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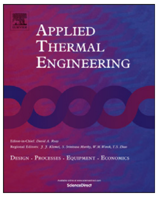

A numerical simulation on recirculation phenomena of the plume generated by obstacles around a row of cooling towers

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ABSTRACT

The present paper addresses the recirculation phenomena of the plume generated by obstacles around a row of cross-flow type forced draft cooling towers. In order to consider the interaction between external and internal flow of the cooling tower, both outside and inside of the cooling tower are involved in a computational domain. A three-dimensional in-house program based on a non-orthogonal, non-staggered and unstructured grid system is employed. The standard $k-\varepsilon$ turbulence model is used for the turbulent effect. In order to analyze flow and heat/mass transfers in the cooling tower, the continuity, momentum, moisture fraction and enthalpy equations have been considered for both air and water. The density and moisture fraction for air and water are obtained by using the function of thermal properties. The geometrical parameters investigated in this research are the height of obstacle, the distance between the inlet region of cooling tower and the obstacle wall, existence of the air-guide and effects of front and rear obstacles. The results show that the mean moisture fractions in the cases with air-guide are, in general, lower than the cases without air-guide under the same conditions. Also, in the cases without air-guide, the mean moisture fraction increases as the obstacle height increases. In addition, it is observed that for the cases without the air-guide with the increase in the distance between the tower and obstacle, the mean moisture fraction is decreased. However, the cases with air-guide do not follow a specific pattern in the same situations.

1. Introduction

Cooling towers have been widely used as the most economic and effective method to remove the heat with the minimum energy consumption. The earliest theoretical research on the performance of the cooling tower has been conducted in the 1970s. For example, Kelly [1] carried out a study on a performance curve using a graphical method such as blue book. Since 1980, the researchers have become interested in the environmental issues such as noise, water and air pollution and plume. Buss [2] conducted a study to prevent the plume using a theoretical method, and Campbell [3] predicted the conditions to prevent the plume using a graphical method. To calculate the occurrence and the behavior of plume, Hanna [4] numerically studied this issue. Michioka et al. [5] developed a model for a wind tunnel experiment to predict a visible plume region. Wang et al. [6] investigated the application of the solar collector heating system to control the visible plume of a huge commercial building. Xu et al. [7] performed a study for the evaluation of the plume potential and its effect on the sizing of the plume abatement systems in Hong Kong.

In recent years, with the limitations in the installation space for the cooling towers and also the increasing demands for clean and environmentally-friendly urban designs, the cooling tower location has become an interactive issue between mechanical engineers, civil engineers and architectures. The phenomena such as low pressure and vortex flow generated around the cooling tower often occur in real cases, which are affected by ambient conditions, the cooling tower shape and the obstacles around the tower.

The recirculation phenomenon in a cooling tower occurs when the exit flow re-enters the tower inlet (re-inflow). Typically, the recirculating air is about 34 °C and is approximately in the saturated state. Therefore, it causes a tremendous amount of energy loss during heat transfer. The rate of the recirculating flow depends on the ratio of the velocity of the main flow to the cooling tower

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Nomenclature

a	Area of contact surface of water and air unit volume
a_{nb}^{u}	Influence coefficient of discretized momentum equation
f	Moisture fraction
h	Enthalpy
$\dot{m}$	Mass transfer rate
$\boldsymbol{u}$	Cartesian velocity components
A	Area of the control cell face normal to velocity component
C_μ, C_1, C_2	constants of the standard k–ε turbulence model
$\boldsymbol{F}$	External force
k	Turbulent kinetic energy
K	Mass transfer coefficient
N	Number of velocity heads loss per unit air travel distance in the fill.
p	Pressure
P_k	Production of turbulent kinetic energy
R	Universal gas constant
S	Source term
s_P^u	Source term of discretized momentum equation
$\boldsymbol{T}$	Viscous stress and Reynolds stress of turbulent flow
V	Control volume
W	Molecular weight

Greek symbols

Δp^*	Pressure difference applied to fan region
ε	Dissipation rate of turbulent kinetic energy
φ	Scalar property
Γ	Diffusion coefficients of property
κ	Turbulent kinetic energy
μ	Molecular viscosity coefficient
μ_{eff}	Isotropic effective viscous coefficient
μ_t	Turbulent viscosity coefficient
ρ	Density

Subscripts

amb	Ambient state
g	Gravity
G	Moisture air
s	Saturation state
w	Water

exit flow, the geometry of cooling tower and the shape and position of obstacles around the tower.

