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EXTENDED ABSTRACT

Abstract title: Stochastic Lagrangian Modeling of Wet Cooling Towers Rain Zones

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Abstract

In the context of low-carbon energy production, Wet Cooling Towers (WCTs) are key components for heat rejection in nuclear power plants. While most modeling efforts have traditionally focused on the fill zone, recent studies have highlighted the critical role of the rain zone, where droplet–air interactions significantly impact heat and mass transfer, pressure losses, and overall tower performance. This work presents the development and validation of a hybrid Euler–Lagrange model implemented in the open-source CFD software code_saturne. The model couples a Reynolds-Averaged Navier–Stokes (RANS) Eulerian framework for the humid air with a stochastic Lagrangian formalism for the water droplets. It accounts for turbulent dispersion, interfacial heat and mass transfer, and droplet evaporation. Validation is conducted through analytical benchmarks and simulations of the MISTRAL test facility. Results show excellent agreement with reference solutions and experimental trends, although some limitations persist at high air velocities. While the model does not offer significant advantages over classical approaches in monodisperse, steady-state configurations, it provides a robust and flexible framework for simulating more complex multiphase flows, particularly in scenarios involving polydispersity, transient regimes, or heterogeneous injection conditions.

1 Introduction

Wet Cooling Towers (WCTs) are essential components of thermal power plants, particularly in the nuclear industry, where they ensure efficient heat rejection with minimal environmental impact. Historically, modeling efforts have focused on the fill zone, which accounts for over 85% of the total heat and mass exchange Hawlader and Liu [2002]. However, recent studies have emphasized the importance of the rain zone, where droplets fall freely and interact dynamically with the surrounding air. These interactions affect pressure losses, evaporation rates, and airflow distribution Al-Waked and Behnia [2006, 2007], Al-Waked [2010].

In natural draft configurations (NDWCTs), hot water is sprayed into a rising stream of cooler ambient air, enabling simultaneous heat and mass transfer through convection and evaporation. This process directly influences the thermal performance or operational safety of the facility, as illustrated in Figure 1.

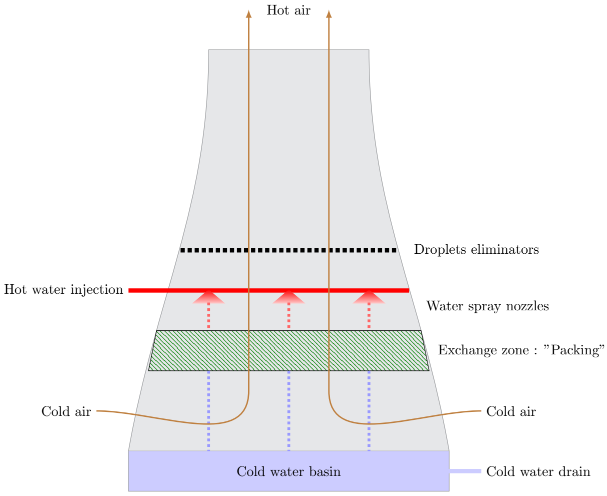

Figure 1: sketch of NDWCT Favre [2024].

Several modeling approaches have been proposed to simulate WCTs. The Merkel model (Merkel [1925]) simplifies the problem by assuming saturated air and a constant Lewis number, but tends to underestimate evaporation under dry conditions. In contrast, the Poppe model (Poppe and Rögener [1991]) solves coupled heat and mass balance equations, offering improved accuracy in predicting water consumption and outlet temperatures (Kloppers and Kröger [2005]; Blain et al. [2016]).

This work builds on these foundations by developing an hybrid Euler-Lagrange model focused on the rain zone. The continuous phase (humid air) is treated using a Reynolds-Averaged Navier-Stokes (RANS) Eulerian framework, while the dispersed phase (droplets) is modeled using a stochastic Lagrangian formalism (Minier et al. [2014]). The model is implemented in the open-source CFD software code_saturne and validated through both analytical benchmarks and experimental data from the MISTRAL test facility.

