The Effect of Wind on Combined Convective Loss from a Bicylindrical Cavity Receiver: An Experimental Study

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Abstract
The performance of the solar cavity receiver is considerably affected by wind specifications in the parabolic dish system. In this paper, an experimental study is performed to investigate the effect of wind speed, wind direction, and cavity inclination on the combined convective loss from a bicylindrical cavity receiver. The steady-state experiments are carried out in the range of 0.3 to 5.7 m/s wind speeds and three wind directions, including side-on, head-on, and back-on wind for downward-facing and horizontal cavity situations. The results show that the head-on wind causes higher combined convective loss comparing the other two wind directions for all wind speeds and cavity inclinations except 90° (vertically downward-facing) where all three wind directions essentially act the same. For the horizontal cavity receiver, the forced convective loss is less than the natural convective loss for all wind directions and speeds. Empirical correlation is also developed for combined Nusselt number as a function of Reynolds number, Grashof number, cavity inclination, wind direction, and the absolute temperature ratio for the downward-facing cavity. Comparing the proposed correlation combined Nusselt number with experimental results shows a maximum deviation of 20%.

Keywords: bicylindrical cavity receiver, combined convective loss, wind effects, Nusselt number.

Introduction
The solar cavity receiver used in the parabolic dish system absorbs concentrated solar radiation and transfers it to the heat transfer fluid. Hence, heat losses from the cavity receiver considerably influence the performance of a system. The combined convective loss under actual conditions depends on the cavity inclination, cavity wall temperature, wind speed, and wind direction. The convective loss due to the wind has been experimentally and numerically investigated over the last years. Ma [1] performed experiments to estimate the convective loss of a cylindrical cavity receiver under no-wind and windy conditions. It was found that for side-on wind, the highest convective loss occurs at the horizontal orientation of the cavity. Also, for wind speeds of 20-24 mph, the total convective loss reaches three times the maximum level of natural convection. Prakash et al. [2] experimentally and numerically determined convective loss from the cylindrical cavity with a wind skirt. They showed, contrary to Ma [1], that the head-on wind results in higher convective loss comparing the side-on wind. Also, the effect of the cavity inclination on the convective loss under side-on wind is less than compared to the no-wind and head-on wind conditions. They found that at 3 m/s

wind speed, the wind direction has no significant effect on the total and convective losses for all inclinations except 0° receiver inclination. Flesch et al. [3,4] investigated the impact of wind on the convective loss of a large scale cavity receiver used in the solar power towers. They showed that the impac of wind is mainly dependent on the receiver inclination. For the horizontal receiver, the wind has a small impact on losses, whereas by increasing the inclination, the cavity is more sensitive to wind. Lee et al. [5] conducted experiments to study convective loss from a cylindrical cavity subjected to uniform wall temperature. They found that at wind speeds up to 12 m/s, the convective loss for the head-on wind is four times greater than the side-on wind case. In another study, they investigated the interaction between aspect ratio, wind direction and speed, and their effects on the convective loss [6]. Their results show that the minimum of mixed convective loss occurs at a 30° cavity inclination for the various wind speeds. Moreover, they claimed that the influence of the tilt angle on the heat losses is less than compared with wind speed and aperture ratio [7]. Shen et al. [8] numerically studied the combined convective loss from an upward-facing cylindrical cavity. They showed that the wind direction has a complex effect on the combined convective loss and depends on the wind speed and cavity inclination.
The investigation of the literature shows that the shapes of the cavity receivers considered experimentally and numerically are rectangular, cubical, cylindrical, and spherical. There is no reported paper of experimental study for a bicylindrical cavity receiver under the windy conditions. This study addresses the experimental investigation of the influences of the wind speed and direction and cavity inclination on the combined convective loss from a bicylindrical cavity receiver subjected to constant heat flux.

