Numerical Simulation of a Rotary Kiln

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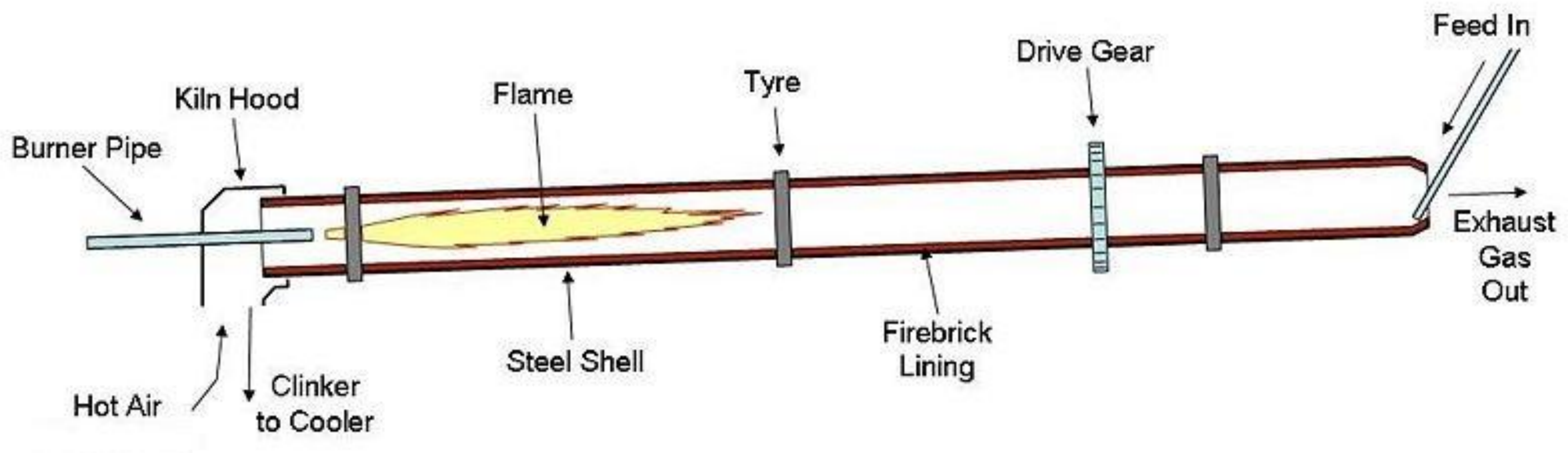
Objectives

A rotary kiln is a long cylindrical equipment slightly inclined tilted on its axis. The objective of this rotary kiln is to drive the specific bed reactions, which, for either kinetic and thermodynamic reasons, require high bed temperature.
The energy originates with the combustion of hydrocarbon fuels via a main burner at the hot end.



