Modelling of radiative heat transfer in a CFB furnace by correlation based zone method

Case: Oxygen fired combustion

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Introduction

Background

- A semi-empirical three-dimensional model for simulating a CFB furnace has been developed earlier (CFB3D).
  - Long distance radiation not considered.
- A radiative heat transfer model based on the zone method has been developed and applied for non-CFB conditions (e.g. pulverized combustion, backpass).

Need

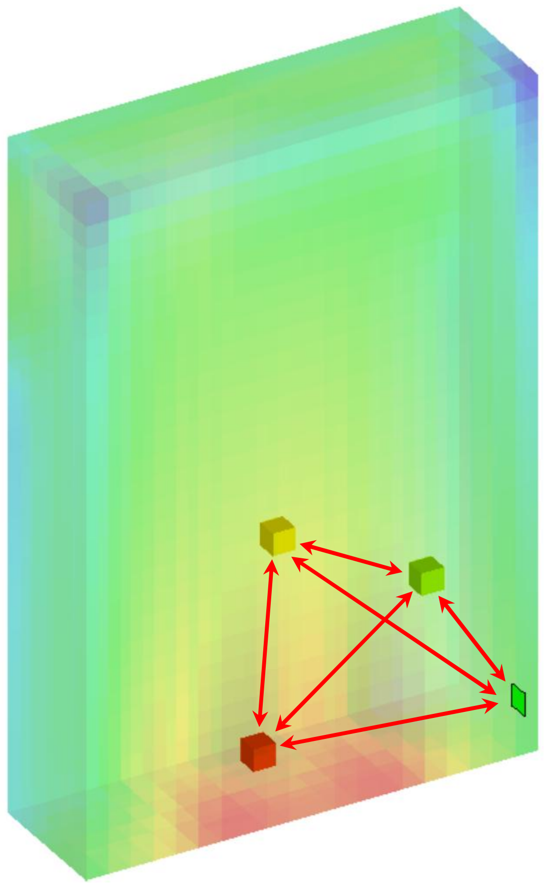
- In oxygen-fired CFB conditions, the proportion of radiative gases (CO_2, H_2O) is high => effect on the radiative heat transfer.
- The role of the radiative heat transfer is high in the upper dilute section of a CFB furnace and especially in low load conditions => long distance radiation to be considered.

Solution

- The purpose of this work is to combine the radiative heat transfer model with the steady-state process model for circulating fluidized bed furnaces.
- The object of study is a large oxygen-fired CFB.
- The following presentation describes the method and initial model results.

Radiation model: zone method

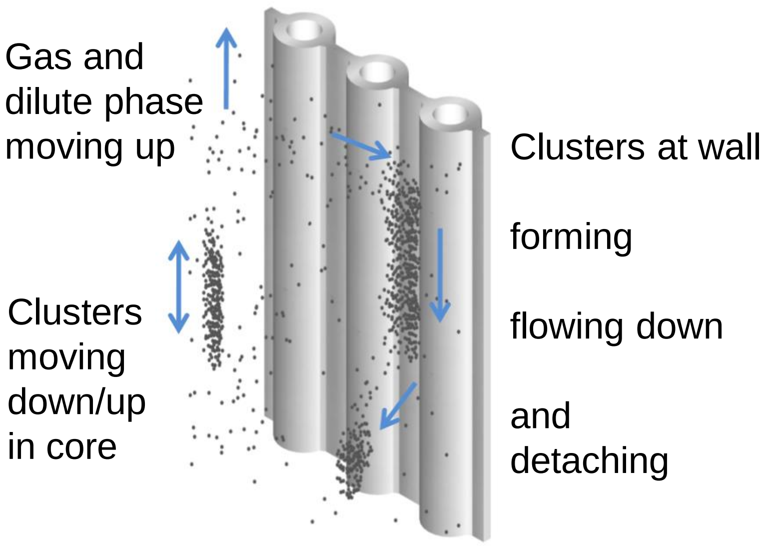
- Principle is old (Hottel and Sarofim, Radiative Transfer, 1967).
- Calculation domain divided to volume zones and surface zones.
- Exchange factors determined between different zones.
- Coefficients for absorption, scattering, and emission defined for each cell and face.
  - In this implementation, weighted sum of gray gas model for gases was used.
  - Effect of particles added -> usually dominating.
- Radiative energy balances defined between each zones and solved.
  - ⇒ Radiative source terms in cells (W/m3)
  - ⇒ Radiative heat flux at faces (W/m2)



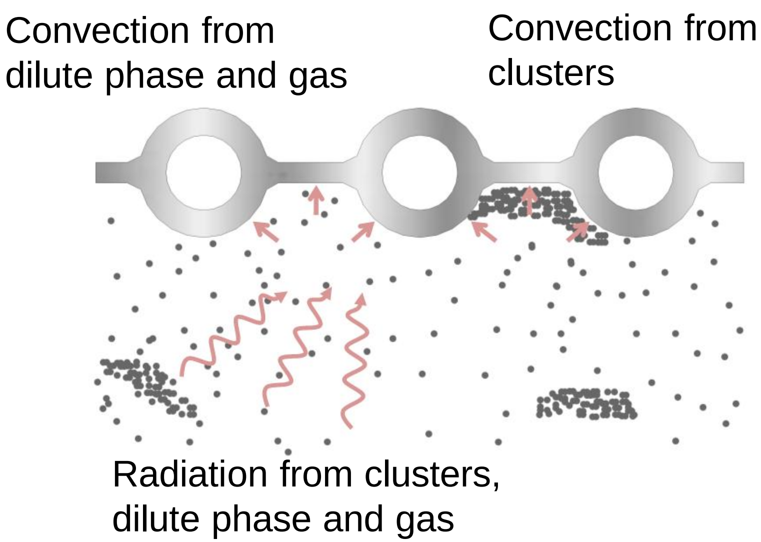
- Limitations of the current model:
  - Rectangular domains.
  - No internal heat exchanger surfaces.
  - Limited mesh size.