Experimental

The model cavity receiver used to assess the heat losses is illustrated in Fig. 1. The bicylindrical cavity receiver consists of two cylindrical cavities of different diameters; a 0.09-m cavity joined to a 0.06-m one exposed to the aperture. Both cylindrical cavities have an aspect ratio (length to diameter) of 1. The receiver is made from aluminum alloy with a wall thickness of 4 mm. The bicylindrical cavity is heated by two silicon-pad heaters with a maximum heating flux of 3850 W/m^2. In order to reduce conductive loss from the cavity, a ceramic fiber blanket is used as insulation for the sidewalls of the larger and the smaller cylinders. At the base (unheated) of the cavity receiver, a 5-cm thick calcium silicate board is fixed between the two 25-mm layers of ceramic fiber. The cavity surface temperature is measured by fifteen thin-film platinum-resistance temperature sensors (JUMO GmbH & Co.). Furthermore, seven temperature sensors are used to record the insulation and ambient temperature. All equipment is placed in a cylindrical casing made from a black steel sheet. A wind tunnel with a size of approximately twice the height of the cavity is used to simulate windy conditions. The Digital vane anemometer is applied to measure wind speed. The experiments are performed for downward-facing and horizontal cavity receiver cases in the range of 0.3 to 5.7 m/s wind speeds and three wind directions including side-on (α = 0°), head-on (α = 90°) and back-on (α = − 90°) wind. In the side-on experiments, the wind blows in the direction parallel to aperture while at head-on tests, the direction is normal to the aperture plane. In the back-on direction, the wind is blowing over the backside of the cavity. The steady-state is reached when a change in temperature is less than 1°C per hour.

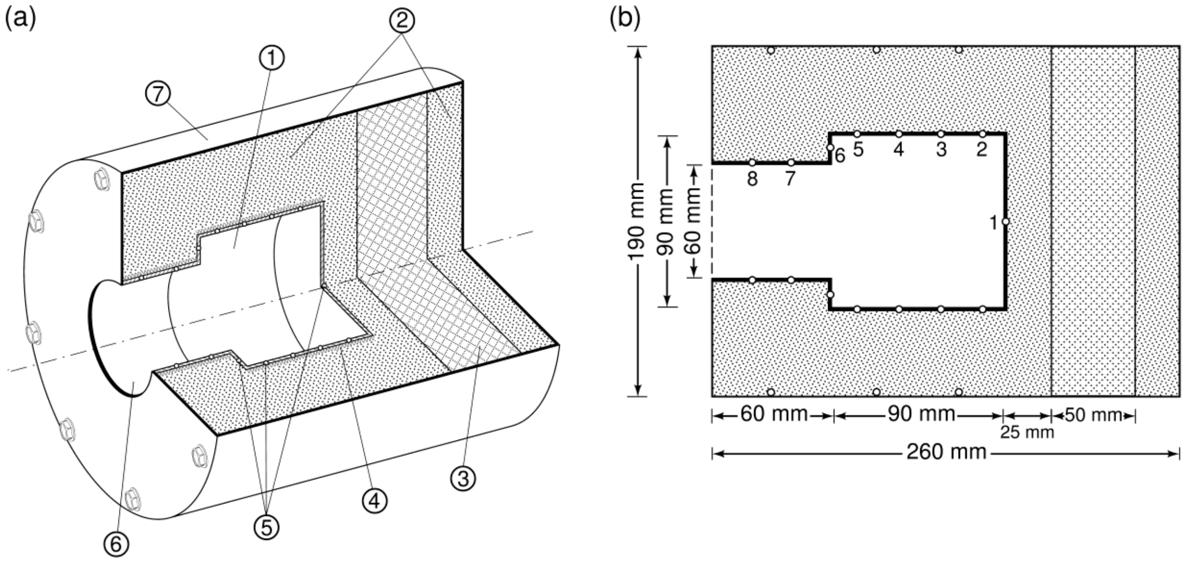

Fig. 1. The model cavity receiver. (a) Three-dimensional view: 1- bicylindrical cavity, 2- ceramic fiber insulation, 3- calcium silicate board, 4- silicone-pad heater, 5- temperature sensors, 6- aperture, 7- receiver casing; (b) cross-sectional view.

Energy Balance

The experimental arrangement provides a direct measurement of overall heat losses from the cavity. Since combined convective loss (q_{conv}) is of interest, conductive (qcond) and radiative (qrad) contributions need to be accounted for in the energy balance:

$$q_{\mathrm{conv}} = q_t - q_{\mathrm{cond}} - q_{\mathrm{rad}} \tag{1}$$

where q_t is the total electrical power input to the cavity.

