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Cooling tower plume abatement using a coaxial plume structure

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ABSTRACT

The traditional approach of cooling tower plume abatement is supposed to result in an unsaturated, well-mixed plume with a "top-hat" structure in the radial structure, but this is an idealization that is rarely achieved in practice. Meanwhile, previous analyses have shown that there may be an advantage in specifically separating the wet and dry air streams whereby the corresponding plume is of the coaxial variety with dry air enveloping (and thereby shielding) an inner core of wet air. Given that a detailed understanding of the evolution of coaxial plumes is presently lacking, we derive an analytical model of coaxial plumes in the atmosphere, which includes the effects of possible condensation. Of particular concern is to properly parameterize the entrainment (by turbulent engulfment) of fluid from the inner to the outer plume and vice versa. We also present and discuss the two different body force formulations that apply in describing the dynamics of the inner plume. Based on the resulting model predictions, we introduce a so-called *resistance factor*, which is defined as the ratio of the average non-dimensional velocity to the average relative humidity. In the context of visible plume abatement, the resistance factor so defined specifies the likelihood of fog formation and/or a recirculation of moist air into the plenum chamber. On the basis of this analysis, we can identify the region of the operating-environmental condition parameter space where a coaxial plume might offer advantages over its uniform counterpart.

1. Introduction

A visible plume is a column of microscopic droplets of condensed water. Hot, moist air emitted from a wet cooling tower cools by entraining cold ambient air and a visible plume, or fog, forms if the plume temperature falls below the dew-point temperature. Though containing no pollutants except in entrained water droplets, which are, in any event, few in number, a visible plume is oftentimes regarded as a nuisance, which is better avoided. This need has led to various strategies for plume abatement (see below) whereas the need to model the fluid- and thermodynamical behavior of cooling tower plumes has produced a voluminous literature on the topic. Indeed, the analytical description of atmospheric plumes, cooling tower and otherwise, dates back to Morton [26], who formulated a one-dimensional, "top-hat" model of vertically ascending thermal plumes in a moist ambient based on the integral approach of Morton et al. [28] (hereafter referred to as MTT). In the work of Morton [26] (but not MTT), the potential temperature and density, which are conserved during adiabatic processes, are used in the governing equations. Morton's model, which can predict the height at which fog will begin to form within the ascending plume, was improved upon by Csanady [6], who included an ambient wind and was the first to note that condensation might occur only over some intermediate range of heights. The subsequent numerical results of Wigley and Slawson [37] support this conclusion but indicate that whatever condensation does occur must do so relatively close to the stack/plume source. Wigley and Slawson further showed ([38] – see also [10,35,36]) that plumes that include condensation rise to greater heights than do plumes in which no fog is formed. Wu and Koh [39] proposed a merging criteria for the multiple plumes that emanate from adjacent cooling tower cells. Their predictions are in good agreement with corresponding laboratory data on dry plumes (without moisture). Carhart and Policastro [5] developed the Argonne National Laboratory and University of Illinois (ANL/UI) model (a so-called second-generation model) to resolve select deficiencies of previous integral models e.g. their inability to correctly and simultaneously predict plume bending and dilution. Furthermore, Janicke and Janicke [15] proposed an integral plume rise model which can be applied to arbitrary wind fields and source conditions.

Based on the above quick review, we now focus on the (hybrid) cooling tower configurations associated with different plume abatement strategies. Arguably the most popular configuration is

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the so-called parallel path wet/dry or PPWD configuration, which has been deployed commercially for more than 40 years. Lindahl and Jameson [21] present a detailed description of PPWD towers, for both counter- and crossflow operation. In the former case, wet air exiting the fill section is co-mingled with comparatively dry air exiting heat exchanger bundle(s) (see Fig. 2.1 below). The two air streams mix in a plenum chamber and are then discharged to the atmosphere by a fan. Although perfect mixing is never achieved in practice, such an idealization serves as a convenient starting point for the development of plume dispersion models. In the crossflow configuration, the strategy is quite different. Here, air flows horizontally through the fill (see Fig. 2.5 below). Once in the plenum, this wet air stream has a velocity approximately twice that of the dry air and so the opportunity for mixing is (deliberately) limited. As a result, the plumes generated by PPWD crossflow cooling towers tend to be of the co-axial variety with dry air enveloping (and thereby shielding) an inner core of wet air. As illustrated in Fig. 3.5 of Lindahl and Jameson [21], the coaxial wet/dry plume above a PPWD crossflow tower results in a cone shaped visible plume that disappears at a vertical distance of about two to three fan stack diameters. Alas, a more detailed understanding of the evolution of coaxial plumes is presently lacking. Given this deficit of knowledge, our present goals are twofold: (i) to adapt ideas from Morton [26], Wu and Koh [39] and many others and thereby derive an analytical model for coaxial plumes in the atmosphere, and, (ii) to identify that region of the operating condition-environmental condition parameter space for PPWD where a coaxial plume might offer an advantage over its uniform counterpart. Of course, one might prefer a crossflow PPWD tower for other reasons: the lack of static mixing devices within the plenum chamber signifies a smaller pressure drop to be overcome by the fan. Such design- and operation-specific details are not of principal concern here. Rather, our primary focus is on the buoyant convection that occurs above the cooling tower.