Heat flux to CFB walls: principles

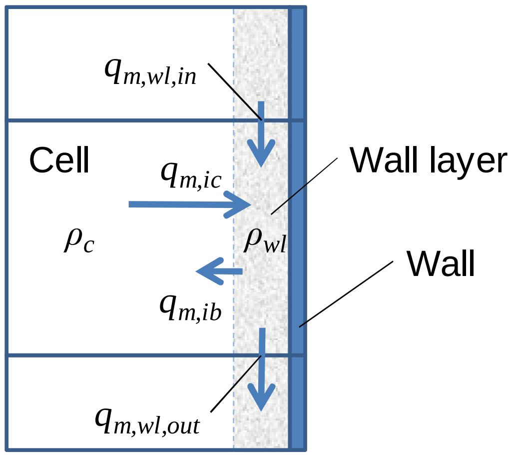
Fluid dynamics

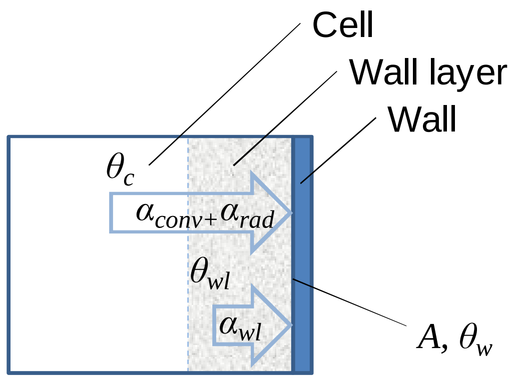


Main heat flow modes



Modeled heat flux modes in CFB3D





$$q''_{tot} = (\alpha_{conv} + \alpha_{rad})(\theta_c - \theta_w) + \alpha_{wl}(\theta_{wl} - \theta_w)$$

- Modeled heat transfer modes in CFB3D
  - Wall layer = convective heat transfer from wall layer to wall
  - Cell convective = convective heat transfer from cell to wall
  - Radiative = radiative heat transfer from cell to wall

$$\Rightarrow \quad q''_{tot} = (\alpha_{conv} + \alpha_{rad})(\theta_c - \theta_w) + \alpha_{wl}(\theta_{wl} - \theta_w)$$

- When the radiation model is applied, the radiative heat flux is defined by the radiation model:

$$\Rightarrow \quad q''_{tot} = \alpha_{conv}(\theta_c - \theta_w) + \alpha_{wl}(\theta_{wl} - \theta_w) + q''_{rad}$$

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Radiative source term

- The radiative source term is directly applied in the CFB3D-code as an extra heat source in the energy equation (see below).
- The radiation model (i.e. radiative source term) affects the mixing of energy inside the model domain.

Energy equation

$$
\begin{aligned}
&\oint_A \varepsilon_g \rho_g c_{pg} T_c \mathbf{v}_g \cdot d\mathbf{A} + \oint_A \varepsilon_s \rho_s c_{ps} T_c \mathbf{v}_s \cdot d\mathbf{A} \\
&- \oint_A \varepsilon_g \rho_g D_g c_{pg} \nabla T_c \cdot d\mathbf{A} - \oint_A \varepsilon_s \rho_s D_s c_{ps} \nabla T_c \cdot d\mathbf{A} \\
&= \int_V \left(\phi_g''' c_{pg} T_g + \phi_s''' c_{ps} T_s + \varphi''' + \varphi_{rad}''' \right) dV \\
&+ \int_V \left(\sum_{rt} \frac{\partial m_{rt}'''}{\partial t} \frac{H_{0,rt}}{M_{rt}} - \sum_{pt} \frac{\partial m_{pt}'''}{\partial t} \frac{H_{0,pt}}{M_{pt}} \right) dV \\
&- \oint_A \alpha_c (T_c - T_w) \cdot d\mathbf{A}
\end{aligned}
$$

Convection of gas and solids

Dispersion/diffusion of gas and solids

Sensible enthalpies of gas and solid feeds

Additional volumetric heat sources

Radiative source term

Reaction enthalpies

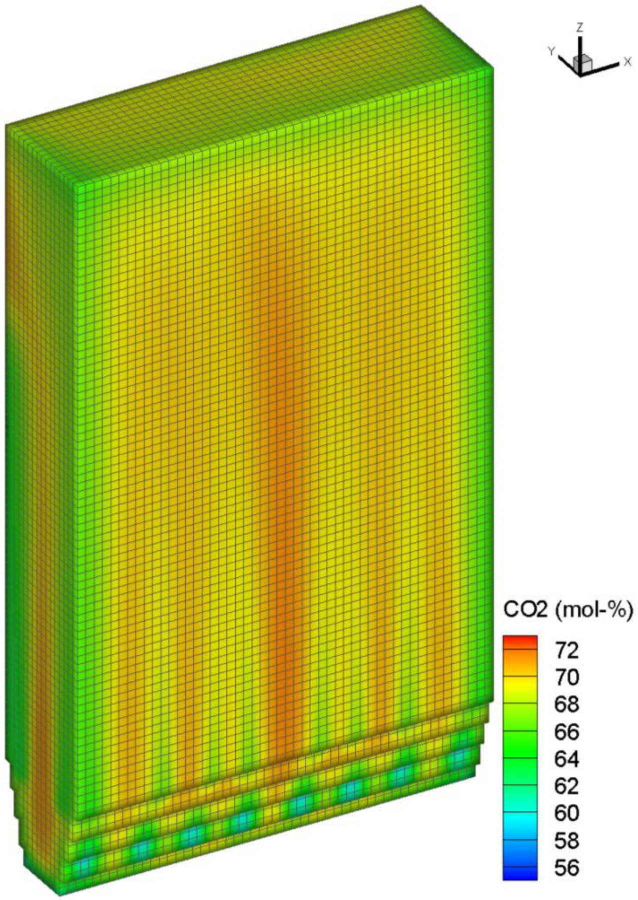
Heat transfer from cell to wall

Calculation case: oxygen fired CFB

- Initial design of Compostilla (OXY-CFB-300).
  - Furnace size 25.2 m x 7.6 m x 44.0 m
  - 100% load point, thermal power ≈ 700 MW.
  - Inlet O_2 = 23.5 %-vol.
  - Flue gas recycle ratio 69%.