Conductive Loss

The conductive loss through the insulation layer q_{cond} is obtained using Fourier's law. Conduction is assumed to be one dimensional through the cavity side walls.

Radiative Loss

Radiative loss is determined analytically by the network method [9], and gray surface and uniformly diffused radiation is assumed. Moreover, the surface of the cavity is divided into nine segments, and the temperature of each segment is recorded by two temperature sensors. The radiant energy balance for a segment is given by

$$J_i = \frac{1}{1 - F_{ii}(1-\varepsilon_i)}\left[(1-\varepsilon_i)\sum_{j \neq i} F_{ij} J_j + \varepsilon_i E_{bi}\right] \tag{2}$$

where J_i is the radiosity, F_{ij} is surface view factor, and E_{bi} is the black body emissive power. A set of 9 equations is solved simultaneously for the segments to calculate the radiosities. The net radiative loss for surface i is given by

$$q_i = \frac{\varepsilon_i A_i}{1-\varepsilon_i}\left(E_{bi} - J_i\right) \tag{3}$$

where A_i is the area of the surface. The radiative loss through the aperture is then obtained from the sum of individual radiative losses. As the combined convective loss is obtained, combined convective heat transfer coefficient, h_c, reads as

$$h_c = q_c / A(T_w - T_a) \quad (4)$$

where A is the cavity total inner surface area, T_w and T_a are the cavity surface average temperature and the ambient temperature, respectively. Then, the combined Nusselt number can be calculated from the convective heat transfer coefficient.

Results and discussion

The effects of wind speed and cavity inclination on the combined convective loss for different wind directions are presented in Figs. 2-4. As the figures show, the combined convective losses increase with increasing wind speed at all cavity inclinations and wind directions. For side-on wind, at lower wind speeds, the combined convective loss decreases with increasing inclination similar to that of the no-wind condition [10] while at the higher wind speeds above 4 m/s, regardless of the cavity inclination, the change in the combined convective loss is very small. For example, the decrease in the combined convective loss from 0° to 90° cavity inclination is 19% at 0.4 m/s wind speed, whereas this change is 4.7% at 5 m/s wind speed.

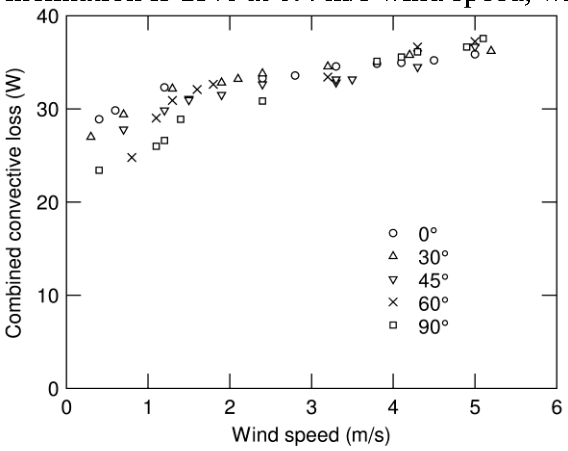

Fig. 2. Variation of the combined convective loss with the wind speed for side-on wind.

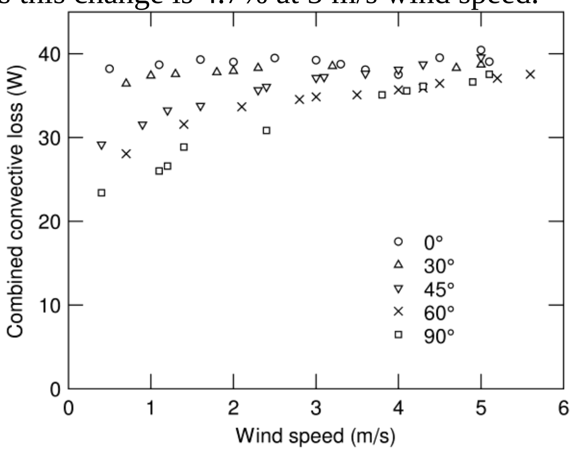

Fig. 3. Variation of the combined convective loss with the wind speed for head-on wind.