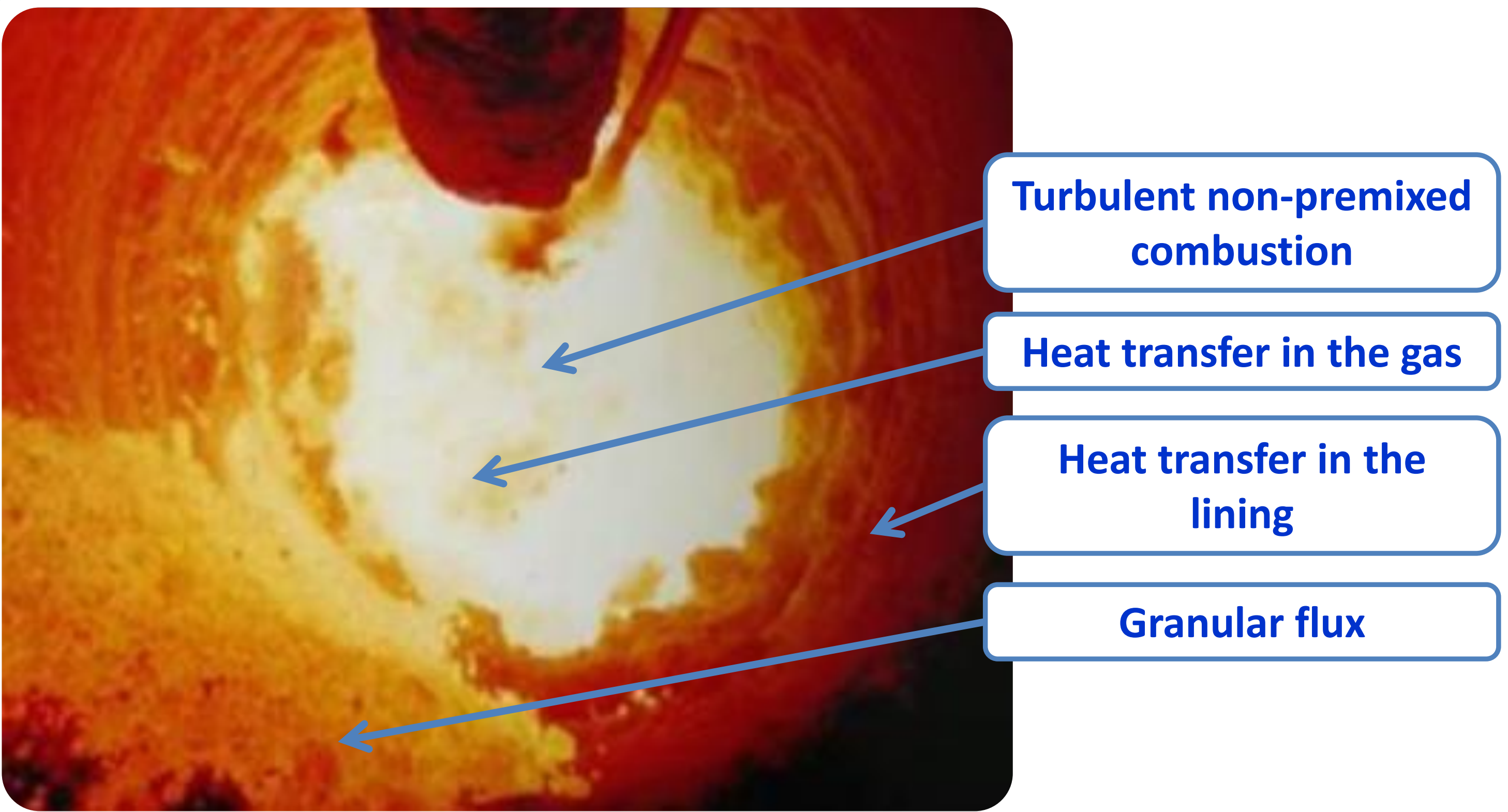
In 1979 the Almatis cement plant (Rotterdam) was built. The kiln was designed to produce Calcium Aluminate Cement (CAC), a very white, high purity hydraulic bonding agents providing controlled setting times and strength development for today's high performance refractory products. The design of the kiln was based only on a downscaling of typical Portland cement plants.

- ✓ Increasing market demand for high purity cement
- ✓ Unscheduled shutdown due to ring formation
- ✓ Restrictive emission regulations (i.e NOx)
- ✓ Future project to expand the plant by building a new kiln

have triggered Almatis' management to increase it's knowledge base on kiln processes.

The model is used to understand in more details what happen inside such a 'black-box' and help to control the standard production procedure but in particular underline critical aspects. In the next stage the model will be used to optimize the kiln production and to test solutions for a new equipment.

Physical Phenomena



Turbulent non-premixed combustion

Heat transfer in the gas

Heat transfer in the lining

Granular flux

The Model

Turbulent combustion results from the two-way interaction of chemistry and turbulence. When a fame interacts with a turbulent flow, turbulence is modified by combustion because of the strong flow accelerations through the flame front induced by heat release, and because of the large changes in kinematic viscosity associated with temperature changes.

