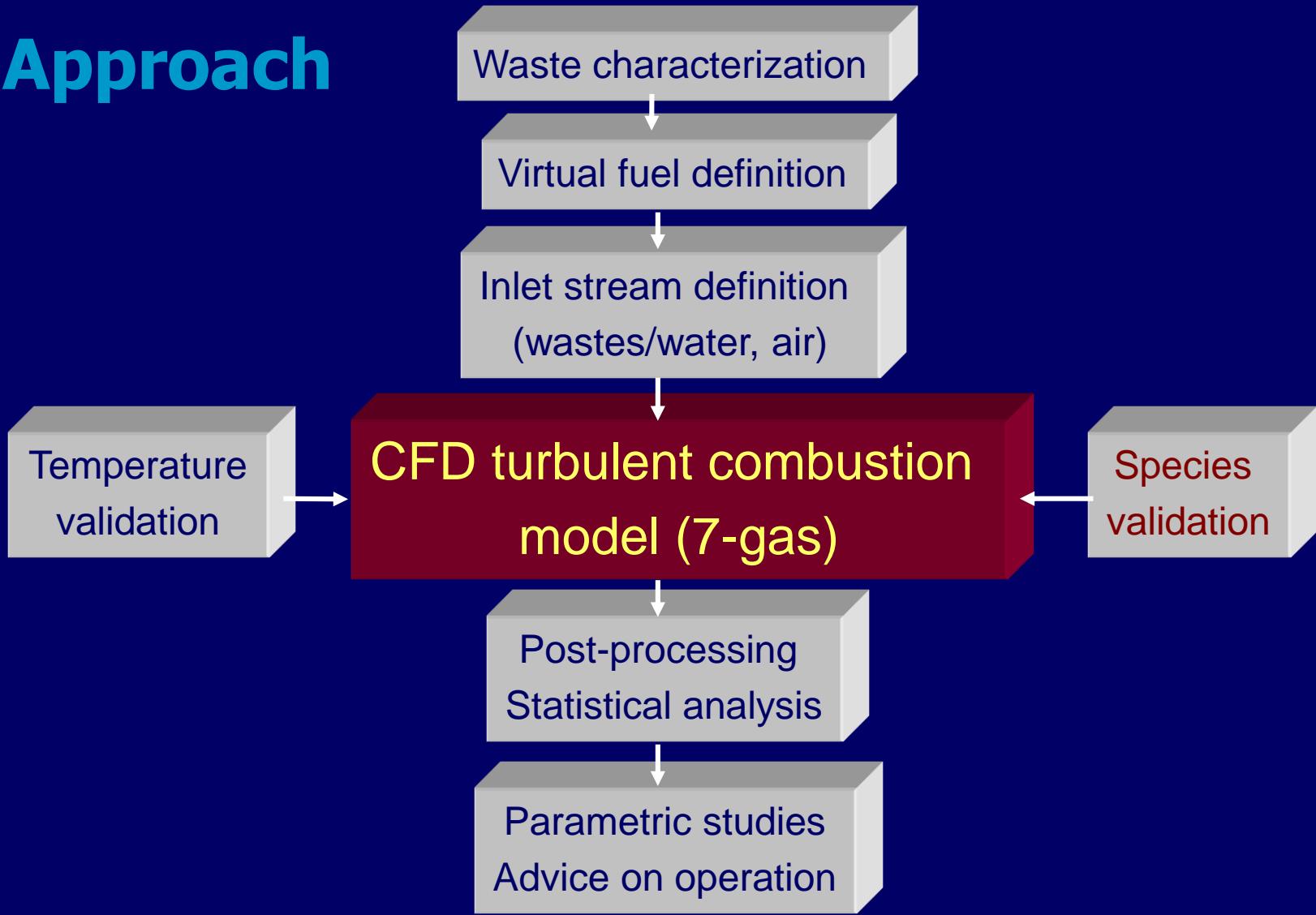


# Waste combustion in the rotary kiln

- Rotary kiln + secondary combustion chamber (SCC)
- Waste supply
  - ~30 MW, 7.2 t/h
  - Main burner ~11.5 MW
  - Sludge burner ~4 MW
  - Solid burner ~11.5
  - SCC burner ~3 MW
  - Fuel lances: non-regular
- Air supply
  - Load chute
  - Cooling ring
  - Air lances (SCC)

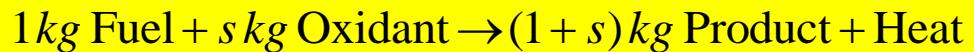


# Approach



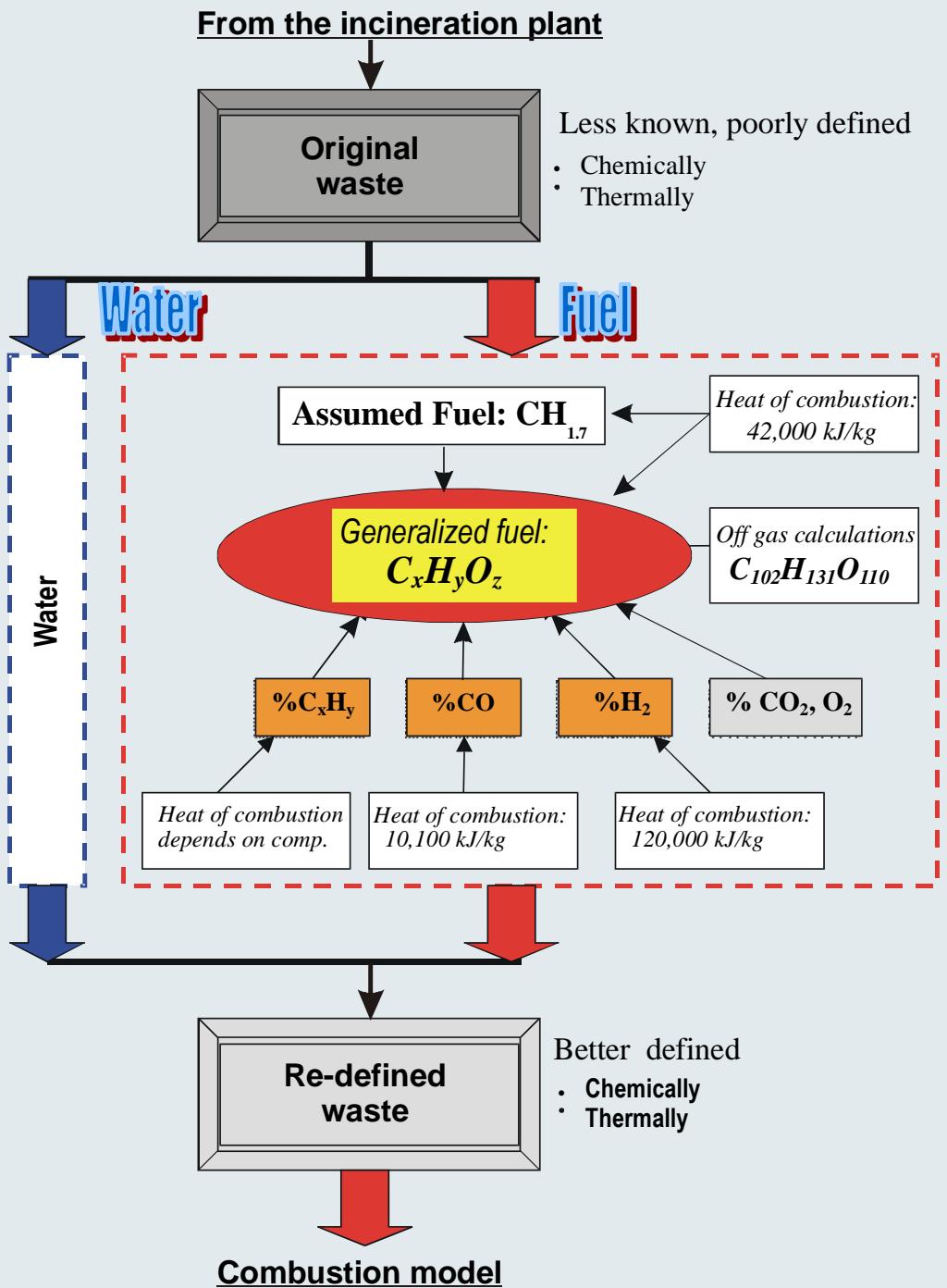
# CFD combustion model

- Assumptions and physical models
  - Gas phase only  
(negligence of gasification and vapourisation)
  - Turbulence flow: k- $\varepsilon$  model
  - Walls: adiabatic (small wall heat loss)
  - Radiation was neglected (adiabatic walls, no effect)
  - Kiln rotation: neglected
- Waste-combustion:
  - Global combustion model (SCRS, 3-gas model)



- Extended global combustion model  
(ESCRS, 7-gas model)
- Real gas/fuel compounds have to be used