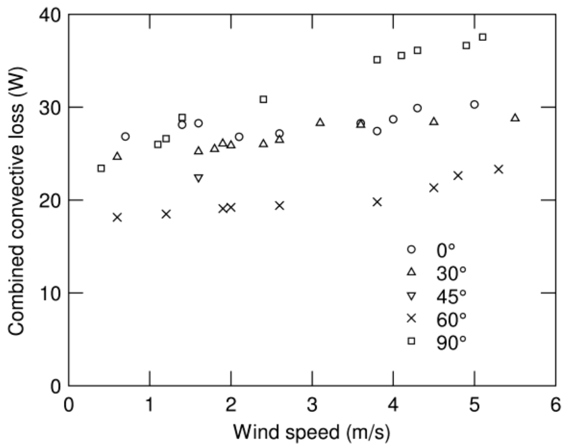

Fig. 4. Variation of the combined convective loss with the wind speed for back-on wind.

In other words, the wind can weaken the influence of the cavity inclination. At higher wind speeds, the forced flow due to the wind dominates, and the influence of receiver inclination on the combined convective loss is insignificant. For 4 m/s side-on wind, the convective loss is about 78% of total heat losses at all inclinations. In contrast, at the no-wind condition, the free convective loss has a maximum value of 58% of total heat losses at 0° and a minimum of 19% at 90° inclination [10]. For head-on wind, the combined convective loss appears to have no significant change with wind speeds at lower cavity inclination. In the horizontal cavity position, by increasing wind speed from 0.5 to 5 m/s, the combined convective loss changes only 5.8%. In this case, the head-on wind prevents the hot air from flowing out of the cavity. For back-on wind, the minimum combined convective loss occurs at 60° cavity inclination despite the other two wind directions and no-wind cases in which minimum convective loss occurs at 90°. The combined convective loss is higher for head-on wind conditions than the other two wind directions for all wind speeds and cavity inclinations except at 90° inclination that three wind directions are essentially the same. This is due to the fact that for downward and side-facing cavities, at the head-on wind, the forced flow due to the wind is in the same direction as the buoyancy flow leads to an increase of heat loss. In the back-on case, the wind suppresses the inlet airflow to the cavity, and thus, the temperature rises, which causes the combined convective loss to decrease. The figures also show that for the horizontal cavity, the convective loss due to wind is lower than the natural convective loss at all wind speeds and directions. In other words, wind reduces the losses below the value of the natural convective loss.

For the downward and side-facing cavities exposed to head-on wind, the forced flow due to wind and the buoyancy force have the same direction of down to up. Thus, the forced convective loss is calculated by subtracting natural convective loss from the combined convective loss. A correlation has been defined between the forced convective loss and the wind speed regardless of the cavity inclination. The correlation is expressed in the following equation with R^2 = 0.9269.

$$q_{\text{forced}} \quad 17.826u^{0.197} \tag{5}$$

where u is the head-on wind speed.
Using non-linear regression analysis, the combined Nusselt number, Nu_c, is estimated as a function of Re number (to consider the wind effect), Gr number (to consider the buoyancy force), cavity inclination (θ), wind direction (α), and the absolute temperature ratio (to consider the influences of variable property). For downward-facing situations, the correlation is proposed as

$$\frac{Nu_c}{Nu_n} \quad 1 \quad 77.80(1 \quad \cos\theta)^{\;1.71}(2 \quad \sin\alpha)^{0.05} \; \frac{Gr}{Re^2}^{\;0.017} \; \frac{T_w}{T_a}^{\;7.29} \tag{6}$$

where Nu_n is the natural Nusselt number that can be obtained from [10]. The proposed correlation shows 20% maximum deviation of the experimental data.

Conclusions

The combined convective loss from a downward and side-facing bicylindrical cavity receiver is conducted experimentally. For this purpose, an electrically heated bicylindrical cavity receiver, which consists of two coaxial cylindrical cavities with different diameters, is fabricated. The results show that the head-on wind causes higher combined convective loss than the other wind directions. An empirical correlation is developed for combined Nusselt number for downward-facing cavity receiver.

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