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Modelling atmospheric effects on performance and plume dispersal from natural draft wet cooling towers

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ABSTRACT

The study of cooling towers in realistic atmospheric conditions is important to assess their performance and plume dispersal as a function of wind speed and hygrometric conditions for their economical and public health consequences. In the present work the plume formation and its dispersal are modeled using a finite volume method on grid including details of the towers. The air mass flow and heat transfer are simulated inside and outside the tower. The equations for the transport of momentum, mass and liquid potential temperature are solved using the CFD software Code Saturne. In contrast to other studies dealing with the performance of cooling towers, the exchange processes inside the tower are represented with a source terms approach. The adiabatic expansion of the plume at the exit of the tower in the atmosphere is accounted for using the thermodynamical laws. The results of the simulation are compared to the measurement at Bugey nuclear power plant. The results of the model are shown to be in good agreement with the field measurements from point of view of the air flow structures, plume patterns and thermodynamical variables. Based on this reference simulation we study the variation of the cooling tower performance against the wind speed and quantify the effect of the ambient wind speed increase on the reduction of the natural draft. We also discuss the sheltering effect that the upstream tower can have on the other.

1. Introduction

A natural draft wet cooling tower (NDWCT) is an important part of the cooling system in thermal power plants. Its use is based on circulating the warm water to be cooled inside the tower where mass and heat are exchanged between air and water and then they are ejected into the atmosphere via a circulation induced by a buoyancy mechanism.

However, the NDWCTs is still a subject of many questions about their efficiency and socio-economical impacts. In fact, the rejected saturated air could be charged with pollutants that can affect the health of the neighbouring populations. The extent of the contaminated zone depends actually on the towers operating conditions, its design and the atmospheric conditions.

For the consideration of the environmental impact, many efforts were deployed to investigate the plumes behavior and their effects in the proximity of towers. For example, a model for seasonal and annual prediction of the plume drift deposition and shadowing effect (SACTI model) was developed by the Argonne National Laboratory of University of Illinois (Policastro et al., 1994). The model is composed of several submodels allowing analytical computation of plume length, plume rise and drift deposition from single and several NDCTs. The different submodels were validated on the basis of the field experiments, like Chalk Point dye tracer experiment where dye is added to the water inside NDWCT to be able to measure the drift deposition at different distance from the tower (Meyer, 1975). In addition, mathematical models for plume trajectory prediction were developed and they are based on the lagrangian plume puff trajectory (Hanna, 1975; Winiarski and Frick, 1976). Carhart et al. (1982) examined the performance of sixteen analytical models by comparison of model prediction with field data. His main conclusion is that the performance of the models is sensitive to some parameters, such as the dilution rate of the plume in the ambient air and the presence of the thermodynamic of the moisture.

Many theoretical and experimental studies were conducted in order to better understand the cooling tower performance with regard to internal and external parameters. Williamson et al. (2008) examined the effect of all parameters related to the warm water and ambient air conditions on the NDWCT performance. His main conclusion is that the NDWCT performance is strongly influenced by the thermodynamical state of the ambient air. Other studies were focused on the effect of the internal operating conditions, considering the NDWCT as an open thermodynamic system

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interacting with a windless atmosphere (Kaiser et al., 2005; Fisenko and Brin, 2007; Heidarinjad et al., 2009; Rahard, 2010). As the windless atmosphere is just an idealized state, numerical and experimental studies were carried out to understand the effect of wind on the flow structure inside and around the NDWCTs and on their performance (Su et al., 1999; Gao et al., 2007; Hyhlik, 2011). Via CFD and experiments, it was found that the performance and flow structure vary as the external wind speed varies (Al-Waked and Behnia, 2006; Al-Waked, 2010). Al-Waked and Behnia (2007) pointed out that there exists a critical wind velocity below and beyond which the performance decreases and increases respectively. For the NDWCTs resembling the Bugey[1] NDWCT, this critical velocity is 7.5 ms^{-1}.

All the previous studies deal with the mass–heat transfer and air flow in the proximity of the tower. In the studies of the plumes emitted from cooling towers and its dispersal in the atmosphere, the NDWCTs are usually considered as filled obstacles (Meroney, 2006; Lucas et al., 2010). The mass rate and plume characteristics are fixed as a Dirichlet boundary conditions at the top of the NDWCT (Bouzereau et al., 2008). Following this approach, the external atmospheric conditions affect the plume and flow structure only outside the NDWCT. Lucas et al. (2010) investigated the effect of psychrometric ambient conditions on drift deposition in the proximity of the cooling tower, by considering the water from the cooling tower as discrete droplets. At this scale, to our knowledge all the available works on drift were undertaken with Lagrangian approach under a predefined wind and thermodynamic temperature conditions.