- Flue gas composition:
  3% O_2, 70% CO_2, 21% H_2O, 6% N_2+Ar+other

- The initial design did not have internal heat exchanger surfaces
  => suitable for simplified radiation model.

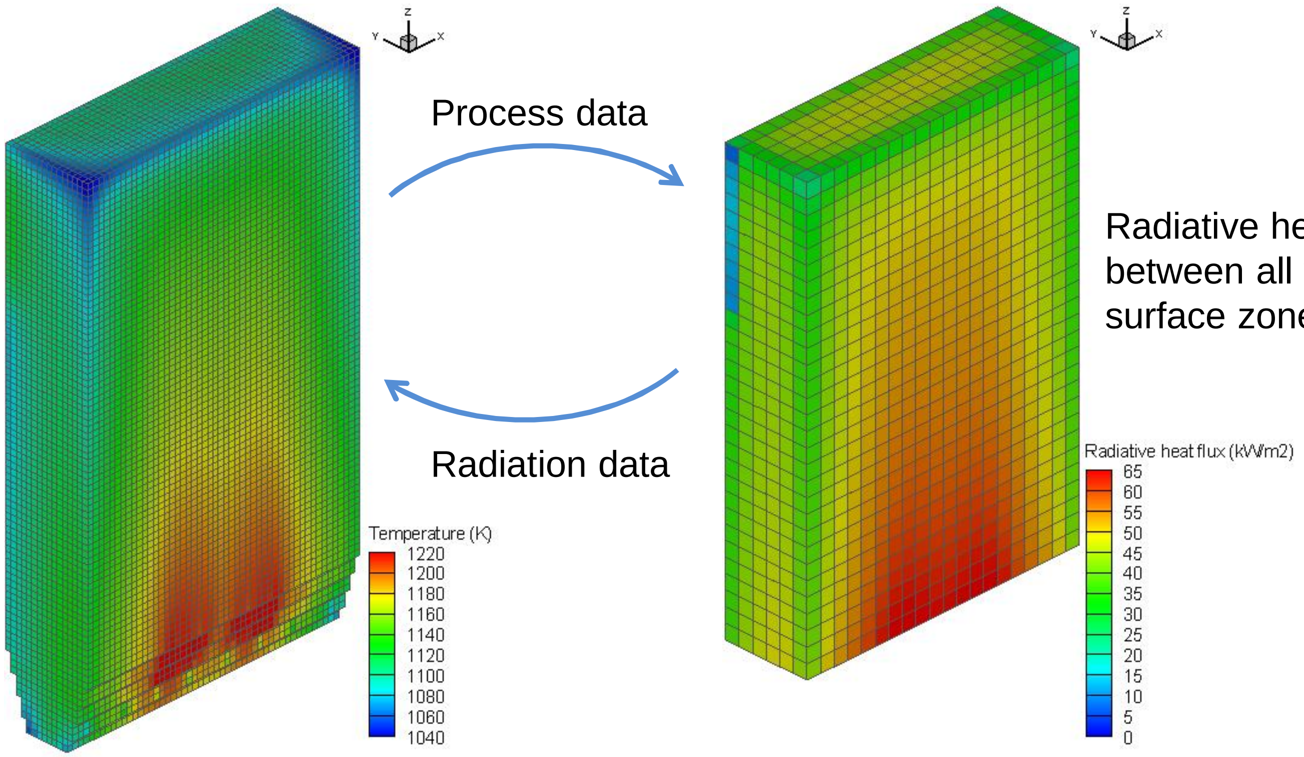


Modelling concept

CFB3D (67800 cells)

Radiation model (3600 cells)

