CFD modeling of heat and mass transfer in cooling towers for humid air plume formation prediction

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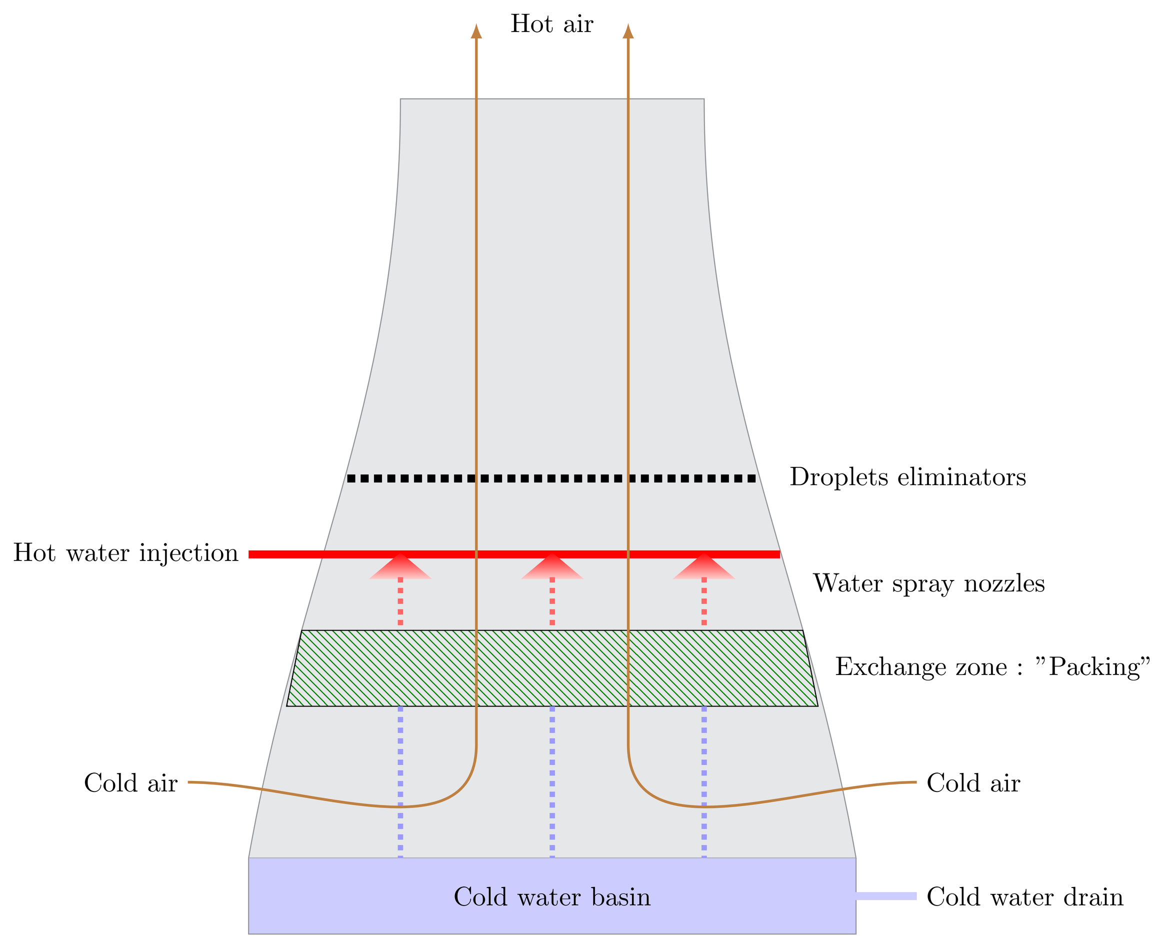
INTRODUCTION

Context: A need for reliable CFD simulations of cooling towers physics to quantify thermal performances, water consumption and climate conditions impact.

Objectives: Develop a specific modeling in code_saturne to simulate the physics at stake (evaporation, interfacial heat transfer, water droplets dynamics, etc.).



PHYSICAL FRAMEWORK

Humid air phase

Humid air h composed of dry air a, water vapor v and water condensate c, in mass fractions:

$$y_h = y_a + y_v + y_c$$

Reynolds-averaged Navier-Stokes equations for the humid air:

$$\frac{\partial \rho_h}{\partial t} + \text{div}\left(\rho \underline{u_h}\right) = \Gamma_w,$$

$$\frac{\partial \left(\rho_h \underline{u_h}\right)}{\partial t} + \underline{\text{div}}\left(\underline{u_h} \otimes \rho_h \underline{u_h}\right) = -\underline{\nabla} p + \underline{\text{div}}\left(\underline{\underline{\tau}} - \rho_h \underline{\underline{R}}\right) + \rho \underline{g},$$

with $k-\epsilon$ with linear production turbulence model [2].