To obtain enough design data, numerical simulations have advantages over experiments, which are very costly and time consuming. Bergstrom et al. [8] performed simulations for the external flow of cooling tower using a two-dimensional numerical program. However, because the flow distribution is three-dimensional, two-dimensional simulations cannot demonstrate the real flow stream. Takata et al. [9] and Ge et al. [10] predicted the behavior of plume for the interaction between the cooling tower exit flow and the external flow using a three-dimensional model. Nevertheless, the flow analysis inside the tower was not performed. Generally, there is no recirculation around a single cooling tower. Therefore, recirculation analysis requires a series (row) of towers to be simulated. Lee et al. [11] investigate the recirculation simulation of plume with external region and interior region of cooling tower in order to compare two-dimensional with three-dimensional characteristics. In their study, the parametric study for the distance between the inlet region of cooling tower and obstacle was carried out in three-dimensional analysis.

Following the above investigation and to address the three-dimensional recirculation and the internal flow in the cooling tower, the present paper studies the plume generated by obstacles around a row of cooling towers. Fig. 1 presents a general view of the geometry and the domain of the present paper. Three-dimensional in-house program based on a non-orthogonal, non-staggered and unstructured grid system is employed. For the turbulent flow consideration, the standard k–ε turbulence model is used. The density and the moisture fraction for air and water are obtained by using the function of thermal properties. The obstacle height, the distance between the cooling tower and the obstacle, the effects of the air-guide and the influence of rear and front obstacles are studied.

2. Theoretical model

The interaction between the air and water in the interior region of cooling tower is considered by defining two sets of equations for water and air domains. In order to simplify the governing equations, the following assumptions are assumed:

2.1. Assumptions

The assumptions for governing equations are as follows:

a. Heat and mass transfer occur in the air–water interface;
b. Air is saturated in the air–water interface;
c. There is no resistance in mass transfer process;
d. Temperature gradient is zero at the air–water interface;
e. Heat and mass diffusion coefficients are the same for air–water system;
f. Only parallel direction to the flow is considered for heat and mass transfer of water.

2.2. Governing equations

2.2.1. Air

The mass conservation equation is defined as:

$$\nabla\cdot(\rho\boldsymbol{u}) = 0 \tag{1}$$

where ρ and $\boldsymbol{u}$ represent the density and velocity vectors of air, respectively.

Also, the momentum conservation equation reads as:

$$\nabla\cdot(\rho\boldsymbol{u}\boldsymbol{u} - \boldsymbol{T}) = -\boldsymbol{F} - (\rho - \rho_{amb})\boldsymbol{g} \tag{2}$$

Here, $\boldsymbol{F}$, ρ_{amb} and $\boldsymbol{g}$ denote the external forces on air, the density at ambient temperature and gravity acceleration, respectively. Moreover in the Eq. (2), $\boldsymbol{T}$ is the effect of the normal stress, viscous stress and the Reynolds stress of turbulent flow.

$$\boldsymbol{T} = -p\boldsymbol{I} + \mu_{eff}\left[\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T\right] \tag{3}$$

In the Eq. (3), μ_{eff} represents the isotropic effective viscous coefficient and is defined as the combination of molecular viscosity coefficient (μ) and turbulent viscosity coefficient (μ_t). The turbulent viscous coefficient [12] is presented in Eq. (4) and is defined as the product of the time scale ($k^{3/2}/\varepsilon$) and the velocity scale ($\sqrt{k}$).

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