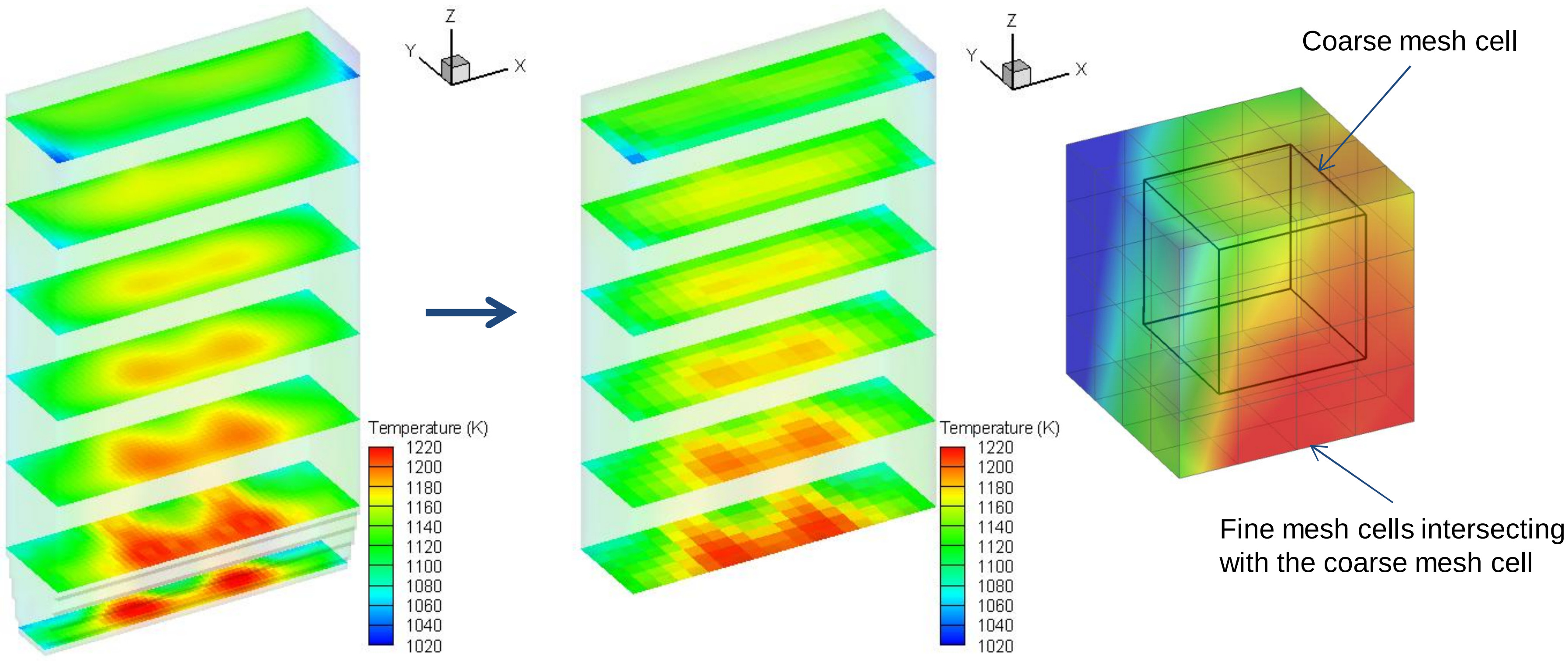
Fluid dynamics
Reactions
Comminution
Heat transfer