Energy conservation solved for humid air temperature T_h, with $C_{p,h}$ its heat capacity:

$$C_{p,h}\left(\frac{\partial \rho_h T_h}{\partial t} + \text{div}\left(\rho_h T_h \underline{u_h}\right)\right) = ST_{T_h},$$

Injected water phase (rain and packing)

Solved equations for the injected water phase w:

- Mass conservation for liquid in packing and for falling rain
- Imposed mass flow in packing (velocity ≈ 0.1 m/s)
- Momentum conservation for rain (dispersed phase) + interfacial friction (head losses)
- Energy conservation: enthalpy in packing and temperature in rain zone

INTERFACIAL EXCHANGES MODELING

Evaporation model

Mass and thermal source term expressed using Dalton's law for evaporation:

$$\Gamma_w = \begin{cases} \beta a_i \left(x_s\left(T_w\right) - x\right) \mathrm{d}V, & \text{if } x < x_s\left(T_h\right) \\ \beta a_i \left(x_s\left(T_w\right) - x_s\left(T_h\right)\right) \mathrm{d}V, & \text{if } x \geq x_s\left(T_h\right) \end{cases}$$

with x the humidity, β the evaporation rate and a_i the interfacial area concentration.

Following Poppe's formulation with Bosnjakovic's formula [4]:

$$\mathrm{Le_f} = \frac{\alpha}{\beta C p_h} = \mathrm{Le}^{2/3}\frac{\zeta - 1}{\ln\left(\zeta\right)}, \quad \zeta = \frac{\delta + x_s\left(T_w\right)}{\delta + x}$$

with $\mathrm{Le} = \dfrac{\chi}{D}$ the Lewis number (heat diffusion over mass diffusion), α the convective heat transfer coefficient and $\delta = \dfrac{M_a}{M_w} \approx 0.622$.

This globally scales the ratio of heat transfer to evaporation in any zone.

In the packing zone

Packings are evaluated in terms of evaporation rate depending on the air mass flux F_a and injected water mass flux F_w, in the form:

$$\frac{\beta a_i}{F_w} = \lambda \left(\frac{F_a}{F_w}\right)^n$$

with λ and n correlated coefficients for each packing type (usually between 0.5 and 1.5).

In the rain zone

The terminal relative velocity of rain droplets d results from gravity / drag equilibrium :

$$u_{rel,lim} = \sqrt{\frac{8 \rho_d D_d g}{6 \rho_h C_D}}, \quad C_D = \frac{24}{\mathrm{Re}_d}\left(1 + 0.15\,\mathrm{Re}_d^{0.687}\right)$$

with $\mathrm{Re}_d = \dfrac{\rho_h u_{rel,lim} D_d}{\mu_d}$ the droplet Reynolds number.