7-Gas model:  
 $C_mH_n, H_2, O_2, CO,$   
 $CO_2, H_2O, N_2$

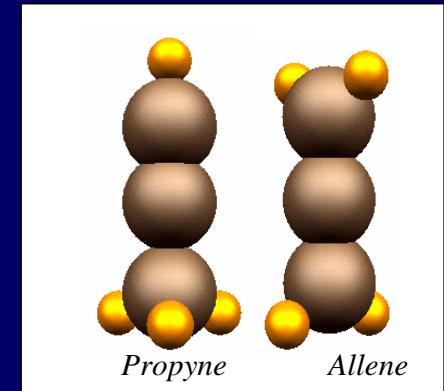


**Average off-gas composition:**

7.5% O<sub>2</sub>, 69.5% N<sub>2</sub>,  
9% H<sub>2</sub>O, 14% CO<sub>2</sub>

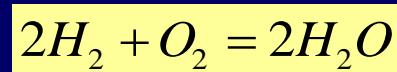
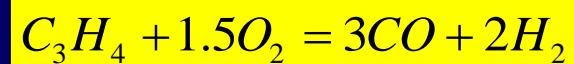
## Modelled virtual fuel

C <sub>3</sub> H <sub>4</sub>	87.37%	46.3 MJ/kg
CO	12.38%	10.1 MJ/kg
H <sub>2</sub>	0.25%	120 MJ/kg



# 7-gas combustion model

- 1 primary reaction
- 2 secondary reactions



- Turbulent combustion rate:
  - Eddy break-up model
  - Dependent on turbulent mixing
  - Fuel concentration + turbulence
  - Regulated by CEBU constant (0.1 – 4.0 tested, 1.0 used)

$$S_{mfu} = -CEBU \times \min\{m_{fu}, m_{ox}/s\} \times \frac{\varepsilon}{k}$$

# Stream definition

- Input streams
  - Waste streams: multi-fuel streams
  - Water content: mixed with wastes
  - Combustion air: multi-feeding ports
- 2 stream constraint (code)
  - Fuel rich stream
  - Fuel lean stream

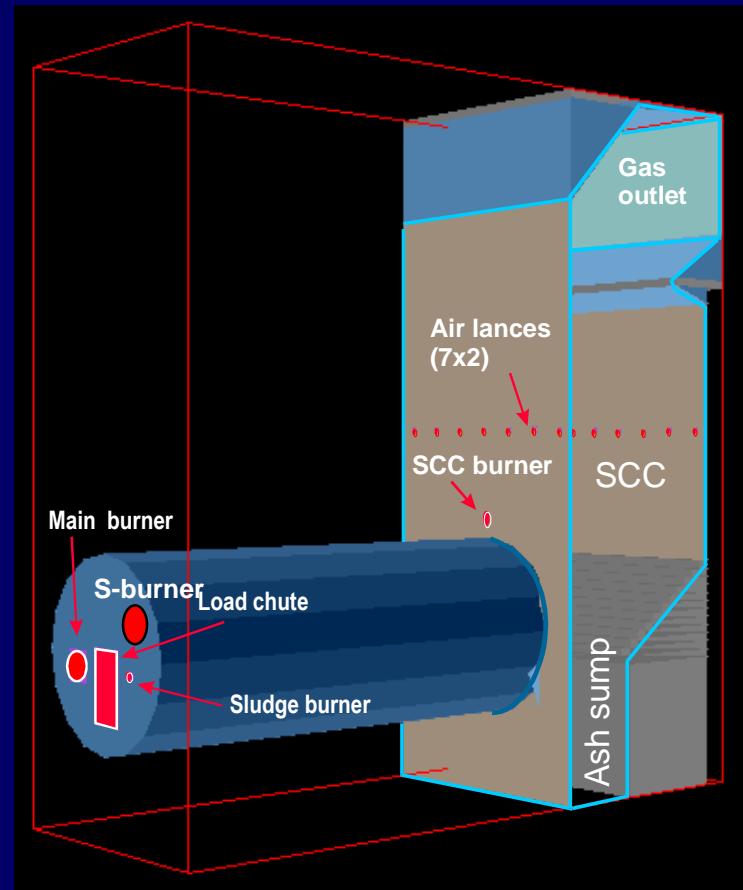
FUEL RICH STREAM								
Compound	C <sub>3</sub> H <sub>4</sub>	O <sub>2</sub>	CO	H <sub>2</sub>	CO <sub>2</sub>	H <sub>2</sub> O	N <sub>2</sub>	Total
Percentage	21,64%	15,64%	3,09%	0,00%	0,75%	4,41%	54,47%	100,0%

FUEL LEAN STREAM								
Compound	C <sub>3</sub> H <sub>4</sub>	O <sub>2</sub>	CO	H <sub>2</sub>	CO <sub>2</sub>	H <sub>2</sub> O	N <sub>2</sub>	Total
Percentage	0,28%	20,97%	0,06%	0,00%	0,00%	5,64%	73,06%	100,0%

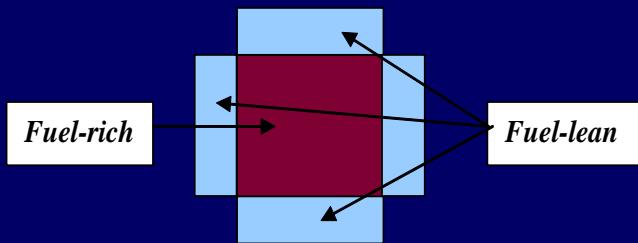
- Individual stream

x% Fuel-rich + y% fuel-lean

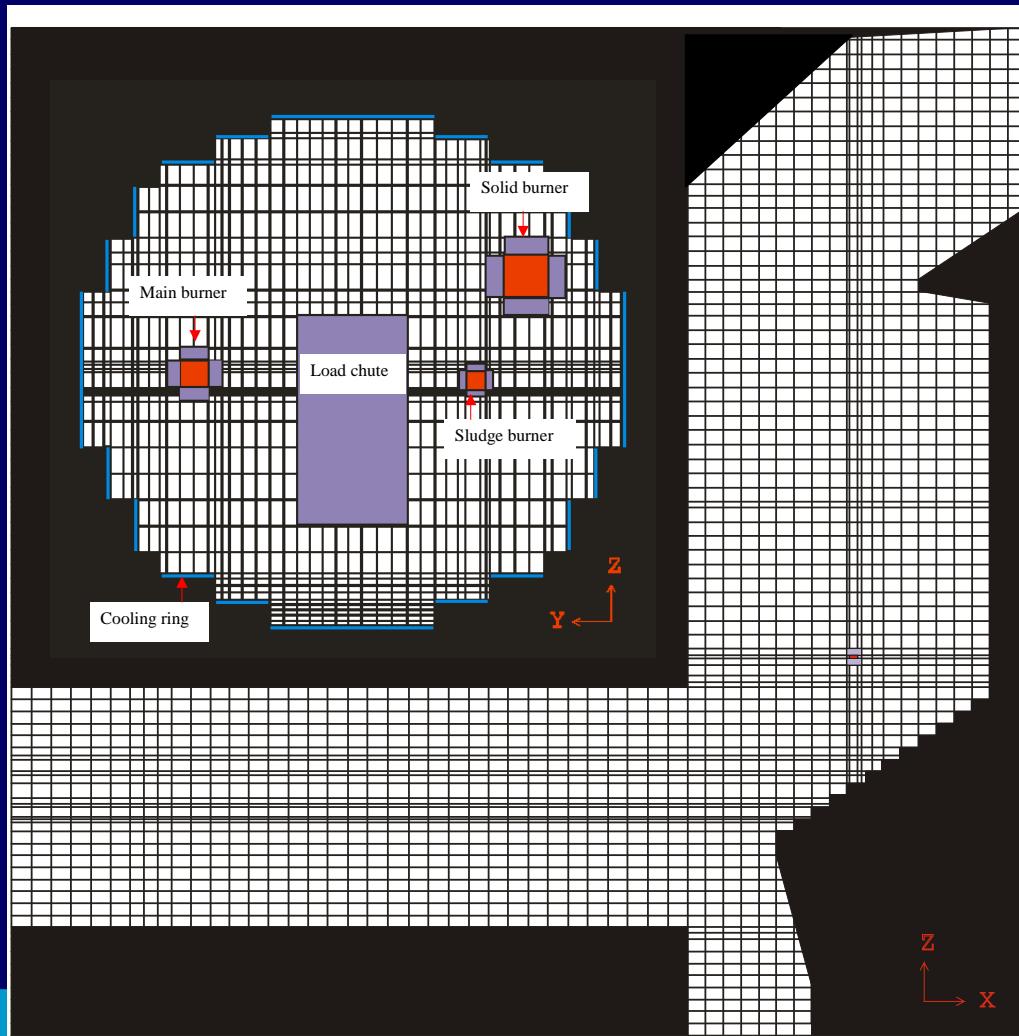


# Computational grid

- Cartesian grid
  - 230,000 – 360,000 cells
  - Using solid blockages to form the kiln and SCC,
  - Difficult to set B.C. for non-rectangular shapes.
- Burner definition
  - 2 stream approximation

