$w$  width of charge regions
$x$  distance in the horizontal direction (thermal analysis)
$X$ distance in the horizontal direction (electrostatic analysis)
$y$ distance in the vertical direction (thermal analysis)
$Y$ distance in the vertical direction (electrostatic analysis)
$\alpha$ slat angle of rotation
$\kappa$ thermal diffusivity
$\rho$ fluid mass density
$\theta$ non-dimensional temperature-$[(T - T_i)(T_i - T_0)]$
$\nu$ kinematic viscosity

References

Second, there is one voltage placed on all slats, and the entire glass surface in front of the slats is grounded. This means that for each slat (all values of \( j \) and \( k \)) the voltage term in Eq. (A.7) is expressed as

\[
V_{ijk} = \begin{cases} 
V, & i = 1, 2, \ldots, n_s, \quad j = 1, 2, 3, \ldots, n_k, \quad k = 1, 2, 3, \ldots, n_l, \\
0, & i = (n_s + 1)(n_s + 2), \ldots, (n_s + n_g), \quad j = 1, 2, 3, \ldots, n_k, \\
& k = 1, 2, 3, \ldots, n_l,
\end{cases}
\]

(A.15)

where \( V \) is the voltage applied to the slats and 0 represents ground. Finally, the entire blind system can be assumed to be infinite in the \( y-z \) plane, wherein the charge distributions over the slats and the glass are assumed to be periodic. This means that the charge distributions will be the same for every slat, or

\[
Q_{i,j,k} = Q_{i,2k} = \cdots = Q_{in,k}.
\]

(A.16)

In practice, \( Q_{ijk} \) is calculated using the smallest number of slats (smallest value of \( n_g \)) that will converge to a solution. For the analysis presented in the results section of this paper, using five slats provided for the convergence of \( Q_{ijk} \). Now, Eqs. (A.7) and (A.8) are used with the simplifications given in Eqs. (A.14)–(A.16) to determine the charge distributions on the slats and glass (\( Q_{ijk} \)).

We now use the charge distributions, \( Q_{ijk} \), calculated in Eq. (A.7) to develop the equations needed to determine the moment caused by the electrostatic forces on the blind slats. The electrostatic force vectors are calculated by applying Coulomb’s law for point charges. Applying Coulomb’s law to the blind system we get

\[
F_{(ijk)} = \sum_{(abc)} \frac{kQ_{(ijk)}Q_{(abc)}}{|r_{(abc)} - r_{(ijk)}|^3}(r_{(abc)} - r_{(ijk)}).
\]

(A.17)

The force vectors are then used to calculate the moment about the axis of rotation of each slat using

\[
(M_{\text{elect}})_j = \sum_{i=1}^{n_s} \sum_{k=1}^{n_l} [(r_{\text{axis}} - r_{(ijk)}) \times F_{(ijk)}],
\]

(A.18)

where \( r_{\text{axis}} \) is the position vector from the origin (set at the end of the axis of rotation of the bottom slat in Eq. (A.11)) to the end of the axis of rotation of the slat you are calculating the moment about (the \( j \)th slat).

The gravitational moment is the same for each of the slats. Because this analysis is concerned only with windows mounted in the vertical direction, the moment is calculated simply by multiplying the weight of the slat with the offset distance and the cosine of the slat angle, or

\[
(M_{\text{grav}})_j = (\text{weight}) \times (\text{offset distance}) \times (\cos \alpha).
\]

(A.19)

Eqs. (A.18) and (A.19) assume a known geometry, however, the slat angles \( \alpha \) are not known in advance. Indeed, the system is not in static equilibrium unless the resultant moment acting on the slats, due to electrostatic forces and gravitational forces, is zero. Therefore, slat angles are determined in an iterative procedure that calculates the resultant moment acting on the slats versus the slat angle.
in which

\[ V_e = V_{(e,0)}, \quad Q_f = n_f Q_{(f)}, \quad P_{ef} = \begin{cases} P_{(e,0)(f,0)}, & f \neq e \\ 1/n_e \sum_{h=1}^{n_e} P_{(e,0)(e,h)}, & f = e \end{cases} \]

(A.6)

in which \( V_e \) is the voltage in the \( e \)th region, and \( Q_f \) is the total charge in the \( f \)th region. Notice that Eqs. (A.5), (A.6) and (A.1) are the same except for the addition of the diagonal term \( P_{ee} \) which includes the average value of the inverse distance of a point in region \( e \) from the center of region \( e \).