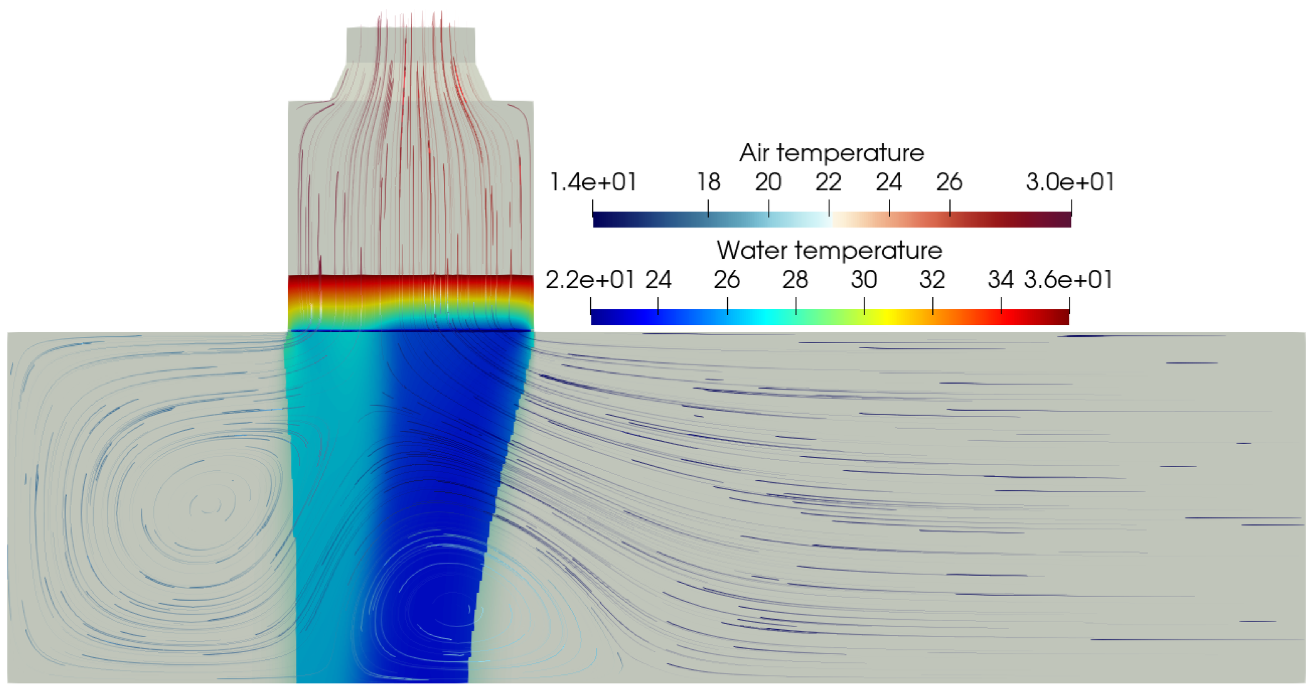
Heat transfer coefficient $\alpha = \dfrac{\mathrm{Nu}\, k_h}{D_d}$ using Ranz-Marshall / Hughmark correlation [3]:

$$\mathrm{Nu} = 2 + 0.6\sqrt{\mathrm{Re}_d}\,\mathrm{Pr}^{1/3}, \text{ or } \mathrm{Nu} = 2 + 0.27\,\mathrm{Re}_d^{0.62}\mathrm{Pr}^{1/3} \text{ if } \mathrm{Re}_d \geq 776$$