2 Physical Modeling and Numerical Implementation

The hybrid Euler-Lagrange model developed in this work couples a Reynolds-Averaged Navier-Stokes (RANS) Eulerian framework for the humid air with a stochastic Lagrangian formalism for the water droplets. This section presents the governing equations and the numerical implementation.

2.1 Governing Equations for the Continuous Phase

The continuous phase is governed by the conservation equations of mass and momentum. The mass conservation equation reads:

$$\frac{\partial \rho_h}{\partial t} + \nabla \cdot (\rho_h \mathbf{u}) = S_\rho \tag{1}$$

where ρ_h is the density of humid air [kg/m^3], $\mathbf{u}$ is the mean velocity field [m/s], and S_ρ is the mass source term due to evaporation [kg/m$^3 \cdot$ s].

The momentum equation includes a source term from droplet-air interaction:

$$\frac{\partial (\rho_h \mathbf{u})}{\partial t} + \nabla \cdot (\rho_h \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \mathbf{S}_m \tag{2}$$

where p is the pressure [Pa], $\boldsymbol{\tau}$ is the viscous stress tensor [Pa], and $\mathbf{S}_m$ is the momentum source term due to the dispersed phase [kg $\cdot$ m/s$^2 \cdot$ m^3].

The thermal behavior of the humid air is governed by the conservation of energy, expressed in terms of temperature T. The governing equation reads:

$$c_{p,h} \left[\frac{\partial (\rho_h T)}{\partial t} + \nabla \cdot (\rho_h T \mathbf{u}) \right] = \nabla \cdot (\lambda_h \nabla T) + S_T \tag{3}$$

where $c_{p,h}$ is the specific heat capacity of humid air [J/kg $\cdot$ K], λ_h is the thermal conductivity [W/m $\cdot$ K], and S_T is the thermal source term [W/m^3] accounting for heat exchanges with the dispersed phase.

2.2 Lagrangian Tracking of Droplets

Each droplet is tracked individually in the Lagrangian frame. Its position $\mathbf{x}_p$ and velocity $\mathbf{U}_p$ evolve according to:

$$\mathrm{d}\mathbf{x}_p = \mathbf{U}_p \mathrm{d}t \tag{4}$$

$$\mathrm{d}\mathbf{U}_p = \left(\frac{\mathbf{U}_s - \mathbf{U}_p}{\tau_p} + \mathbf{g} \right) \mathrm{d}t \tag{5}$$

where $\mathbf{U}_s$ is the fluid velocity seen by the particle [m/s], τ_p is the particle relaxation time [s], and $\mathbf{g}$ is the gravitational acceleration [m/s²].

The fluid velocity seen by the droplet is reconstructed using a Langevin stochastic model:

$$\mathrm{d}\mathbf{U}_s = \mathbf{A}\mathrm{d}t + \mathbf{B}\mathrm{d}\mathbf{W} \tag{6}$$

where $\mathbf{A}$ is the drift vector part [m/s] and $\mathbf{B}$ is the diffusion tensor [$\mathrm{m/s}^{\frac{3}{2}}$] part of the model (see Minier et al. [2025]), and $\mathrm{d}\mathbf{W}$ is a Wiener process increment.

2.3 Heat and Mass Transfer

The droplet temperature T_p evolves as:

$$\mathrm{d}T_p = -\left(\frac{T_p - T_s}{\tau_{th}} + \frac{\dot{m}_p L_v}{m_p c_{p,p}} \right) \mathrm{d}t \tag{7}$$

where T_s is the fluid temperature seen by the droplet [K], τ_{th} is the thermal relaxation time [s], $\dot{m}$ is the evaporation rate [kg/s], L_v is the latent heat of vaporization [J/kg], m_p is the droplet mass [kg], and $c_{p,p}$ is the droplet specific heat capacity [J/kg · K].

