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Cross scale simulation on transport phenomena of direct air-cooling system of power generating units based on reduced order modeling

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ABSTRACT

Air-cooling system in power plant is of typical multi-scale system, of which the characteristic length covers from millimeter to hundreds of meters. In order to predict the thermo-flow performance of 2×300 MW air-cooled power generating units, a cross scale modeling methodology was proposed in the present study. Two neighbor characteristic lengths were considered, including that of the air cooling island region containing air-cooled condensers (ACCs) with 10^1 m length scale, and the large-scale one consisted of power plant buildings and the geomorphology with 10^2 m length scale. The small-scale region was described by reduced order model based proper orthogonal decomposition (POD), and the large-scale one by Navier–Stokes equations. The interfaces between the two regions were coupled by the measure that the lumped parameters on the interfaces obtained from information in small-scale region were transferred to the large-scale region as boundary condition. The air side flow velocity, turbulent kinetic energy, turbulent dissipation rate and temperature of air cooling island were solved by POD method under various natural winds. The results indicated that the errors of the thermo-flow characteristics were less than 7.75% relative to that of the multi-gird CFD results for the overall calculating region, implying that the parameters could be well coupled in the overlap regions between small and large scales by the present approach. The inverse flow phenomena of the air cooling island caused by environmental natural wind, as well as the heat transfer deterioration of downwind ACC cells were revealed. The calculating time and resources were significantly saved through the present cross scale modeling methodology with acceptable accuracy.

1. Introduction

In the past decades, direct air-cooled condensers (ACCs) of power generating units gained considerable development in the arid areas due to its significant water-saving advantage. The thermo-flow of direct air-cooling system in power plant possesses typical multi-scale characteristics. As shown in Fig. 1, the air side heat transfer in ACCs generates between the wavy fins, which takes off the condensing latent heat of the exhaust steam from turbine [1]. The heat transfer essentially occurs among the cascade breaking process of numerous vortexes with different scales. While the air flow between fins is restricted to finned tube bundle configuration, such as the relative location of fins on the elliptical tube, and the Λ-frame air-cooled condenser [2]. Moreover, the thermo-flow characteristics of air cooling island are strongly restricted to the buildings of power plant [3,4], as well as the topography and the geomorphology in 10^3 m length scale, especially under the conditions with the ambient natural winds [5]. During design and operation of air-cooling power generating units, computational fluid dynamics/numerical heat transfer (CFD/NHT) and in-field experiments [1–7] are always adopted to investigate the flow and heat transfer characteristics of air-cooling system. However, several scale effects are often neglected by the general approaches due to gigantic calculating time and resource finiteness consumed, which leads to the loss of detail information of transport phenomena.

The multi-scale problems widely exist in various fields of natural science, including that of environmental science, biological science, material science, crustal movement, and as well as flow and heat transfer. One of the typical solving approaches for thermo-flow multi-scale problem is establishing different physical models on two different scale computational domains, and then coupling the two calculating solution systems on the interface [8–12]. The problems with different physical mechanisms on different scale regions can be attributed to multi-scale processes [13]. In addition, there is the other multi-scale problem that has the same physical mechanism on different order of characteristic

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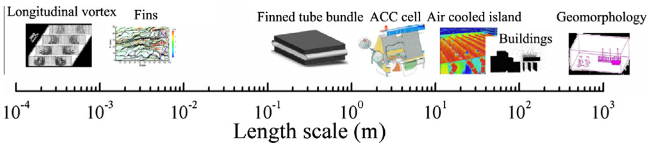

Fig. 1. Multi-scale thermo-flow of direct air-cooling system in air-cooling power plant.

length. The present air-cooling system can be classed to such multi-scale system. The solving methodology for cooling process in data center, which is one typical multi-scale system problem, has been greatly developed. A multi-grid embedded multi-scale measure, of which global model was established using coarse grids, and then gradually refined to the concerned region, is applied to analyze the thermal and flow characteristics of printed wring boards, chip packages and heat sinks packaged in one box [14]. Rambo et al. [15] proposed a new multi-scale procedure based proper orthogonal decomposition (POD) method to predict the temperature and flow fields for thermoelectrically cooled electronic cabinets in data center. In this method, individual reduced order models for velocity and temperature field based POD were built for plenum and server component. And then the POD solution of downstream module was solved by the flux matching procedure (FMP) on the interface between the two modules having obtained the POD solution of upstream module. The multi-scale method has been improved and obtained successfully application for the multi-scale convective heat transfer in data center [16,17].