Let us now apply Eqs. (A.5) and (A.6) to the three-dimensional powerblind. Toward this end, a triple location index \((i,j,k)\) is used. The first index \( i \) moves down the slat from 1 to \( n_s \), and up the glass from \( n_s + 1 \) to \( n_s + n_g \); \( j \) counts slats moving up the window from 1 to \( n_t \), and \( k \) counts across each slat from 1 to \( n_l \) (see Fig. A.2). Eqs. (A.5) and (A.6) are rewritten as

\[ V_{(i,j,k)} = \sum_{(abc)} P_{(i,j,k)(abc)} Q_{(abc)} \]

(A.7)

in which

\[ V_{(i,j,k)} = V_e, \quad P_{(i,j,k)(abc)} = P_{ef}, \quad Q_{(abc)} = Q_f. \]

(A.8)

We will now develop the position vectors required for determining values of \( P_{(i,j,k)(abc)} \) in two steps. First, the two-dimensional \( X \) and \( Y \) coordinates for the conductive regions on each slat and corresponding section of glass are determined by

\[ X_i = \left[ -d_1 + \left( i - 1/2 \right) \left( \frac{d_1 + d_2}{n_s} \right) \cos \alpha \right]\]

Slat

\[ Y_i = \left[ d_1 - \left( i - 1/2 \right) \left( \frac{d_1 + d_2}{n_s} \right) \sin \alpha \right], \quad i = 1, 2, 3, \ldots, n_s, \]
validates the infinite model reduction assumption. This data will be used to set the voltages for the desired slat angles. The analysis proves that a well constructed, convergent model, with appropriately chosen conductive regions, can be used to accurately predict charge distributions and the resulting electrostatic forces.

The convective heat transfer results show that the energy savings associated with the blinds will be found in their operation. A window with the blinds closed has a slightly lower convective heat transfer than a standard insulated glass window. Therefore, closing the blinds at night (either actively or passively) would make the blind a slightly better thermal insulator than a standard insulated glass window with respect to convection. During the day, opening the blinds when sunlight is available for daylighting reduces energy needed to provide artificial light and allows radiant heat transfer. With the blinds open, the window loses more energy to the outside through convection than standard insulated glass windows. However, if conditions are right for daylighting, the energy gained through solar radiation will far outweigh the energy lost through convection.

There are many possibilities for future modifications to the electrostatic blind model. The finite element software used in the thermal analysis (Ansys) can be extended to include the electrostatic charges. One model that could perform the thermal and electrostatic analyses simultaneously would be able to account for the coupling effects, however small, of the thermal and electromechanical analyses. The models could also be adapted to include the glass in both the analyses. Finally, the analyses could be adapted to include radiative heat transfer.

Appendix A. Electrostatic theory development

The electrostatic analysis begins with the general electrostatic relationship between the voltages and the charges of a discrete system of conductive particles [7], given by

\[ V_i = \sum_{j \neq i}^{n} P_{ij} Q_j, \quad P_{ij} = \frac{k}{r_{ij}}, \tag{A.1} \]

where \( V_i \) is the voltage of the \( i \)th particle, \( Q_j \) is the charge of the \( j \)th particle, where \( P_{ij} \) is a geometric parameter called the coefficient of potential, where \( r_{ij} \) is the distance between the \( i \)th and \( j \)th particles, and where \( k = 1/(4\pi\varepsilon_0) \) is the electrical constant in which \( \varepsilon_0 \) is the permittivity of free space.

In relation to the powerblinds, the charged particles in Eq. (A.1) represent surface charges applied to the slats and induced on the glass. The charges are partitioned into approximately square, small conductive regions, as shown in Fig. A.1. The regions are necessary so that the system, which contains an infinite number of particles, can be discretized to obtain a numerical solution. Consequently, the single counting index \( i \) used in Eq. (A.1) is replaced with the double counting index \((e, g)\), in which the first index counts the regions and the second index counts the particles in the region.
Fig. 8. Temperature distribution and velocity profile of windows with 78° slats.

Fig. 9. Temperature distribution and velocity profile of windows with 7° slats.