Instantaneous balance equations

$$\frac{\partial}{\partial t}(\rho) + \frac{\partial}{\partial x_j}(\rho u_j) = 0$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = \left[-\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i\right]$$

$$\frac{\partial}{\partial t}(\rho Y_k) + \frac{\partial}{\partial x_j}(\rho Y_k u_j) = \left[-\frac{\partial}{\partial x_i}(J_{k,j}) + \dot{\omega}_k\right]$$

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_j}(\rho h u_j) = \left[-\frac{\partial}{\partial x_i}(q_j) + Q\right] + \ldots$$

Chemical source

Heat flux

Heat source

Exact equations for mean properties

$$\frac{\partial}{\partial t}(\overline{\rho}) + \frac{\partial}{\partial x_i}(\overline{\rho}\tilde{u}_i) = 0$$

$$\frac{\partial}{\partial t}(\overline{\rho}\widetilde{u}_i) + \frac{\partial}{\partial x_i}(\overline{\rho}\widetilde{u}_i\widetilde{u}_j) = \left[-\frac{\partial \overline{p}}{\partial x_j} + \frac{\partial \overline{\tau}_{ij}}{\partial x_i} + \widetilde{\rho} g_j\right] - \frac{\partial}{\partial x_i}(\overline{\rho}\underbrace{\overset{①}{\widetilde{u_i'' u_j''}}}_{})$$

$$\frac{\partial}{\partial t}(\overline{\rho}\widetilde{\phi}_k) + \frac{\partial}{\partial x_i}(\overline{\rho}\widetilde{\phi}_k\widetilde{u}_i) = \left[-\frac{\partial}{\partial x_i}(\overline{J}_i^k) + \underbrace{\overset{③}{\overline{\rho}\widetilde{S}_k}}_{}\right] - \frac{\partial}{\partial x_i}(\overline{\rho}\underbrace{\overset{②}{\widetilde{\phi_k'' u_j''}}}_{})$$

Realizable k-epsilon model

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\varepsilon - Y_M + S_k$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(P_k + C_{3\varepsilon}P_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon$$

① **Reynolds stress tensor** $\widetilde{R}_{ij} = \widetilde{u_i'' u_j''}$

② **Turbulent scalar flux** $\widetilde{F}_ij = \widetilde{\phi_k'' u_j''}$ → $-\rho\widetilde{\phi_k'' u_j''} = \frac{\mu_t}{\sigma_\phi}\frac{\partial \widetilde{\phi}_k}{\partial x_j}$ **Eddy diffusivity model**

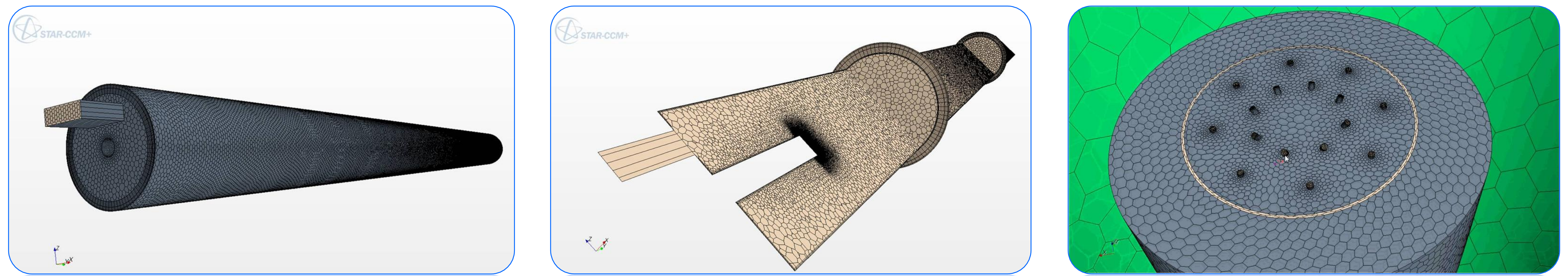
③ **Mean source term** $\overline{\rho}\widetilde{S}_k$ → $S_i = M_i \sum_{j=1}^{n_r} v_{ij} R_j$

Eddy Break-Up Model (EBU)