The mass of the droplet evolves according to:

$$\mathrm{d}m_p = -\dot{m}_p \mathrm{d}t \tag{8}$$

2.4 Two-Way Coupling and Source Terms

The coupling between phases is ensured by summing the droplet contributions onto the Eulerian mesh. For a given cell c of volume V_c, the source terms are:

$$V_c \left[S_\rho\right]_c = \sum_{p \in c} \dot{m}_p, \quad V_c \left[\mathbf{S}_m\right]_c = \sum_{p \in c} \dot{m}_p (\mathbf{U}_p - \mathbf{u}_h), \quad V_c \left[S_T\right]_c = \sum_{p \in c} \left(\dot{m}_p L_v + h_c (T_p - T_h)\right) \tag{9}$$

where h_c is the convective heat transfer coefficient [W/m² · K] and T_h is the local air temperature [K].

3 Model Validation and Results

To assess the reliability of the hybrid Euler-Lagrange model implemented in code_saturne, a two-step validation strategy is adopted. First, the model is compared to analytical solutions for simplified cases. Second, it is applied to simulate the MISTRAL test facility, with experimental comparisons planned.

3.1 Analytical Validation

Analytical validation is conducted along three physical dimensions: mass (via droplet diameter $d_p(t)$), momentum (via droplet velocity $\mathbf{U}_p$) and thermodynamics (via droplet temperature T_p). Only the first two are presented here.

The analytical evolution of the droplet diameter $d_p(t)$ under quasi-steady conditions is given by:

$$d_p(t) = d_{p,0} \sqrt{1 - \frac{2Kt}{d_{p,0}^2}}, \quad \text{with} \quad K = 2 \frac{\rho_f}{\rho_p} D \, \mathrm{Sh} \ln \left(\frac{1 - Y_v^\infty}{1 - Y_v} \right) \tag{10}$$

using the fact that $\dot{m}_p = \pi d_p \rho_f D \,\mathrm{Sh}\, \ln\left(\frac{1-Y_v^\infty}{1-Y_v}\right)$ (Bird [2002]), where D is the diffusion coefficient of water vapor in humid air [m²/s], Sh is the Sherwood number characterizing convective mass transfer, Y_v is the vapor mass fraction at the droplet surface, and Y_v^∞ is the vapor mass fraction far from the droplet.

Numerical simulations using an explicit Euler scheme show excellent agreement with this solution, with relative errors below 0.1% throughout the droplet fall time (see Figure 2, left panel).

As for droplet velocity evolution, a more refined analytical solution is derived by considering the balance between gravitational acceleration and aerodynamic drag. The droplet velocity $u_p(t)$ is governed by a nonlinear first-order ODE, which accounts for the quadratic drag force acting on a falling sphere in a viscous medium.

Assuming that the droplet diameter d_p, fluid density ρ_f, and drag coefficient C_D remain approximately constant during the fall, the drag parameter $k = \frac{3 C_D \rho_f}{4 \rho_p d_p}$ can be treated as constant. This simplification, although not strictly exact, is justified by the relatively small variations of C_D and d_p over the droplet trajectory.

Under these assumptions, the governing equation reads: $\dfrac{\mathrm{d}u_p}{\mathrm{d}t} = g - k u_p^2$.

This nonlinear ODE is solved using separation of variables, leading to the analytical solution:

$$u(t) = \frac{u_0 + \sqrt{g/k}\,\tanh\left(\sqrt{gk}\;t\right)}{1 + \dfrac{u_0}{\sqrt{g/k}}\tanh\left(\sqrt{gk}\;t\right)}. \tag{11}$$

where u_0 is the initial droplet velocity. The solution describes the transient acceleration toward the terminal velocity $u_{\mathrm{lim}} = \sqrt{\frac{g}{k}}$, offering improved accuracy over classical exponential models, especially when inertial effects are significant.

As for the droplet diameter, the droptlet velocity closely matches the analytical solution throughout the droplet fall with a relative error below 1% (Figure 2, left panel).