The manuscript is arranged as follows. In Section 2 we recapitulate the theoretical model germane to uniform plumes encountered in PPWD counterflow towers. Following a discussion of coaxial plume structures in the open literature in Section 2.3, we formulate in Section 3 the theory for coaxial plumes above PPWD crossflow towers. Thereafter, in Section 4, we study the range of process/ambient conditions where a coaxial plume structure offers some advantage with respect to plume abatement. Finally Section 5 provides conclusions for the work as a whole and also identifies ideas for future research.

2. Theory for uniform plumes and its application to counterflow cooling towers

Fig. 2.1 is a simplified sketch of a PPWD counterflow cooling tower. A dry section that consists of finned tube heat exchangers is added above the wet section, which consists of a spray zone, fill zone and rain zone. Thus warm, less humid air from the dry section and hot, saturated air from the wet section flow into the plenum chamber located just upstream of the axial fan. The two air streams are mixed thoroughly then discharged to the atmosphere with an average relative humidity below saturation. Streng [32] suggests that the PPWD counterflow cooling tower, with its series connection of the dry and wet sections on the water side and parallel connection of these sections on the air side, produces the most effective overall cooling performance.

To describe the uniform plume that forms above the PPWD counterflow cooling tower illustrated in Fig. 2.1, we adapt the integral model of Wu and Koh [39], which allows prediction of the plume temperature, moisture (vapor and liquid phases), vertical velocity, width, and density as well as the visible plume length in case of condensation. The main assumptions are:

(i) Molecular transport is negligible compared to turbulent transport as a result of which (a) model output is independent of the Reynolds number, and, (b) the Lewis number, defined as the ratio of thermal to mass diffusivity, is unity [17]. Because Le = 1, the dilution curve that appears in the psychrometric chart connecting the cooling tower exit to the far field ambient is a straight line.

(ii) The cross-sectional profiles of the plume vertical velocity, temperature, density, vapor and liquid phase moistures are all self-similar. More specifically, plume properties are assumed to exhibit "top-hat" profiles [8].

(iii) The variation of the plume density is small, i.e. no more than 10%. As such, the Boussinesq approximation can be applied.

(iv) The pressure is hydrostatic throughout the flow field.

(v) The plumes emitted from adjacent cooling tower cells are initially axisymmetric and propagate vertically upwards. At larger elevations, plume merger may occur as a result of which the shape of the combined plume is assumed to be a combination of a finite line plume in the central part and two half axisymmetric plumes at either end. The criterion for plume merger follows from Wu and Koh [39] and is summarized in Appendix A.

(vi) The ambient is, to a first approximation, assumed to be uniform in temperature and humidity. It is also devoid of liquid phase moisture.

2.1. Formulation

The plan-view schematic of Fig. 2.2 shows the coordinate system chosen for a typical array of (equidistant) cooling towers. The x-axis is parallel to the line connecting the centers of the cells whereas the z-axis is the vertical axis with $z = 0$ corresponding to the top of the fan shroud.

The conservation equations for mass, momentum, energy and (vapor and liquid phase) moisture are written symbolically as

$$\frac{d}{dz}\left\{\int_A \rho_p U_p \, dA\right\} = \rho_a E, \tag{2.1}$$

$$\frac{d}{dz}\left\{\int_A \rho_p U_p^2 \, dA\right\} = g \int_A \left(\rho_a - \rho_p\right) dA, \tag{2.2}$$

$$\frac{d}{dz}\left\{\int_A (t_p - t_a) U_p \, dA\right\} = \int_A \frac{L_v}{c_{pa}} \sigma_p U_p \, dA, \tag{2.3}$$

$$\frac{d}{dz}\left\{\int_A \left[(q_p - q_a) + \sigma_p\right] U_p \, dA\right\} = 0, \tag{2.4}$$

where ρ_p, U_p and A are, respectively, the plume density, vertical velocity, and cross-sectional area. Moreover, q is the specific humidity, t is the air dry-bulb temperature,[1] σ is the specific liquid moisture, E specifies the rate of entrainment of external ambient air, g is gravitational acceleration, $L_v(t) = 4.1868 \times 10^3 [597.31 - 0.57t]$ J/g is the latent heat of condensation in which t is measured in °C, and $c_{pa} = 1.006$ J/g °C is the specific heat capacity of air at constant pressure. The subscripts p and a indicate values in the plume and in the ambient, respectively. According to Taylor's entrainment hypothesis [28]

$$E = S\alpha U_p. \tag{2.5}$$

where α is an entrainment coefficient whose value is typically 0.117

[1] Below the plume origin and consistent with Fig. 2.1, we use a lowercase t to indicate the temperature of a gas stream and an uppercase T to indicate the temperature of a liquid stream. Above the plume origin, the lowercase t is retained for the temperature of the moist plume and ambient air.