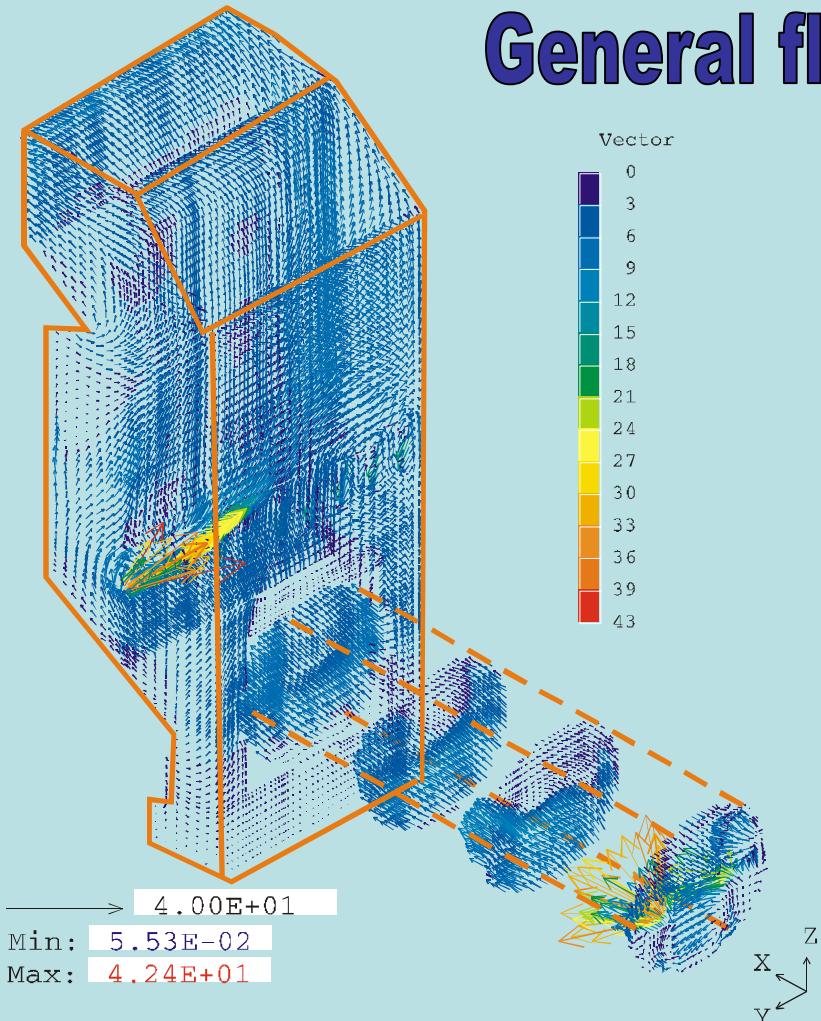


Example: main burner

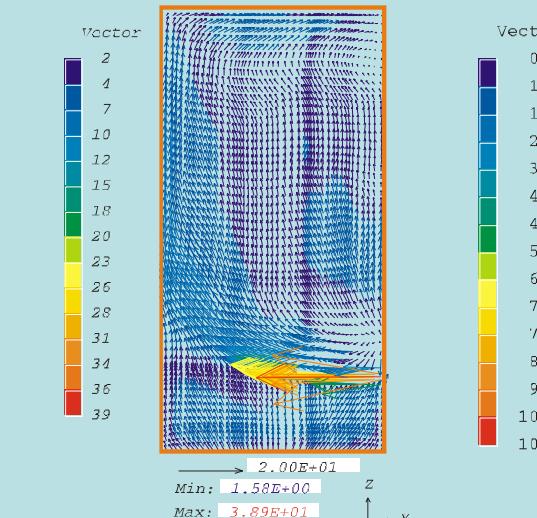


# Typical CFD predictions

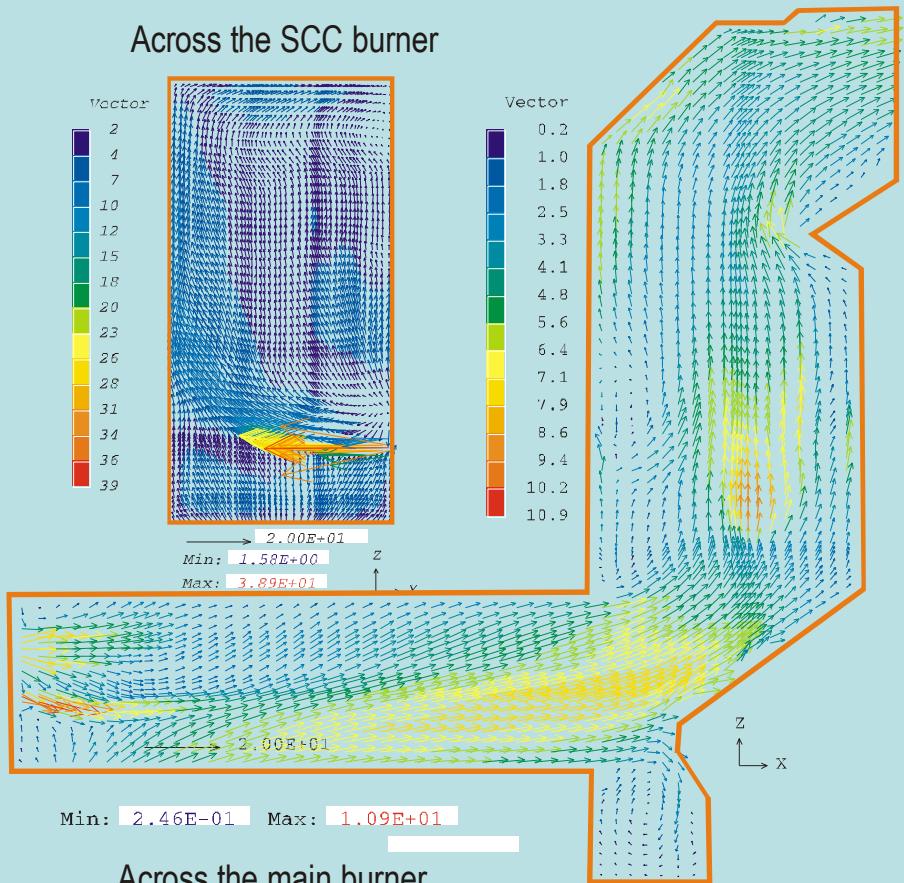
## General flow pattern



Across the SCC burner

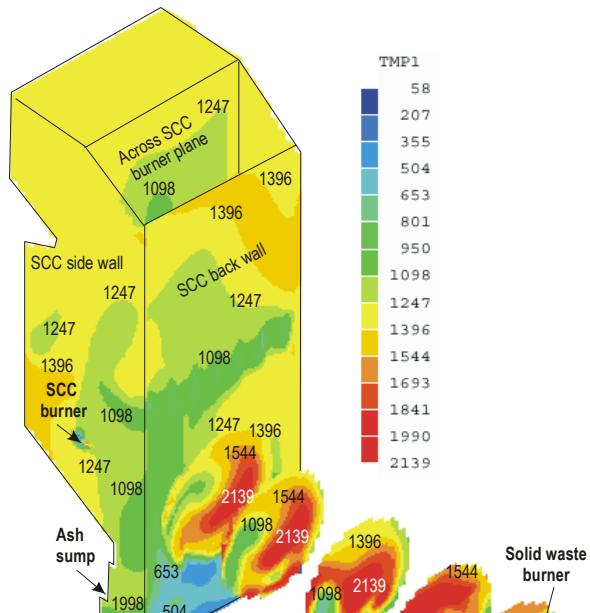


Across the main burner

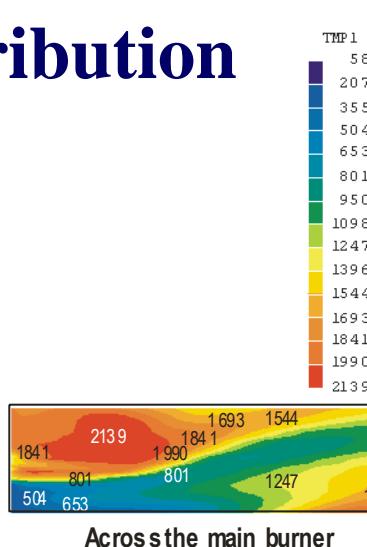


# Typical CFD predictions

## Temperature distribution

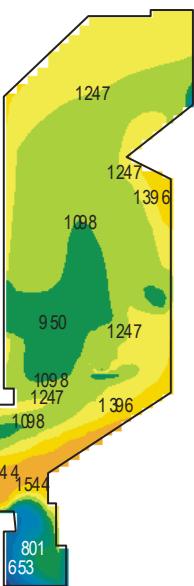


TMP1  
58  
207  
355  
504  
653  
801  
950  
1098  
1247  
1396  
1544  
1693  
1841  
1990  
2139



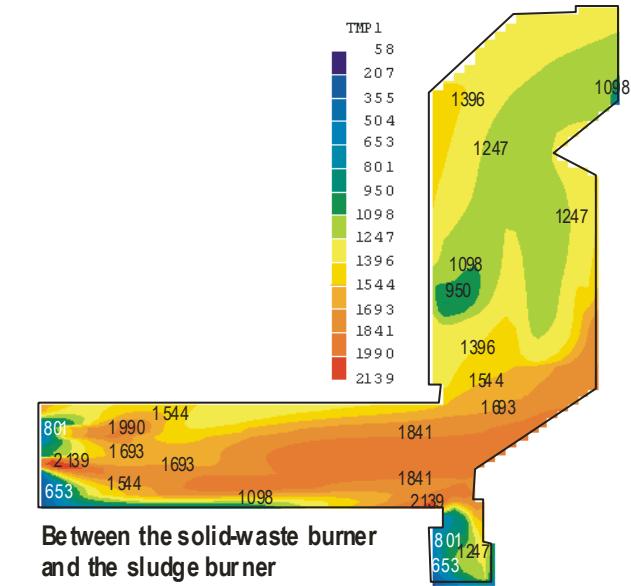
Across the main burner

TMP1  
58  
207  
355  
504  
653  
801  
950  
1098  
1247  
1396  
1544  
1693  
1841  
1990  
