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Reduced order analysis of flow and heat transfer for air-cooled condenser of power generating unit

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HIGHLIGHTS

► POD method was employed to reconstruct flow and temperature fields of air-cooled condenser.
► Cubic spline interpolation and flux matching procedure to obtain the weight coefficients were compared.
► The 10^5 DOF in CFD was reduced to 10^1 DOF by POD method.

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ABSTRACT

The flow and heat transfer exhibit complex non-linear characteristics for the air-cooled condenser (ACC) of power generating unit because numerous factors, including the meteorological and the geographic conditions, as well as the configurations of wavy finned tube bundles, can affect its performances. In order to quickly and accurately predict the air side velocity and temperature fields of ACC, the reduced order models (ROMs) based proper orthogonal decomposition (POD) method were established, by which the previous 10^5 DOF in CFD model was reduced to 10^1 DOF for new case prediction .The weight coefficients for POD modes were obtained by cubic spline interpolation and flux matching procedure (FMP). The air flow fields and correlating temperature fields influenced by environmental natural winds were revealed. It is found that accuracies of the POD solution with cubic spline interpolation are better than that of FMP. However, the FMP procedure, which can extract flow and thermal information from fewer observations, has better robustness than interpolation method. Hence, it is more appropriate for the POD solution of extrapolated cases. The present research may provide a rapid and reliable approach for the optimization of real-time operation of air-cooled power generating units.

1. Introduction

Air-cooled condensers (ACCs) with obvious water conservation benefit can be an important alternative for power plant near coal mines where water source is of shortage. In direct air-cooling system of a power generating unit, the ambient air replaces water as the cooling medium. Multiscale factors, including the meteorological and the geographic conditions, as well as the configurations of finned tube bundles, can affect the thermal performance of the air-cooled condensers directly. Both experimental and numerical researches require numerous cases to describe the correct velocity and temperature distributions and reveal the influences of corresponding factors. Besides, in order to obtain the overall characteristics, the computational or experimental domain for total power generating unit with environmental factors can be as large as hundreds of meters for each case, which covers several scales. The experiments or CFD simulations can consume huge amounts of resources.

Proper orthogonal decomposition (POD) technique is a low-dimensional, high-efficient mathematical tool that completely based on existing data rather than the physical mechanism. The main idea of POD method is that compressing a series of experimental or numerical data into a limited set of POD modes. The new solution in specific case can be obtained by expansion theorem having calculated the weight coefficient of each POD mode. Holmes et al. [1] described and analyzed the foundational theories of POD and Galerkin projection in detail. Ma et al. [2,3] constructed low-

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Nomenclature

a	weight coefficients of pod modes
C	correlation matrix
c_p	specific heat at constant pressure (J kg^{-1} K^{-1})
E	contributing energy of pod modes
F	flux function
G	goal value
h	convective heat coefficient (W m^{-2} K^{-1})
I	turbulent intensity
k	turbulent kinetic energy (m^2 s^{-2})
l	turbulence integral scale
N	observation number
p	pressure (Pa)
Pr	Prandtl number
q	heat flux (W m^{-2})
R	observation space
T	Temperature (K)
u	air flow velocity (m s^{-1})
w	normal component of velocity (m s^{-1})
x,y	Cartesian coordinates

Greek symbols

α	local ground roughness exponent
Γ	boundary domain
δ	mean error
ε	turbulent kinetic energy dissipation rate (m^2 s^{-3})
θ	variable fields
κ	observations
λ	eigenvalue
μ	dynamic viscosity (kg m^{-1} s^{-1})
ν	air thermal conductivity (W m^{-1} K^{-1})
ξ	dimensionless pressure loss coefficient
ρ	air density (kg m^{-3})
σ	turbulent Prandtl number
Φ	pod mode space
φ	POD modes
Ω	computational domain

Subscripts

C	CFD
c	any case
eff	effective
P	POD
T	temperature
t	turbulent
u	velocity

dimensional models for flow past a circular cylinder using POD method, calculated the weight coefficients via Galerkin projection, and realized the predictions of velocity and temperature fields based on the snapshots obtained from direct numerical simulation (DNS) [2] and experimental data by PIV samples [3], respectively. Rowley et al. [4] studied the dynamics over a few periods of oscillation in the flow past an open cavity using POD method and Galerkin projection. Ravindran [5] investigated the reduced-order controller for flow separation over a forward-facing step based on POD method and Galerkin projection. Gurka et al. [6] analyzed spatial characterization of coherent structures based on POD modes of vortices. Park and Lee [7] investigated the natural convection in cavity. From 2003, Joshi et al. [8–13] have applied POD method in the analysis of data center cooling system with typical multi-scale characteristics. They proposed flux matching procedure (FMP) to calculate weight coefficients. Ding et al. [14] applied POD method to analyze the flow and heat transfer in three typical cases, which were natural convection in a cavity, lid-driven cavity flow and heat conduction problem with a time-dependent heat source by adopting cubic spline interpolation method for steady problems and Galerkin projection method for transient problems. Other applications of POD method include that of the fluid flow with moving boundaries by cavitating, phase change and fluid–membrane interaction [15], pitching and plunging airfoil flow in [16], and flow between a backward facing ramp and an adjustable flap [17]. In addition, POD method has been widely used in numerous other areas, such as the atmospheric flows, the velocity and concentration fields of contaminant between urban buildings [18,19].

In the present paper, the POD method is introduced to establish the reduced order model to investigate the air flow velocity and temperature fields of air-cooled condenser in power generating unit influenced by environmental natural winds. For the velocity and temperature characteristics of ACC are the basis for the air-cooling system, the present investigation may provide an accurate and rapid approach of real-time operating optimization of power generating unit.

2. Physical and mathematical model

2.1. Physical model

The physical model in the present study is an air-cooled condenser cell in the cooling system of a 2 × 330 MW power plant. As shown in Fig. 1(a), the typical structure of air-cooled condenser of power generating unit is Λ-frame configuration, which consists of steam duct, two inclined arranged finned tube bundles, and an axial flow fan. And the included angle between the two finned bundles is set as 60°. The exhaust steam out of turbine condenses inside the wavy finned tube bundles, and the latent heat is carried off by the air flow between the fins generated by the axial fan. In order to reveal the influences of the ambient natural wind on the air flow and temperature field in the trigonal region of the air-cooled condenser, the ACC cell is simplified to a two-dimension model as shown in Fig. 1(b).

The observations of the air velocity and temperature fields for ACC under different natural winds used in reduced order models (ROMs) are generated by CFD simulations. The selected ACC surrounded by the wind-break wall of 13 m in height is set on a platform with the height of 45 m. According to research results of Oliverlia and Younis [20], the size of upstream inflow length (L_1) and the total computational domain height (Y) are respectively not less than 15 and 10 times of structure in order to ensure the calculating solution are independent on computational domain size. As to this model, total height (Y) of computational domain equals to 138 m, and inflow length (L_1) and outflow length (L_2) are respectively equal to 200 m and 260 m. For this consideration, the computational domain is set to be 472 m × 138 m ($X \times Y$), which is shown in Fig. 1(c).

2.2. Governing equations with boundary conditions

2.2.1. Governing equations

Assuming the air flow is the incompressible fluid. The momentum equation based on Reynolds-Averaged Navier Stokes is solved adopted standard k–ε two equations model. The governing