Radiative heat transfer between all volume and surface zones

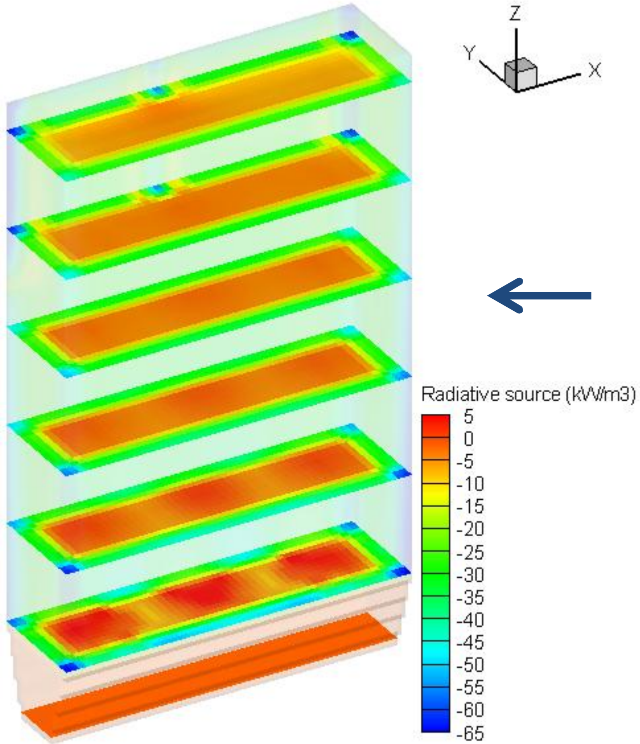
Example of data exchange: temperature

CFB3D Radiation model

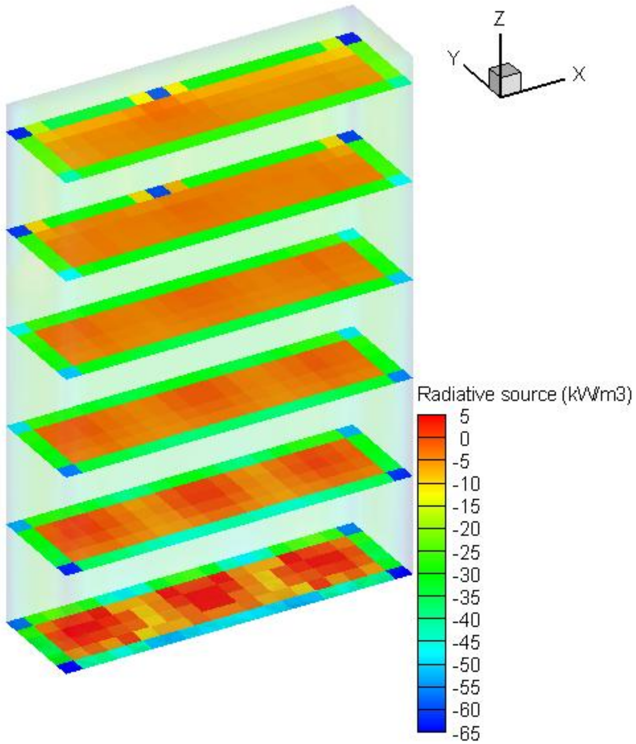


Example of data exchange: radiative source

CFB3D

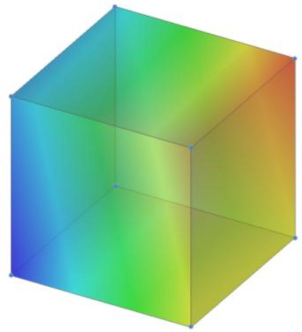


Radiation model

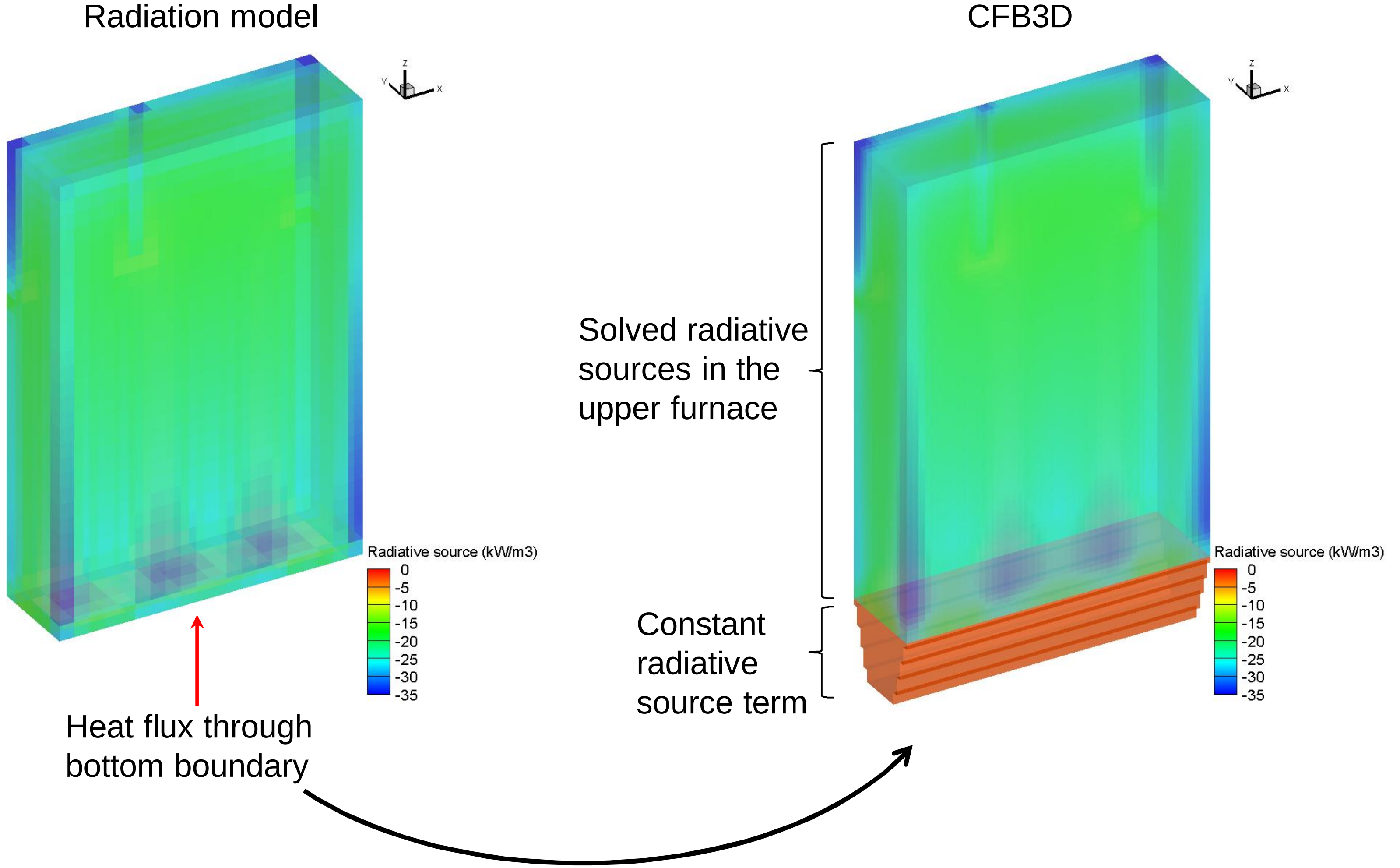


Bilinear interpolation

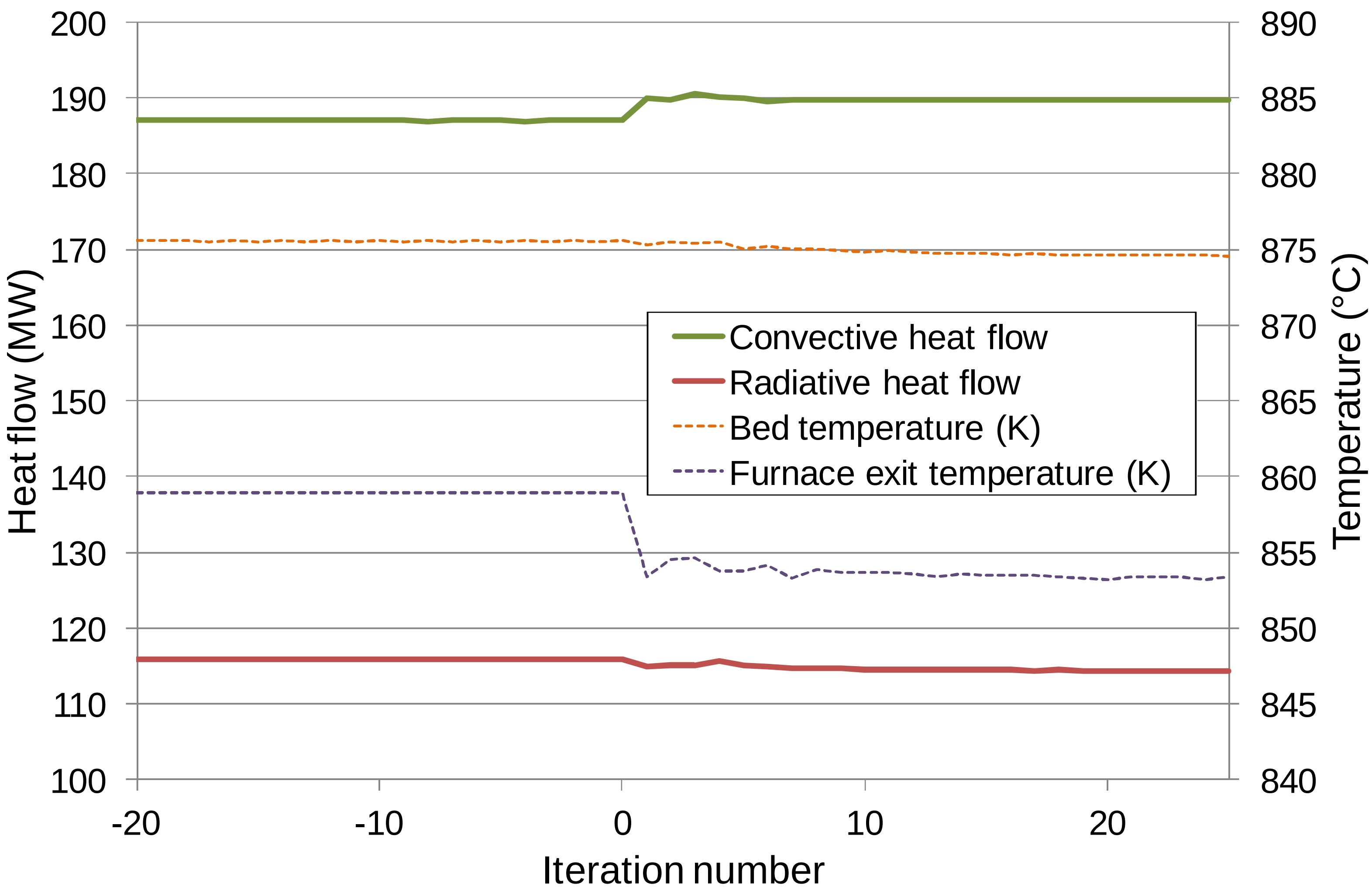