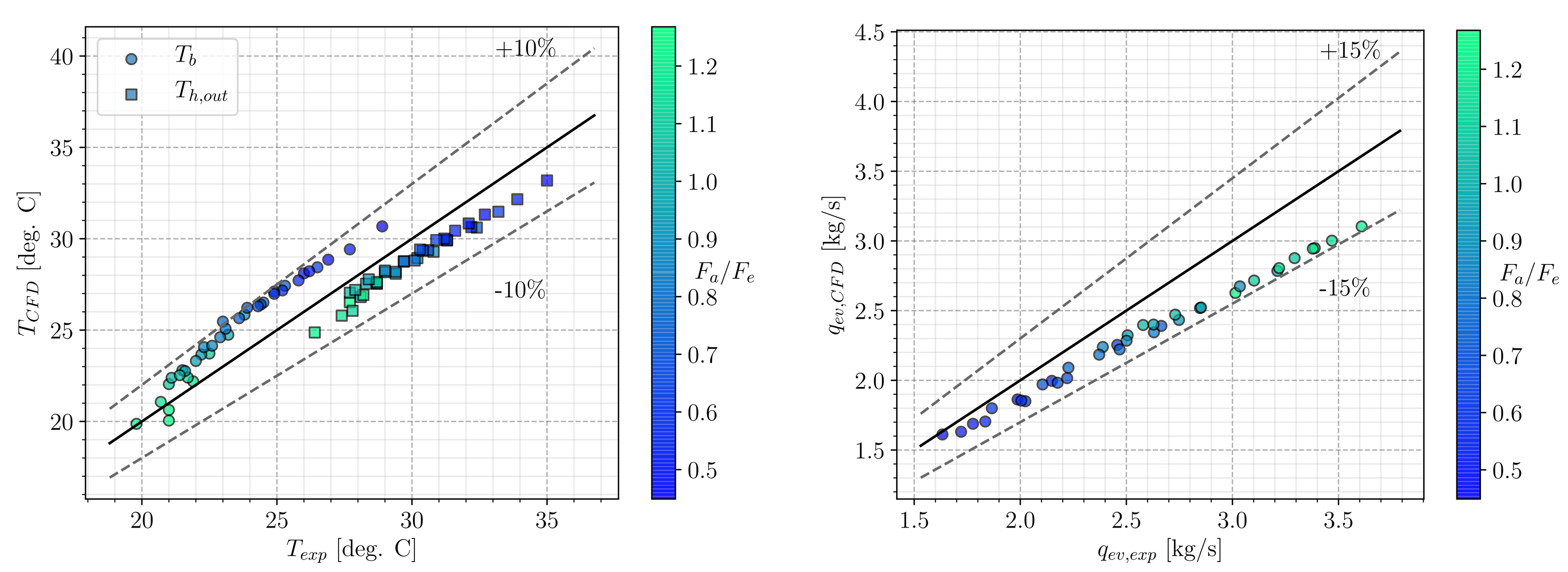
CONCLUSION

- Conclusion: Reasonable experimental results reproduction (phases temperature + evaporation rate, 55 cases), including some advanced physical modeling (*e.g.* rainfall). Possibility to quantify inhomogeneity in cooling tower humid air plume.
- Perspectives:
  - Enhance multiphase flow modeling: numerical robustness and physics (condensation).
  - Energy equation for liquid potential temperature → couple with atmosphere physics → full simulation **inside** and **outside** the cooling tower for plume dispersion [1].
  - Using modeling framework for fog water collection studies.

VALIDATION : MISTRAL EXPERIMENTAL CASE

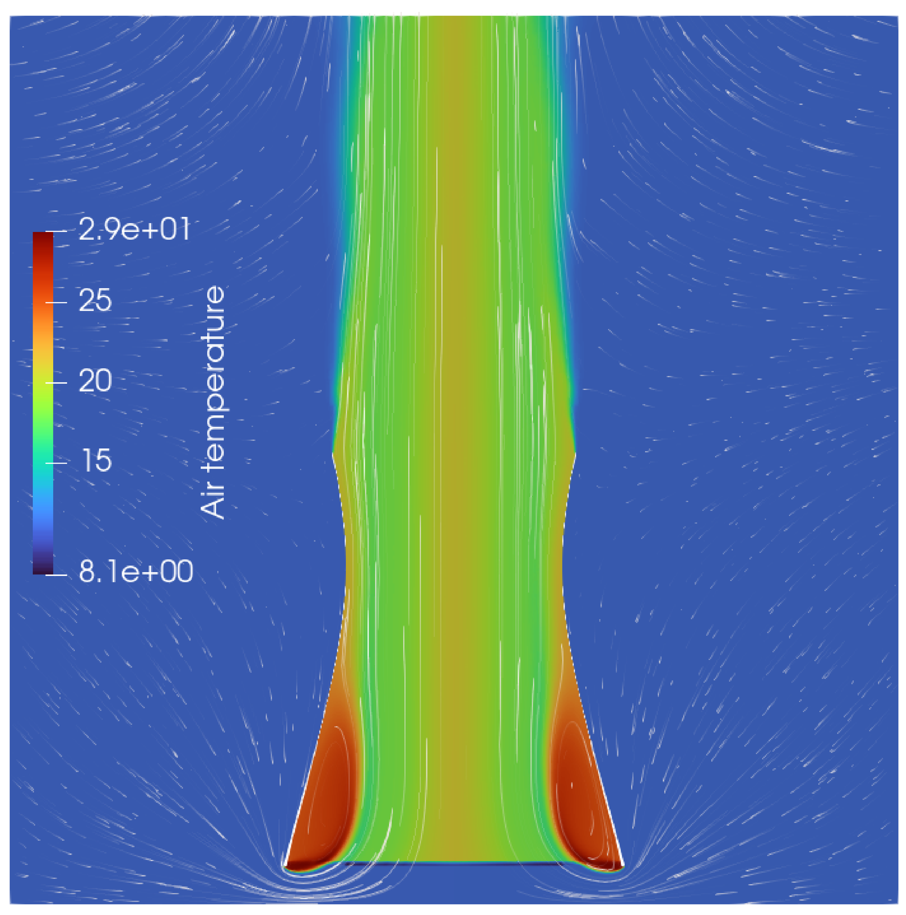


Exprimental facility located at Bugey industrial plant. Qualification of packings thermal performances, measurements of humid air temperature, water temperature, evaporation rate and head losses. Used for validation of code_saturne CFD model for cooling towers.



Temperatures T (left) and evaporation rates q_{ev} (right) CFD results vs. experiments

COOLING TOWER SIMULATION



Example of code_saturne simulation of Bugey NPP cooling tower

References

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