2139



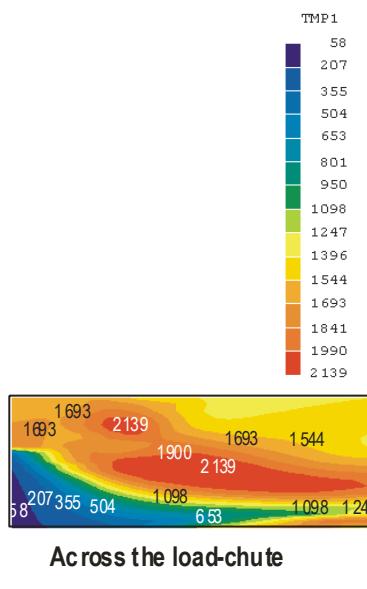
Between the solid-waste burner  
and the sludge burner

TMP1  
58  
207  
355  
504  
653  
801  
950  
1098  
1247  
1396  
1544  
1693  
1841  
1990  
2139



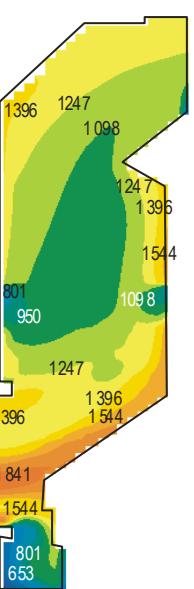
801  
653

Centra colder zone due  
to air injection lances



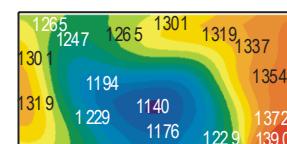
Across the load-chute

TMP1  
58  
207  
355  
504  
653  
801  
950  
1098  
1247  
1396  
1544  
1693  
1841  
1990  
2139



Across the SCC-burner

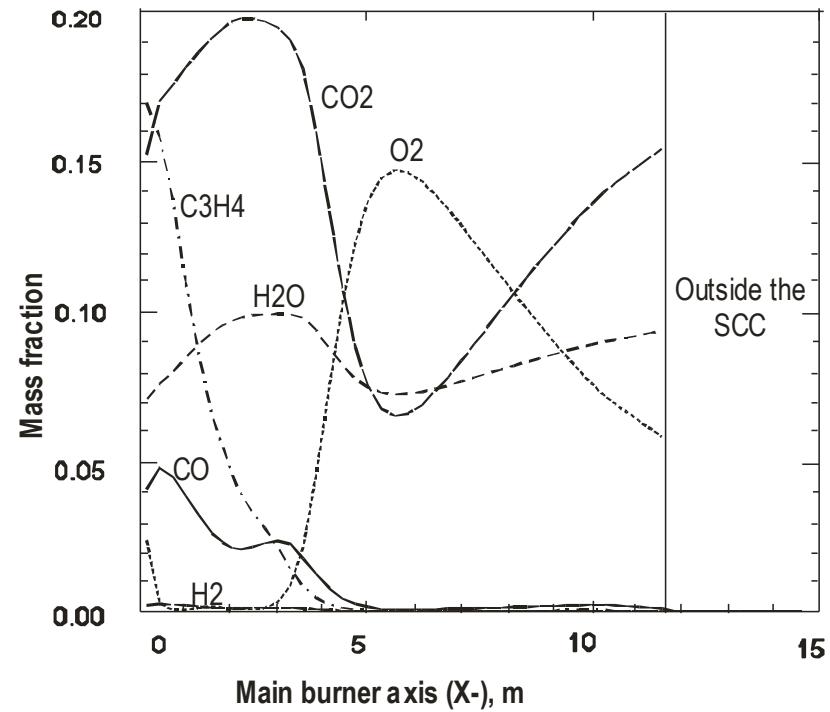
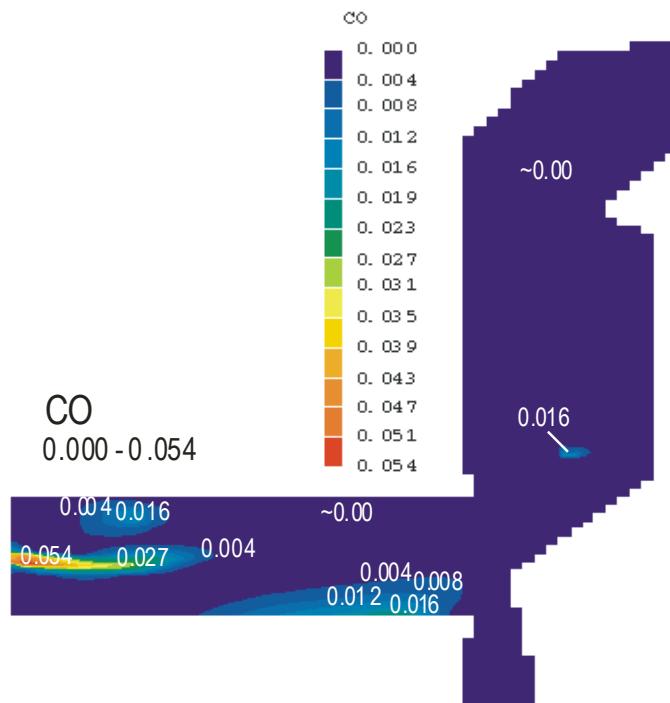
TMP1  
1140  
1158  
1176  
1194  
1212  
1229  
1247  
1265  
1283  
1301  
1319  
1337  
1354  
1372  
1390