Trilinear interpolation



Radiative source term for the inclined bottom part



Development of total heat flows and average furnace temperatures



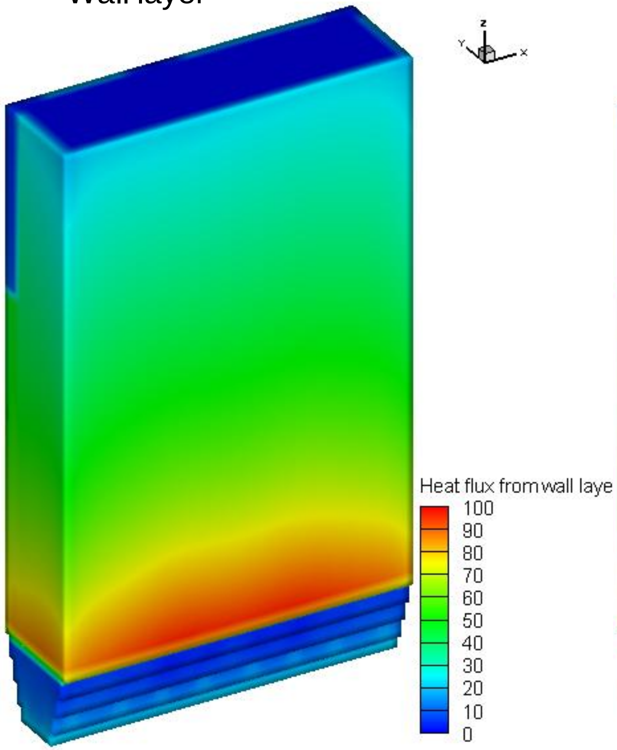
Iteration 0 is the converged solution without the radiation model.

Heat flux modes without the radiation model

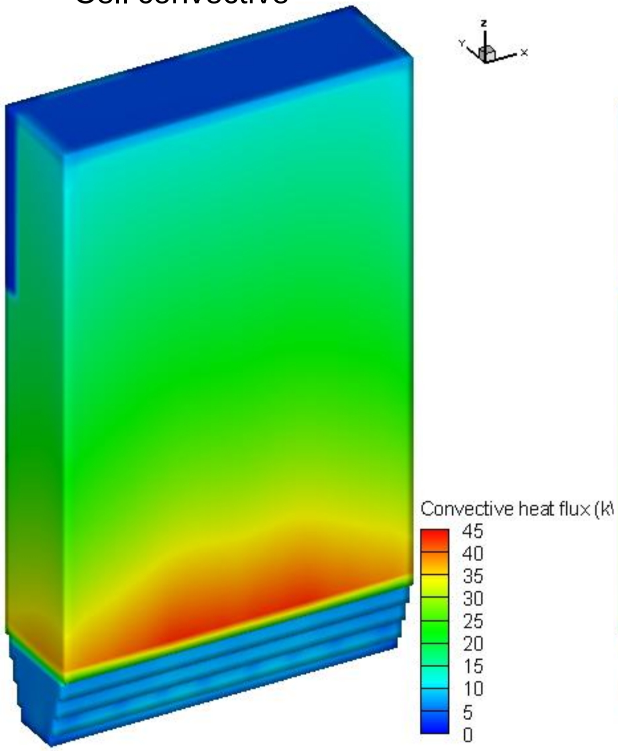
– Total heat flows by different modes (MW):