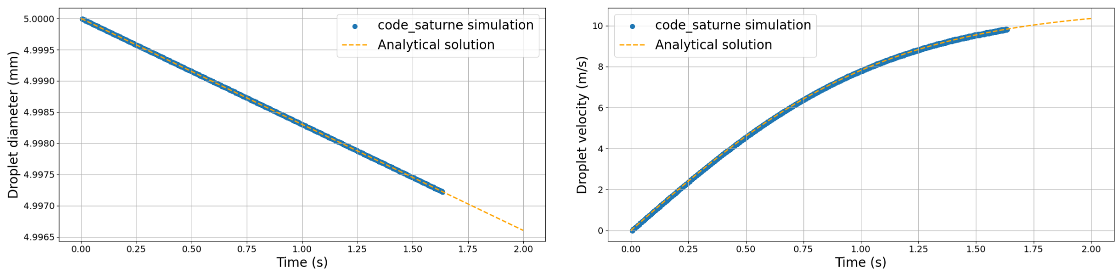

Figure 2: comparison between analytical and numerical solutions for droplet diameter (left) and droplet velocity (right). The apparent linearity of the diameter curve is due to the very small numerical coefficients involved, which mask the underlying nonlinear behavior. Simulation points stop around t = 1.65 s, corresponding to the droplet fall time after which it is removed from the domain.

3.2 Experimental Validation: MISTRAL Test Bench

The second validation step involves simulations of the MISTRAL test facility operated by EDF at the Bugey nuclear site. This experimental setup reproduces the geometry and operating conditions of a full-scale wet cooling tower, including a 10-meter rain zone and instrumented fill.

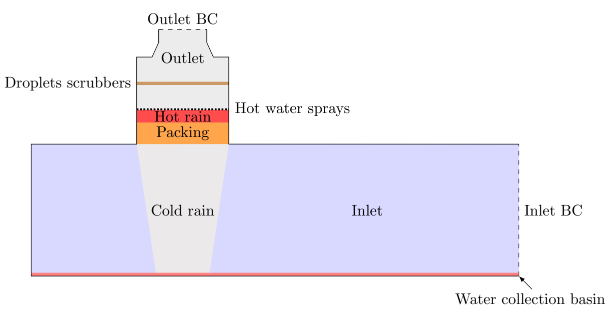

Figure 3: sketch of the MISTRAL test bench (Favre [2024]).

Key quantities targeted for comparison include: 1) Air and water outlet temperatures, 2) Pressure losses across the fill 3) Evaporation rates and 4) Thermal power transferred.

At the time of writing, simulations using the Lagrangian model are ongoing. Preliminary results indicate that the model performs correctly and yields results consistent with experimental data. However, in the case of a classical monodisperse flow configuration such as the one simulated here, it does not offer a significant advantage over the traditional Euler–Euler approach. Nonetheless, given the inherently polydisperse nature of the experimental spray, the Euler–Lagrange framework is expected to perform better. This will be assessed through quantitative comparison with experimental Mistral data, once the Lagrangian simulation results are consolidated.

4 Conclusion and Perspectives

The hybrid Euler–Lagrange model developed and implemented in code_saturne successfully captures the coupled dynamics of humid air and falling droplets in wet cooling tower configurations. The model has been rigorously validated against analytical solutions for both droplet evaporation and thermal evolution, demonstrating excellent agreement and confirming the validity of the numerical implementation.

Preliminary simulations of the MISTRAL test bench further support the model's reliability, with results consistent with experimental trends. However, in the specific case of a monodisperse droplet distribution under steady-state conditions, the added complexity of the Lagrangian formalism does not yield significant improvements over the classical Euler–Euler approach. This suggests that the relevance of the hybrid model should be assessed through sensitivity analyses on the Mistral test bench, by comparing Euler–Lagrange and Euler–Euler approaches and evaluating whether observed differences justify the added complexity.

Nonetheless, the Euler–Lagrange framework offers promising perspectives. Its ability to naturally handle polydispersity, track individual droplet histories, and resolve localized interactions makes it particularly suited for more complex scenarios, such as transient regimes, non-uniform injection, or heterogeneous packing structures. Future work will focus on extending the validation to such configurations, as well as exploring GPU-based acceleration to mitigate the increased computational cost. Additionally, the role of droplet coalescence and fragmentation—currently neglected—should be investigated, as these phenomena may significantly influence global exchange processes and could prove as critical as polydispersity itself. Ultimately, this approach could provide a robust and versatile tool for high-fidelity simulations of multiphase flows in industrial cooling systems.

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