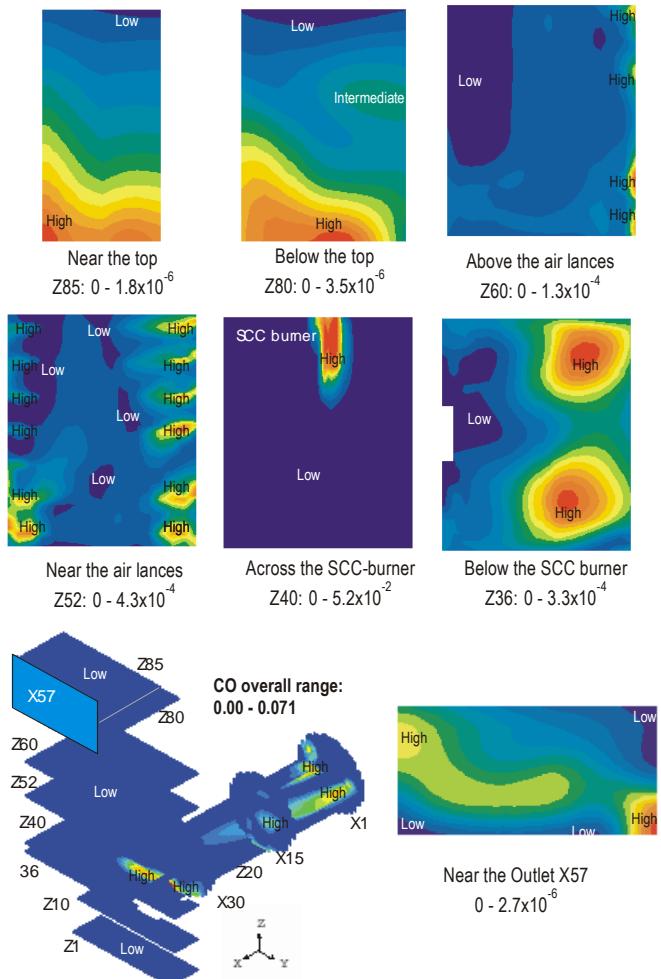
Near the outlet to WHB

# Typical CFD predictions

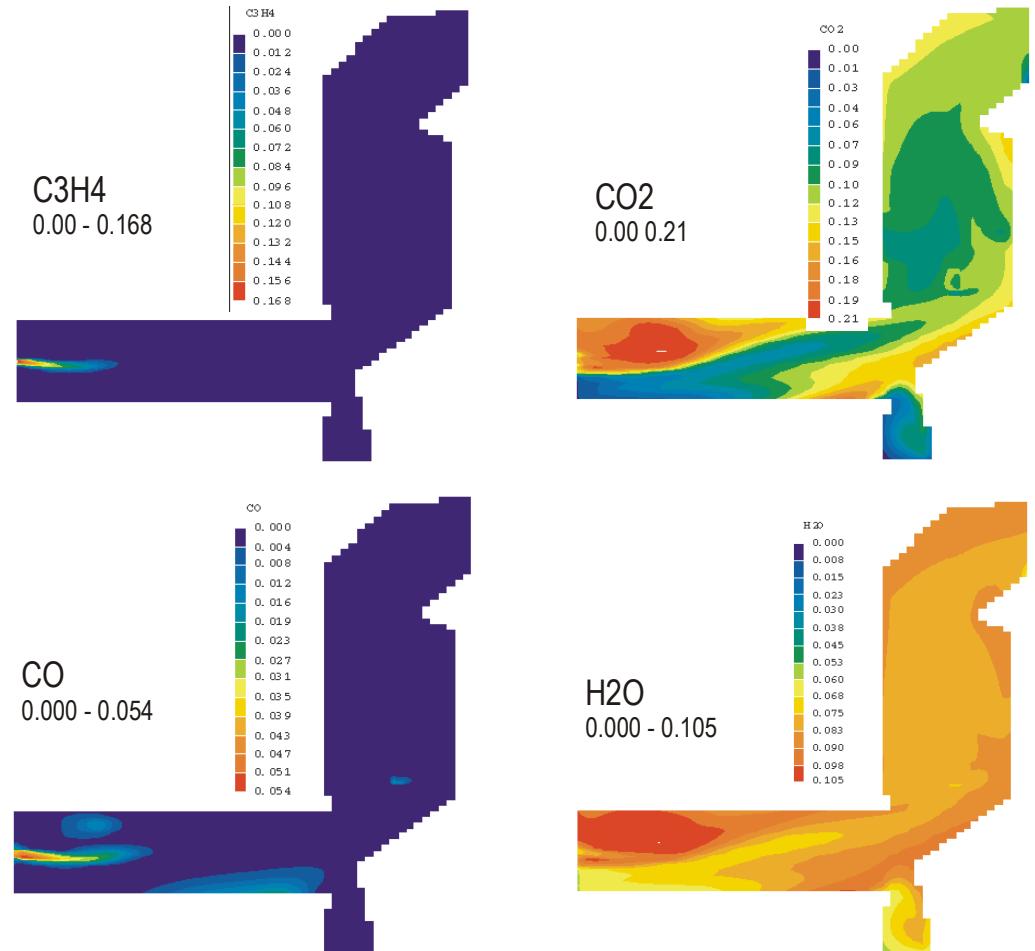
## Species distribution



# Typical CFD predictions

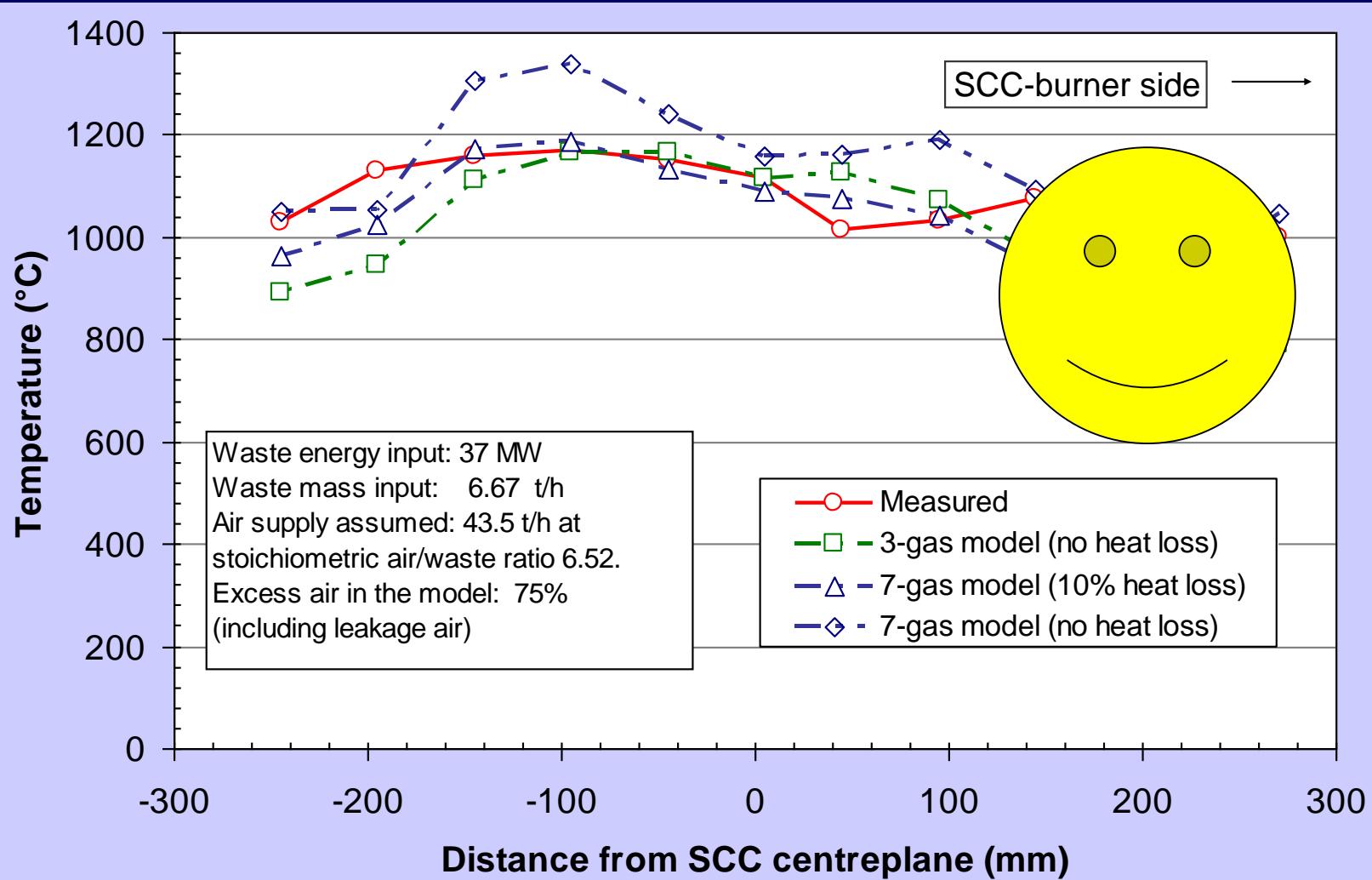


CO

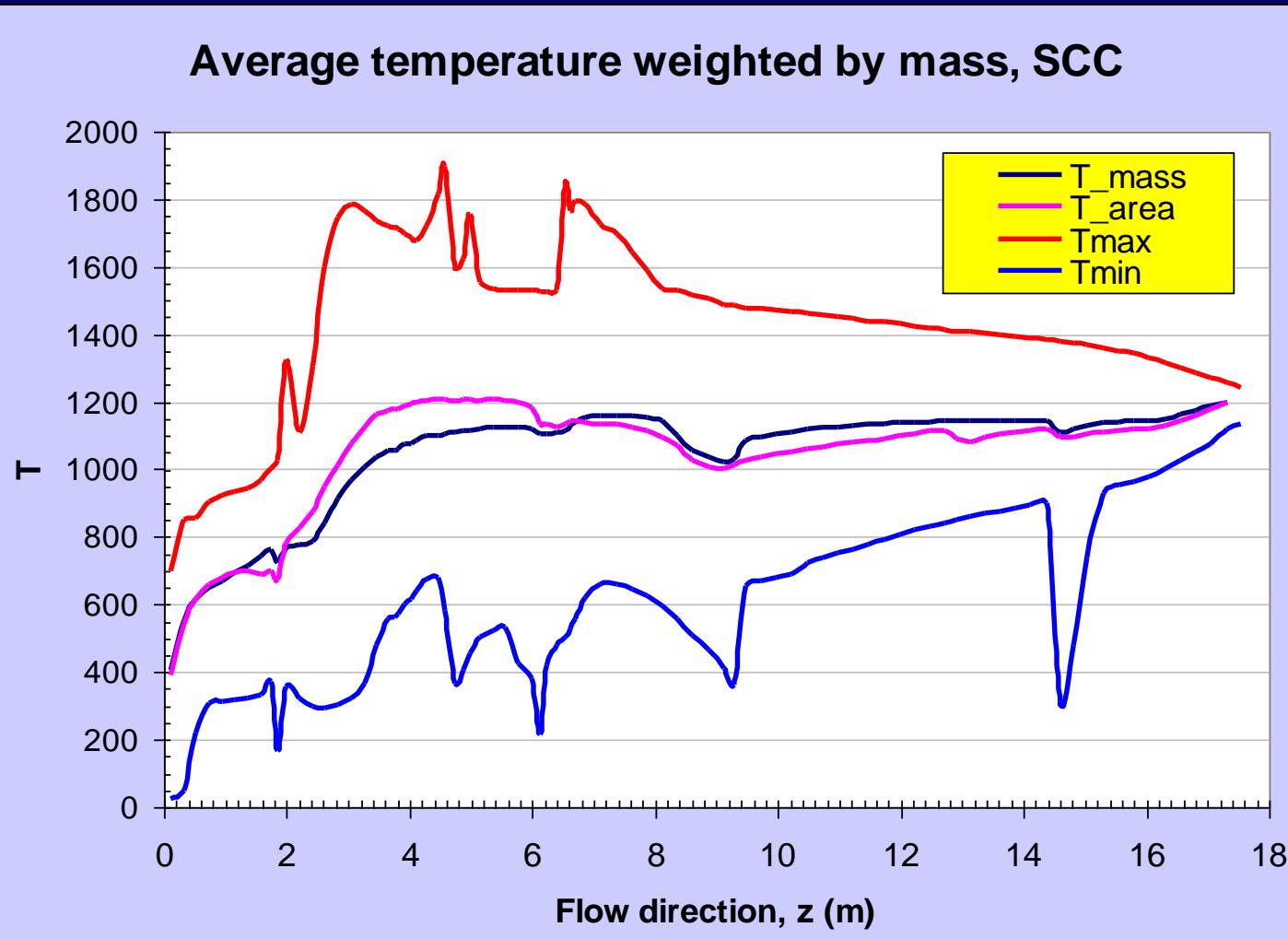


Other species

# Model validation



# Temperature profiles: statistical



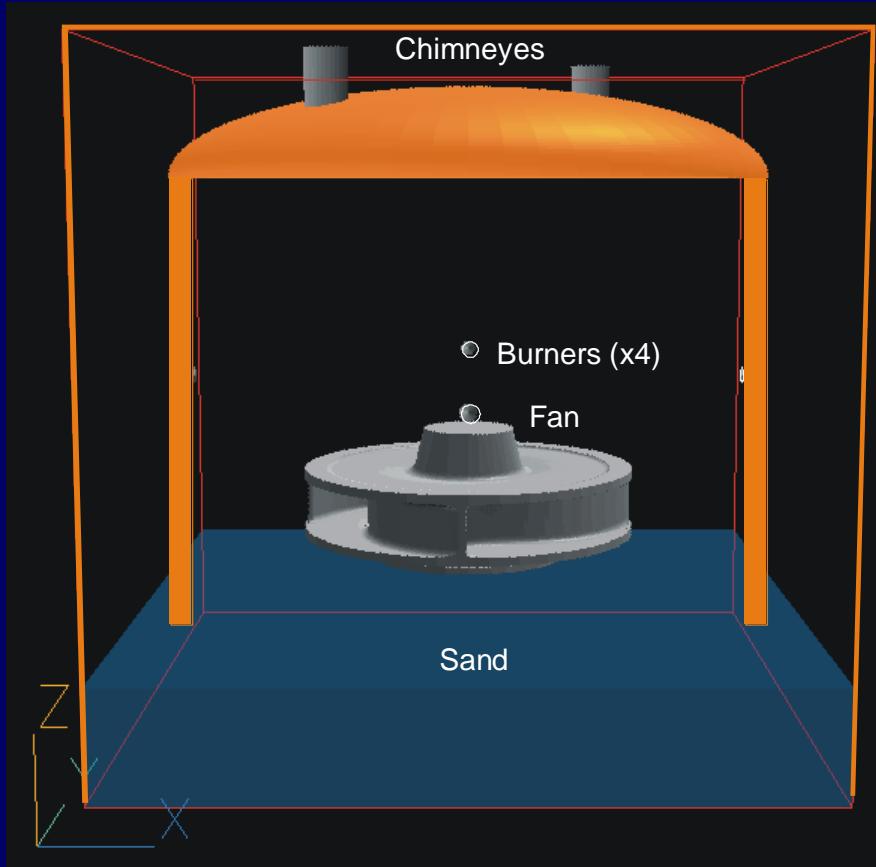
## Example 2: Simulation of transient heating of dredging impellers in a mobile furnace

- Fuel combustion
  - Oil (red diesel) simplified as gas, 3-gas model ( $CEBU=25$ )
- Radiation