Wall layer	Cell convective	Radiative
127.6	59.3	115.8

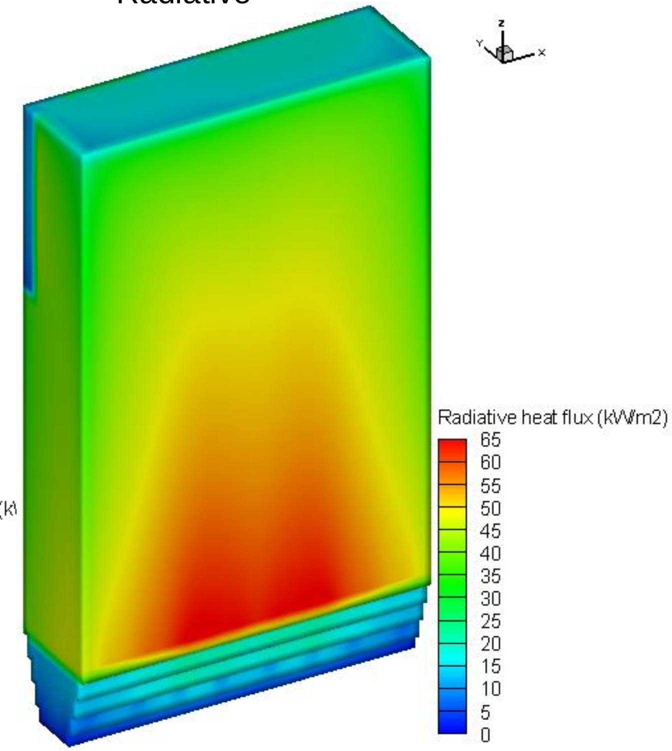
Wall layer



Cell convective



Radiative



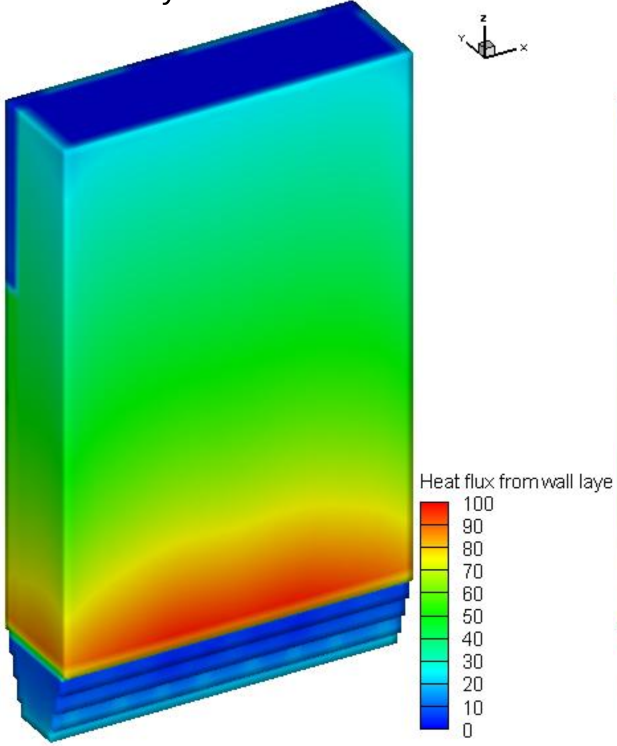
Heat flux modes with the radiation model

– Total heat flows by different modes (kW):

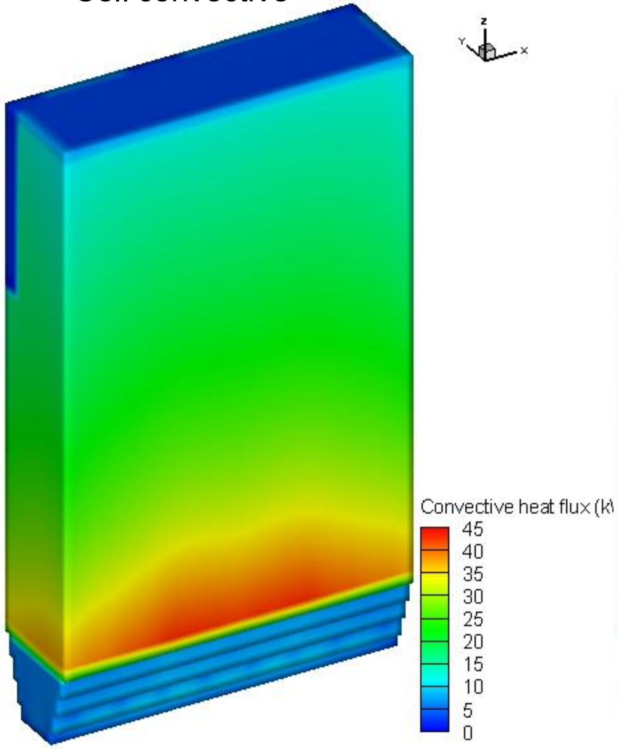
Wall layer	Cell convective	Radiative	
130.0	59.7	114.3	
+1.8%	+0.6%	-1.3%	(compared to results without radiation model)

