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Numerical study of wind effects on combined convective heat loss from an upward-facing cylindrical cavity

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Abstract

Cavity receivers play a key role in the utilization of solar energy, and the convective heat losses in them can directly affect their efficiency. Yet the effect of wind on convective heat losses has not been investigated extensively. In this paper, taking an isothermal upward-facing cylindrical cavity as object, the combined convective heat loss under windy condition was studied by three-dimensional numerical model. The influences of surface temperature, cavity tilt angle, wind incident angle and wind speed were analyzed. The results were compared with those in no-windy condition. To facilitate engineering applications, empirical correlations for predicting combined convective heat loss were developed. Results show that the combined convective heat loss increases with increasing surface temperature. With the disturbance of wind, the effect of cavity tilt angle becomes complicated and is related to wind condition. For almost all of cases, as wind speed increases from zero, the combined convective heat loss is initially dropped and then increased, i.e., a minimum is observed. And the minimum is even below that in no-windy condition. The wind incident angle for maximizing combined convective heat loss is not fixed and can be affected by cavity tilt angle and wind speed.

Keywords: Upward-facing cylindrical cavity; Combined convective heat loss; Wind effect; Numerical study; Empirical correlation

1. Introduction

The available solar energy received on the surface of earth is about 3.6×10^4 TW and is more than 3000 times the world power consumption in 2012 (Hosenuzzaman et al., 2015). Hence, the energy crisis and environmental pollution caused by fossil fuels can be partly alleviated by the utilization of solar energy. Solar to thermal conversion, as one of the solar energy technologies, has received ever-increasing attention because it can provide broad ranges of temperature to satisfy various applications, such as domestic hot water, solar power plants and solar thermoelectric generations. Considering that the cavity-type receivers can absorb the solar radiation effectively and has a lower radiative heat loss than external-type receivers (Ho and Iverson, 2014; Larrouturou et al., 2014), cavity-type receivers are preferred for solar medium and high temperature applications. To improve the thermal efficiency of cavity and promote the commercialization of above applications, the mechanisms of heat losses including conductive, radiative and convective in cavity must be fully clarified. Among them, the conductive and radiative heat losses can be determined analytically, but the

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Nomenclature

A	total inner surface area of cavity, m^2
C_1, C_2, $C_{1\varepsilon}$, $C_{2\varepsilon}$ and C_μ	coefficients in the turbulent model
c_p	specific heat capacity of air at constant pressure, J/(kg K)
d	cavity inner diameter, m
g	gravitational acceleration, m/s^2
Gr	Grashof number based on constant temperature condition, $g\alpha_V(T_w - T_\infty)d^3/v^2$
G_b	generation of turbulent kinetic energy due buoyancy, $kg/(m\ s^3)$
G_κ	generation of turbulent kinetic energy due mean velocity gradients, $kg/(m\ s^3)$
H	cavity inner height, m
k	thermal conductivity of air, W/(m K)
Nu_c	combined convective heat loss Nusselt number
p	pressure, Pa
p_t	pressure induced by the fluctuating velocity, Pa
Q_c	combined convective heat loss, W
Ra	Rayleigh number based on constant temperature condition
Re	Reynolds number, Vd/v
Ri	Richardson number, Gr/Re^2
S	average strain rate, s^{-1}
T_w	surface temperature, K
T_∞	ambient temperature, K
T_f	film temperature, K
V	wind speed, m/s
x, y and z	Cartesian coordinates, m
y^+	dimensionless wall distance
Y_M	contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, $kg/(m\ s^3)$
Greek symbols	
φ	cavity tilt angle, °
α	wind incident angle, °
α_V	thermal expansion coefficient of air, K^{-1}
δ_{ij}	Kronecker delta function
v	kinematic viscosity of air, m^2/s
ρ	density of air, kg/m^3
κ	turbulence kinetic energy, m^2/s^2
ε	turbulence dissipation rate, m^2/s^3
μ	dynamic viscosity, kg/(m s)
μ_t	turbulent eddy viscosity, kg/(m s)
σ_T	turbulent Prandtl number for T
σ_κ	turbulent Prandtl number for κ
σ_ε	turbulent Prandtl number for ε

determination of convective heat loss is a tough task because of the complexity of geometry and the complex temperature and flow fields in and around the cavity (Clausing et al., 1987; Taumoefolau et al., 2004). Much effort has been poured into to investigate the convective heat loss from various cavities, and the relevant studies were reviewed by Wu et al. (2010). As reported by this review, the majority of researches were focused on no-windy condition, in other words, the knowledge about the combined convective heat loss under windy environment was limited. This did not match the actual situation, where the wind occurred inevitably.

A summary about the combined convective heat loss from cavities under windy condition is shown in Table 1, where the cavity geometries, adopted methods, boundary conditions and affecting factors in each study are shown. For clarity and simplicity, the definitions of cavity tilt angle φ and wind incident angle α are provided in Figs. 1 and 2 respectively. As shown in Fig. 1, φ is defined as the angle between the normal of cavity aperture plane and the horizontal XOZ plane. When cavity rotates from vertical upward-facing position to vertical downward-facing position, φ changes from −90° to 90° (Shen et al., 2015). Wind is parallel to horizontal XOZ plane, and the wind incident angle α is the angle between X-axis and wind blowing direction. α is viewed as −90° in back-on wind direction, 0° in side-on wind direction and 90° in head-on wind direction (Reddy et al., 2015; Wu et al., 2015).

From the literature review presented in Table 1, one important feature is identified. For the effect of wind on combined convective heat loss from cavities, almost all of investigations are focused on the sideward or downward facing positions except Leibfried and Ortjohann (1995) and Pavlović and Penot (1991), where $\varphi = -45°$ and $\varphi \leqslant -45°$ were briefly experimented respectively. This feature implies that the study on combined convective heat loss from upward-facing cavities under windy condition is at an early stage.

Recently, due to the rapid development of second-stage concentrators and lens systems, especially Fresnel lenses, the application fields of upward-facing cavities are extended extensively. The fields include solar beam-down tower systems (Li et al., 2015; Mokhtar et al., 2014), solar thermoelectric generation systems (Suter et al., 2011) and testing the behaviors of materials (Morris et al., 2015). This urges us to know more about the convective heat loss mechanisms in upward-facing cavities.

To partly fill up the gap between the current research status and practical applications, in this paper, taking an upward-facing cylindrical cavity subjected to constant temperature condition as object, the combined convective heat loss under windy environment is numerically investigated. This paper is organized as follows. At first, by using both unsteady and steady state numerical models, the influences of wind speed, wind incident angle and cavity tilt angle at one surface temperature are simulated, and the deviations