  - IMMERSOL model ( $K_a=0.1$ ,  $K_b=0.001$ )
  - Metal surface emissivity: 0.05-1.0
  - Wall emissivity: 0.8
- Conjugate heat transfer
  - CAD geometry for the impeller



# Simulation of a heat treatment furnace

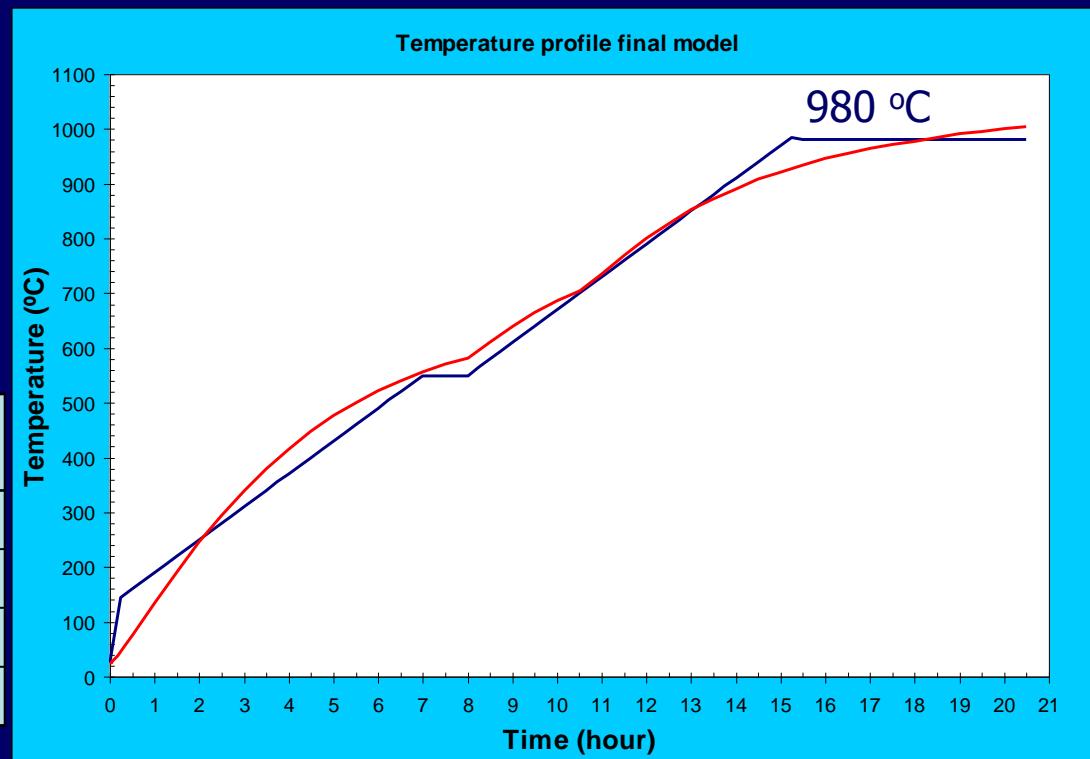
- Construction of furnace geometry and grid
  - Cylindrical furnace, curved roof (spherical cap)
  - BFC or Cartesian?
  - Handling of furnace walls and boundary conditions
  - Handling of furnace roof
  - Using high conducting solids combined with normal refractories to form the cylindrical and curved walls