=> Slightly higher heat transfer in convective heat transfer modes

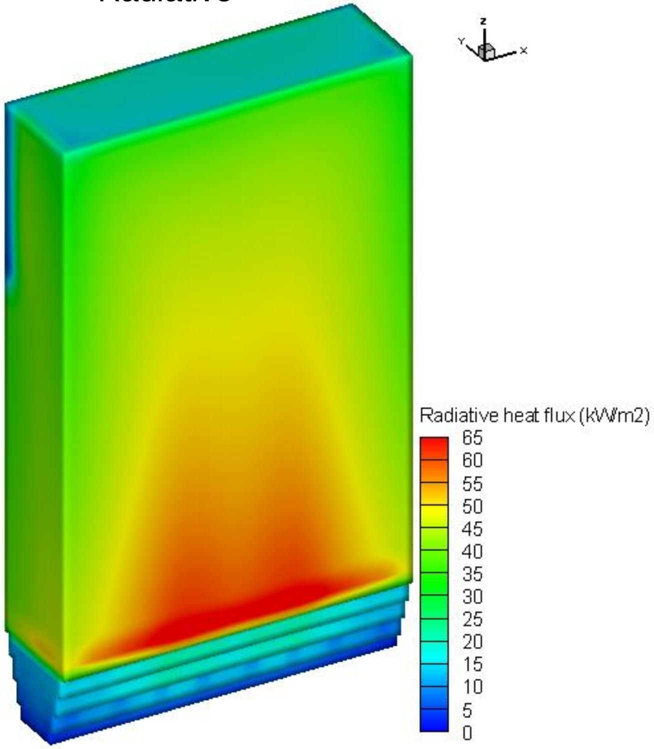
Wall layer



Cell convective

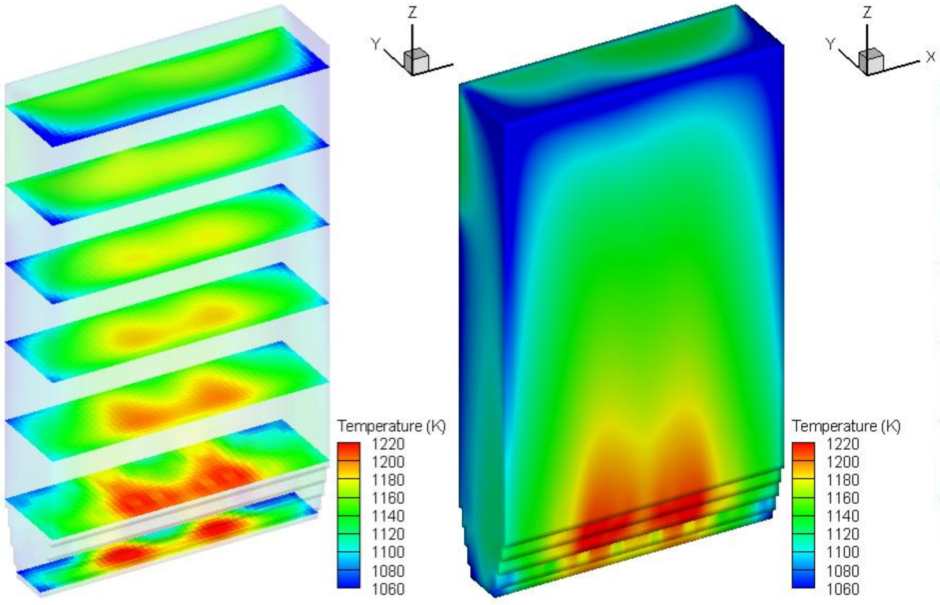


Radiative

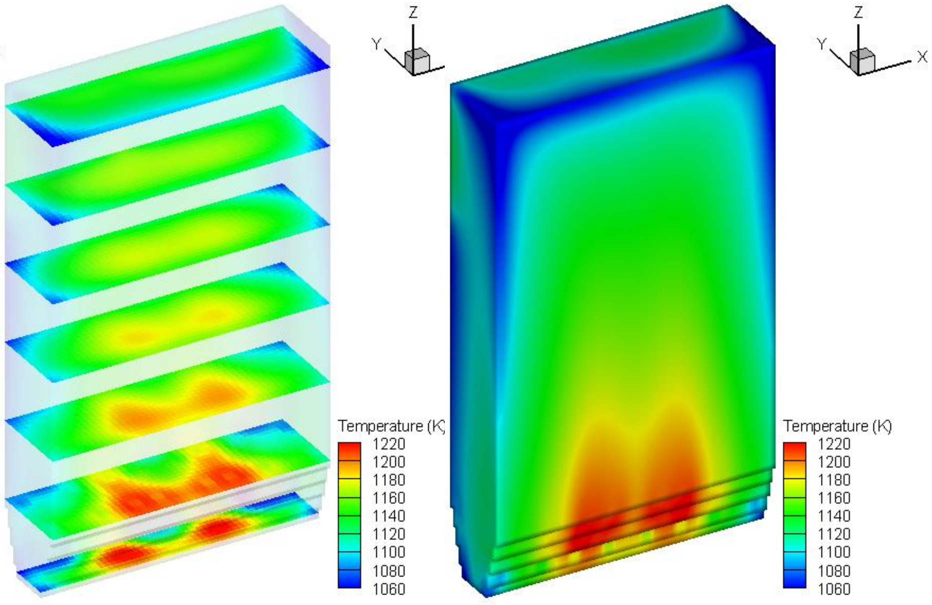


Effect of radiation model on temperature field

Without radiation model



With radiation model



- With the radiation model, the temperature profiles are more uniform at the upper furnace.
- The temperature near the walls increases, which increases the convective heat transfer.
- All in all, the changes are relatively small in this case. The situation may change in small load calculations.

Summary

- The radiative zone model and the 3D process model for circulating fluidized bed furnace were succesfully integrated.
- The radiation model can be (and has been) combined with other solvers as wells, e.g. with Fluent.
- With the radiation model, the temperatures inside the furnace were more uniform and the total heat flux to furnace walls was slightly increased.
  - In this case (100% load point), the changes were small.
- The radiation model will be further developed to overcome the current limitations.
- The modeling concept can be applied to study different process conditions, e.g. operation with small load.

References

Bordbar, M.H., Hyppänen, T. (2007). Modeling of radiation heat transfer in a boiler furnace. Adv. Stud. in Theor. Phys. 1, 571-584.

Myöhänen, K., Hyppänen, T. (2011). A three-dimensional model frame for modelling combustion and gasification in circulating fluidized bed furnaces. Int. J. of Chem. Reactor eng., 9, Article A25.