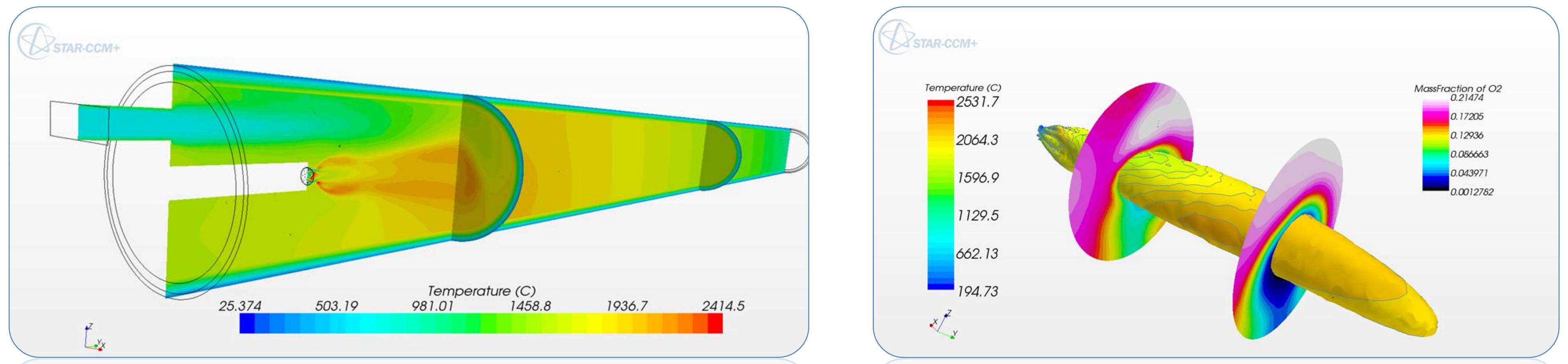
$$R_F = -\frac{\rho}{M_F}\left(\frac{1}{\tau_R}\right) A_{ebu}\, min\left[\overline{Y}_F, \frac{\overline{Y}_O}{s_O}, B_{ebu}\left(\frac{\overline{Y}_{P1}}{s_{P1}} + \ldots + \frac{\overline{Y}_{Pj}}{s_{Pj}}\right)\right]$$

+ Radiation: Participating Media Radiation Model (DOF)
+ NOx: Zeldovich Model

The grid was done using polyhedral elements: **2.8 Millions of elements**



Some results:



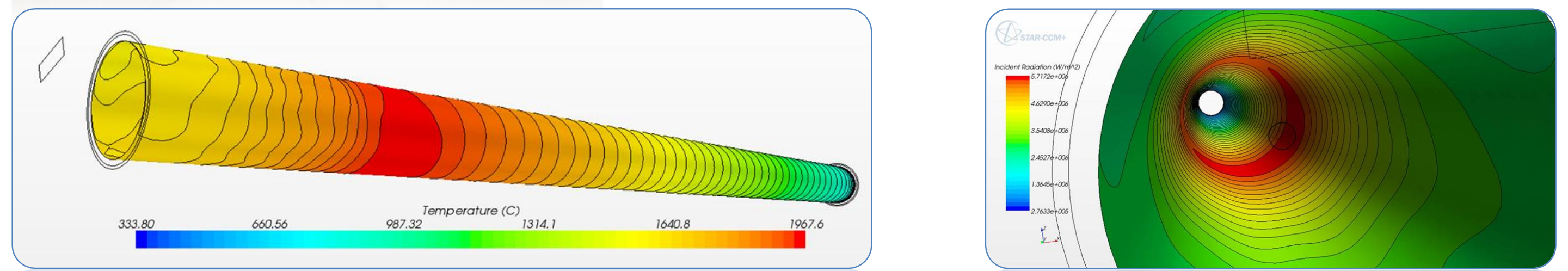
Practical Applications

Counteracting ring formation: different configurations of the kiln was tested to find the best one to reduce such negative effect.
In severe cases, ring grows rapidly and can cause unscheduled shutdown of the kiln in less than a month. Depending on the severity of the problem, maintenance labour, make-up lime purchease, and lime mud disposal can bring the cost of a ring outage very high due to several days production loss.