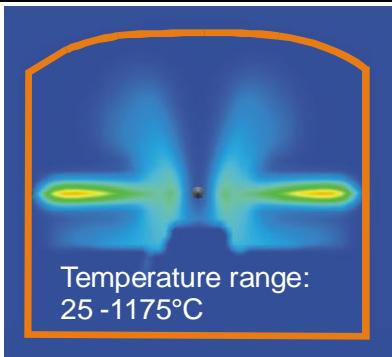


# Simulation of a heat treatment furnace

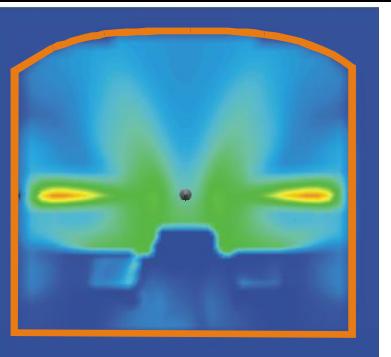
- Comparison of predicted and pre-set surface temperature profile on the dredging impeller
  - 3 steps of fuel supply
  - Varying excess air rate

Period (hour)	Excess Air (%)	Mixture Fraction	Fuel (kg)	Energy per burner (kW)
0-8	226%	0.02	214	80
8-10.5	160%	0.025	84	100
10.5-20.5	85%	0.035	356	85
Total	-	-	654	-

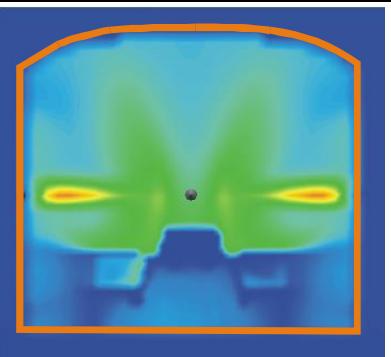




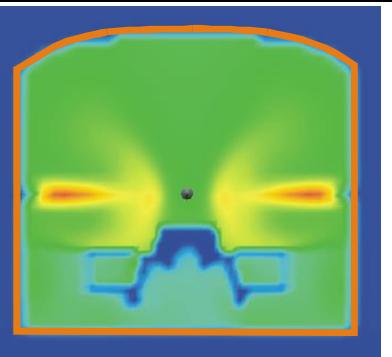
4 seconds



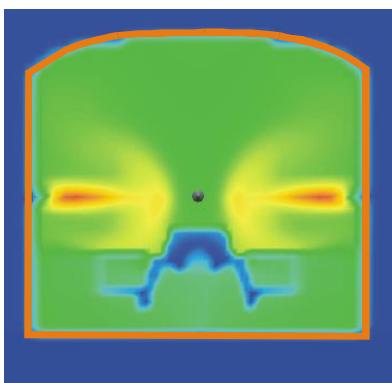
20 seconds



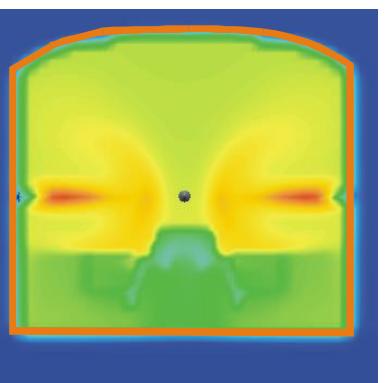
30 seconds



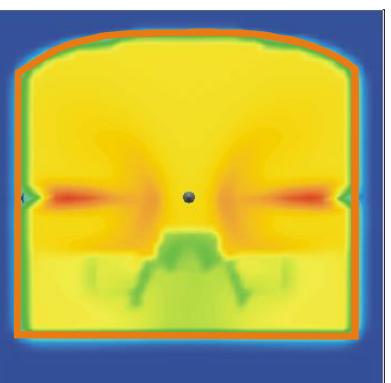
240 seconds



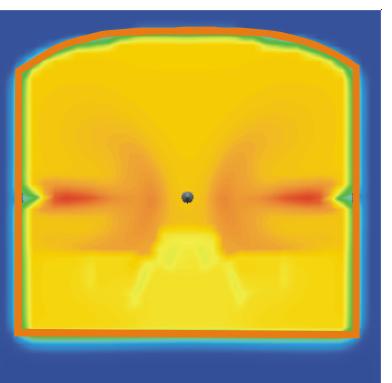
1800 seconds



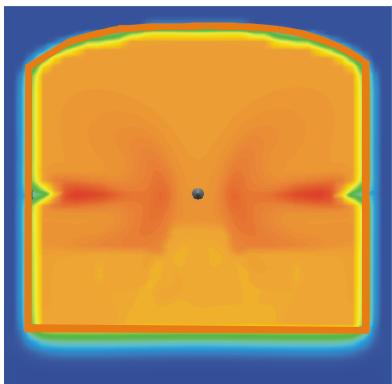
7200 seconds



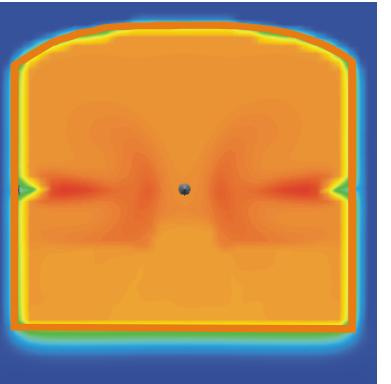
12600 seconds



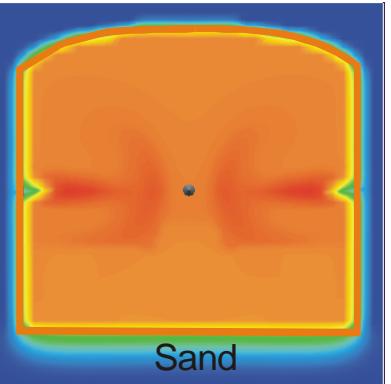
18000 seconds



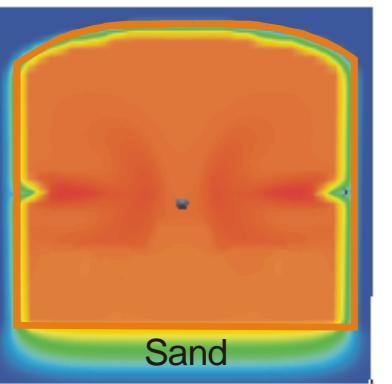
36000 seconds



45000 seconds



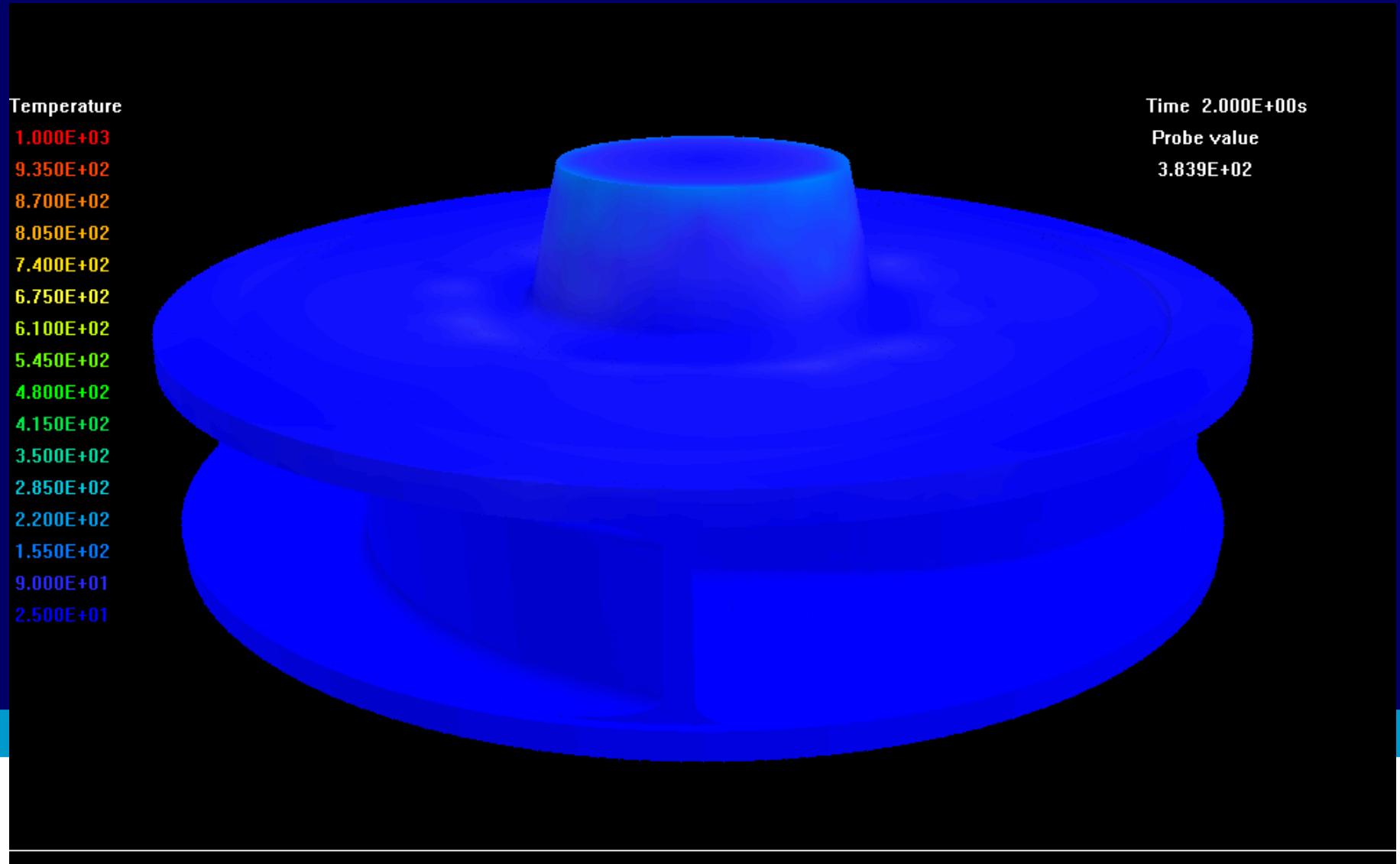
Sand  
End of the transient model  
73800 seconds