For the present multi-scale system regarding the flow and heat transfer in the air-cooling island of power generating units, the thought of hybrid measure used for multi-scale process problem, which is modeling separately on the two divided sub-domains, and coupling the information on the interfaces between them, is referred. The cross scale simulation on air-side flow and heat transfer of direct air-cooling system in power plant is developed, in which, a POD solution is obtained in air-cooling island containing 2×30 small-scale air-cooled condensers (ACCs) for two neighbor 300 MW power generating units. Then the parameter information of POD solutions are extracted on the interfaces between ACCs and large-scale power plant buildings under the environmental conditions. Such parameter information are given to the large-scale region as boundary conditions, under which, the air flow fields, as well as corresponding temperature distributions of large-scale region of power plant can be solved by CFD simulation with both influences of transport characteristics of small-scale ACCs and environmental conditions.

2. Cross scale modeling methodology

The physical model of air-cooling power generating units is illustrated in Fig. 2. Apparently the thermo-flow in small-scale ACCs is strongly influenced by the larger-scale buildings of power plant, as chimney, boiler and turbine house, especially at the case of environmental natural wind blowing behind the boiler. The present cross scale simulation combined both the POD procedure and CFD based on Navier–Stokes equations.

The multi-scale air cooling system was divided into two sections, as the air cooling island in characteristic length of air-cooled condensers shown in Fig. 3(a), and also the remaining part in large scale involving the buildings of power plant, the calculating domain of which was shown in Fig. 3(b). The overlap sections between these two parts simultaneously belonged to both of them. The air flow fields and the corresponding temperature distributions in small and large-scale domains were respectively obtained by POD reduced order modeling and CFD simulations.

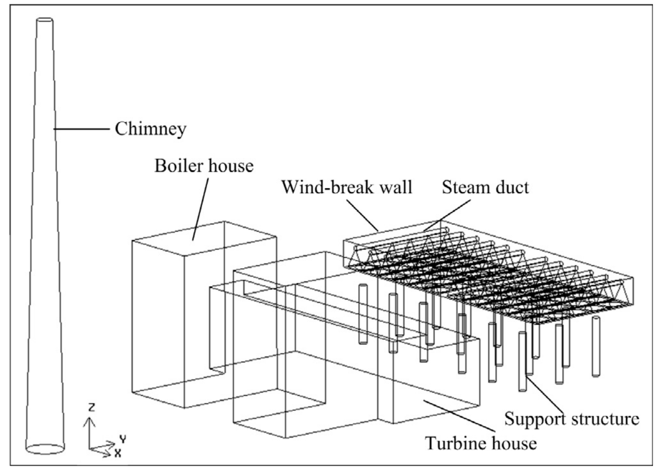

Fig. 2. Physical model of 2×300 MW air-cooling power generating units.

2.1. Physico-mathematical model for CFD simulations

The mathematical model was firstly established for the overall computational domain of the objective power plant to investigate the air-side flow and heat transfer performance under environmental natural wind conditions. The government equations with boundary conditions of the whole calculating domain shown in Fig. 3(b) were as following.

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \tag{2}$$

of which,

$$-\rho\overline{u_i' u_j'} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(\rho k + \mu_t\frac{\partial u_i}{\partial x_i}\right)\delta_{ij} \tag{3}$$

$$\rho c_p\left(u_i\frac{\partial T}{\partial x_i} + u_j\frac{\partial T}{\partial x_j}\right) = \frac{\partial}{\partial x_i}\left(\lambda_{eff}\frac{\partial T}{\partial x_i}\right) + \frac{\partial}{\partial x_j}\left(\lambda_{eff}\frac{\partial T}{\partial x_j}\right) \tag{4}$$

where ρ is air density, u_i is the velocity component of the x, y or z direction, p represents pressure and T is the air flow temperature. μ and μ_t respectively represent the dynamic viscosity and turbulent viscosity. The effective thermal conductivity, λ_{eff}, can be represented as,

$$\lambda_{eff} = \lambda + \frac{c_p \mu_t}{\mathrm{Pr}_t} \tag{5}$$

where λ is the thermal conductivity, and the constant values of turbulent Prandtl number, Pr_t, and specific heat at constant pressure, c_p, are respectively set with 0.85 and 1006.43.

In k–ε two equations viscous model, μ_t can represent as $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$, and the equations about the variables, turbulent kinetic energy, k, and turbulent dissipation rate, ε, are as following,

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon \tag{6}$$

$$\frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{7}$$

where the following model constants are set with the default values, $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_\mu = 0.09$, $\sigma_k = 1.0$, and $\sigma_\varepsilon = 1.3$.