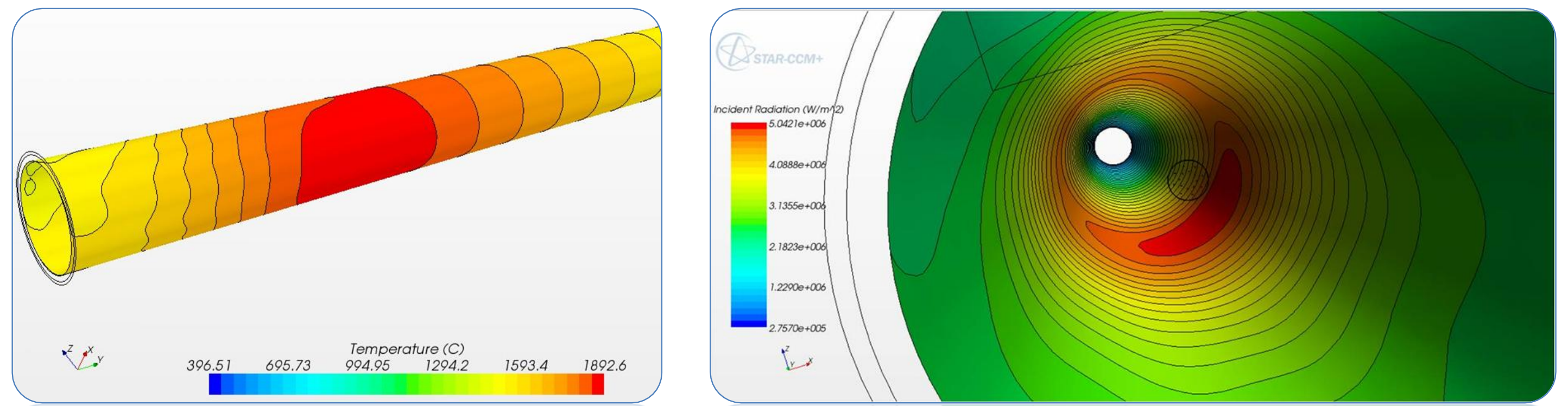
Here an example of a severe ring formation that was observed in our kiln.

The standard production configuration (A/G=10) of the kiln shows a limited region in the interface between the gas and the solid lining where we identified a peak in temperature and radiative absorption.

Std_Configuration (A/G ratio 10)

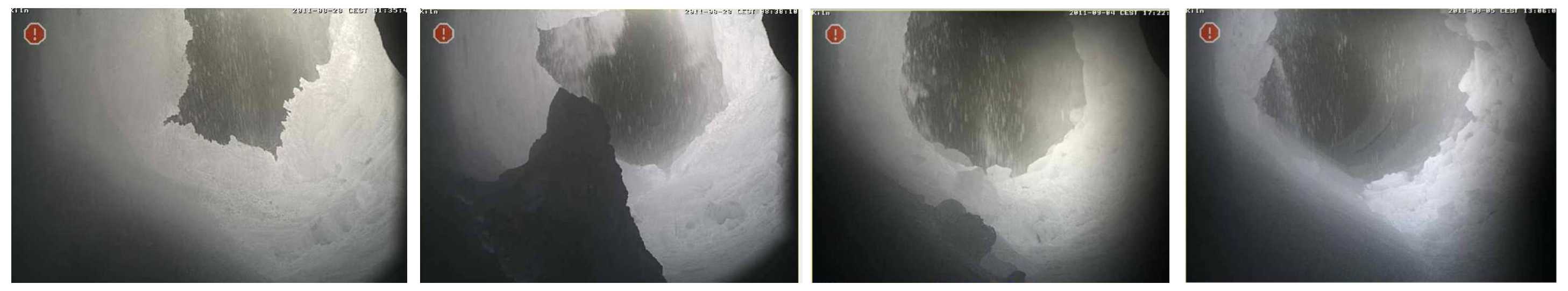


H_Air (A/G ratio 12)



As presented it is evident that we reduced the peak temperature and the incident radiation only by increasing the A/G ratio.

This setup was tested during a severe ring formation and as the images below shows, after a few hours we destroyed the ring. With a lower temperature the liquid phase is too low that the vibrations due to the rotations are able to break lumps from the ring and clean the kiln.



Ring **After 4h** **After 24h** **After 40h**

We are using now this model to find out other configurations that can prevent or counteract ring formations in the kiln but also that can reduce NOx production.

References

Counteracting Ring Formation in Rotary Kilns by Fuel-Air Composition, M. Pisaroni, D. J. P. Lahaye and R. Sadi.

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ALMATIS
PREMIUM ALUMINA