Sand  
steady-state model

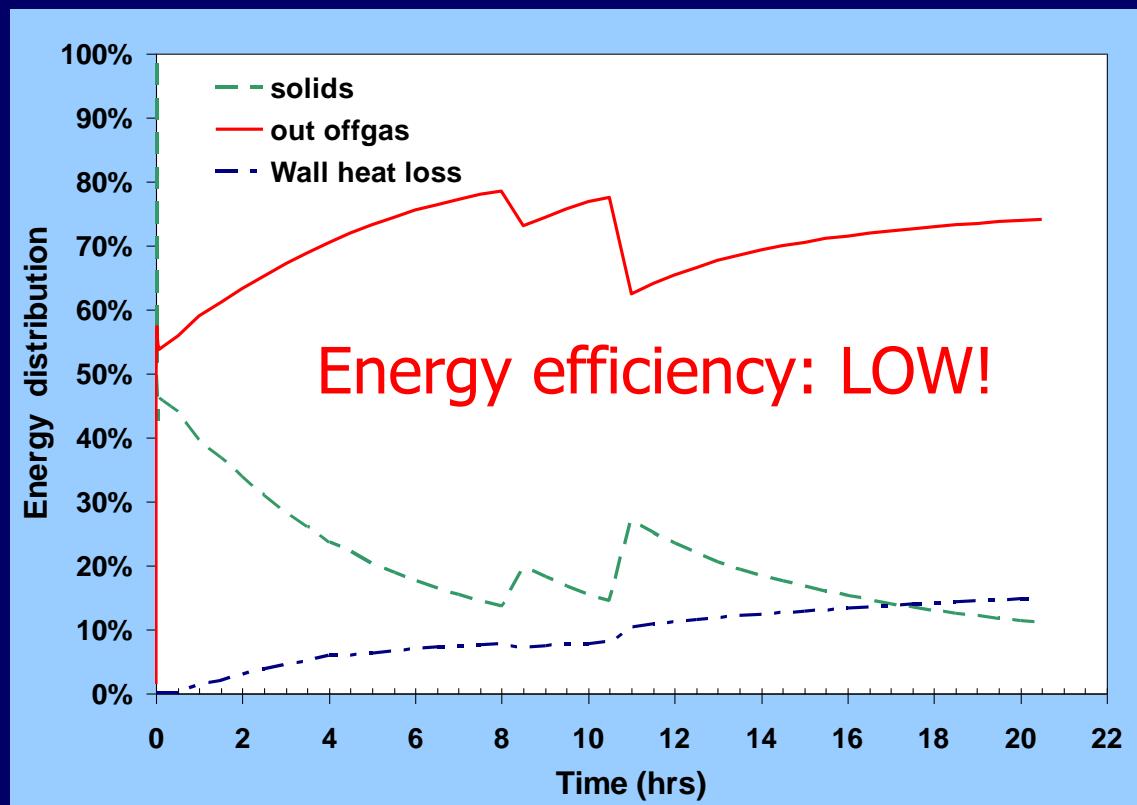
# Simulation of a heat treatment furnace

- Surface temperature evolution of the impeller (0-20 hrs)



# Simulation of a heat treatment furnace

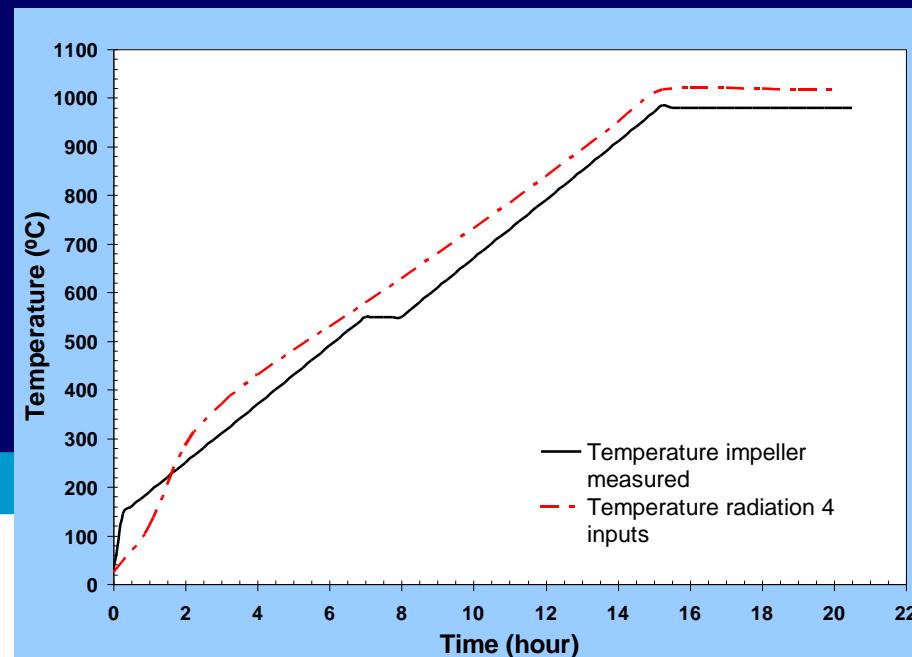
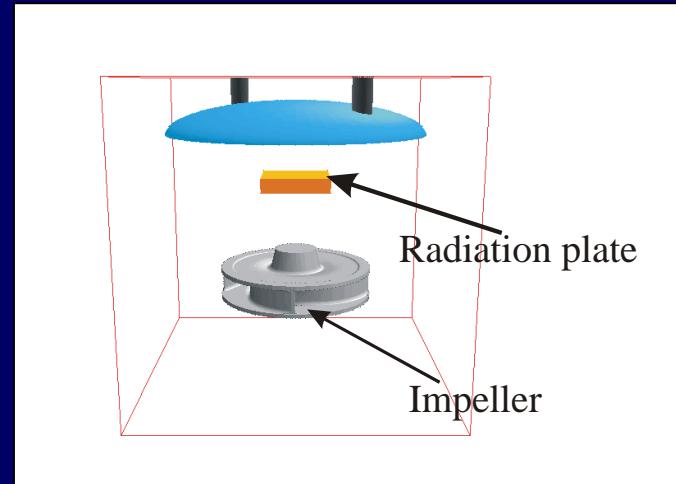
- Energy balance
  - Heating: 50 – 10%
  - Wall loss: 0 – 15%
  - Off-gas: 50 – 75%



# Simulation of a heat treatment furnace

- Alternative heating source:  
Using radiation plate
  - Substantially reducing heat loss by off-gas
  - Easy to regulate and control
  - Energy saving:
    - Oil: 43 MJ/kg $\times$ 654 kg – 28 GJ
    - Radiation plates:  
2233 kWh – 8 GJ (70% saving)  
€ 178 vs € 520 (65% saving)

Time period	Hours	Energy setting	Total energy
0-2	2	200 kW constant	400 kWh
2-8	6	75 – 105 kW linear	540 kWh
8-15	7	105 – 150 kW linear	893 kWh
15-20	5	80 kW constant	400 kWh
Total (0-20)	20		2233 kWh



# Summary

- CFD is a useful and handy tool in education and research at universities, as well as in industrial design and process R&D.
- Various aspects of high temperature materials processing operations could be reasonably simulated.
- More insight understanding of the transport phenomena and process performance can be obtained.
- Still a lot of challenges: complex geometry, reactive and multi-phase flows in industrial applications.
- We need more functionality and power of the Code!