In fact, under the realistic atmospheric stability state of the atmosphere, the hot plume at the exit of the cooling tower is subject to the adiabatic expansion and diffusion limiting the rise of the plume and influencing the droplet deposition. Moreover, at the exit of the cooling tower, the plume of saturated air undergoes condensation when it meets the atmosphere. Hence, the concentration of the droplets of water is very sensitive to the drift eliminator efficiency and the atmospheric condition at the top of the tower and the Lagrangian study of droplet cloud dispersal becomes difficult to perform. One advantageous alternative is the use of the droplets of liquid water as dispersed phase within the Eulerian approach. The fraction of liquid water in proximity of the tower is then determined from the thermodynamic equilibrium between the liquid and gaseous phases of water in the atmosphere (Bouzereau et al., 2008). This approach is promising especially when the plume rises to higher altitudes where the water phase distribution is governed by the microphysics laws.

So, in the present work we deal with modelling air flow inside and outside the NDWCT and plume dispersal under realistic atmospheric conditions with an Eulerian approach. The atmosphere state is almost neutral over the first kilometer, followed by a stably stratified layer. The liquid water phase evolution is solved with the Eulerian approach and its phase change is represented by specific laws of microphysics. As the plume dispersals at the exit of the towers are adiabatic in the absence of the abrupt phase change, we use the potential temperature which is a conservative variable in the energy equation. The concept of potential temperature will be discussed at length in Section 4. In addition, the heat and mass transfer between the warm water and air inside the cooling tower will be represented by the global source term approach, without accounting for the heat and mass exchange mechanisms required when the liquid phase is treated by lagrangian approach. The momentum loss in the towers will be also represented by a specific source term. The use of the global source term approach would allow easy understanding of the flow structure and plume dispersal under several atmospheric conditions. The approach with source term was already used at little extent by Hyhlik (2011) for studying cooling tower flow. The model will be used to simulate the realistic plume dispersal test case for validation purpose. The data and observations of plume dispersal from NDWCT of Bugey collected by EDF will be used.

Some aspects on NDWCTs are given in Section 2, while in Section 3 we describe the cooling tower of Bugey site and the measurement protocols. In Section 4 the numerical description of the model and different theoretical schemes are presented. Next, the used methodology will be described, and the qualitative and quantitative analysis of the results will be made in Section 5. Sensitivity of the NDWCT behaviour to the external wind speed will be done in Section 6. Finally, we conclude with discussions and drawing conclusions concerning the results and methodologies in Section 7.

2. Background on NDWCTs

A NDWCT is a thermal system that extracts heat from the warm water by evaporative and, to a lesser extent, convective processes. The heat extraction is ensured naturally by the buoyancy effect resulting from the temperature gradient between the indoor and outdoor air of the tower. In Fig. 1 are illustrated the main parts of NDWCT used in thermal and nuclear power plants. The warm water at the temperature T_{wi} is sprayed from the water system in the spray zone. Just below, we find a fill of height ranging between 1 and 2 m. The fill allows the heat and mass exchange between air and water. It is the zone where the main mass and heat exchange occurs; about 82% of total heat is exchanged (Al-Waked and Behnia, 2006). Next, once the water has left the bottom of the fill it falls down over a distance of about 8–9 m in the rain zone before reaching the water bassin at the temperature T_{wo}.

Thus, the efficiency of the cooling tower is characterized by the temperature decrease of the water $\delta T_w = T_{wi} - T_{wo}$. Usually, the performance of the cooling tower is defined by the following expression:

$$\xi = \frac{\delta T_w}{T_{wi} - T_{awb}} \tag{1}$$

where T_{awb} represents the wet bulb temperature of the ambient air, it is the minimal temperature that water could reach at the end of its course in the rain zone.

From the point of view of energy balance, the factor ξ gives an incomplete picture, as δT_w represents only the sensible heat lost by the water, without including the latent heat due to the evaporation of water. If we note $\delta\dot{m}$ the rate of water exchanged and rejected into the atmosphere, the total heat gained by air and lost by water is given by this expression:

$$\delta Q = \dot{m}_w Cp_w \delta T_w + \delta\dot{m} L_v \tag{2}$$

where $\dot{m}_w$ is the warm water flow rate (kg/s), Cp_w (J/kg K) is the heat capacity of water and L_v (J/kg) is the latent heat of water vaporization.

This extracted energy is also equal to the enthalpy gained by the air at the exit of the tower.

$$\delta Q = \dot{m}_a Cp_m (T_{ao} - T_{ai}) + \dot{m}_a (C_o - C_i) L_v \tag{3}$$

where $\dot{m}_a$, T_{ao} and T_{ai} are the air flow rate, the outlet and inlet air temperature respectively. The parameter Cp_m represents the heat capacity of the mixture air and vapor. The symbols C_o and C_i stand for the fraction of water vapour content at the outlet and inlet of the tower (kg/kg).

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[1] Near Lyon, France.