3 kV the electrostatic forces are weak and the slat angles vary from slat to slat in the experimental model.

4.2. Thermal analysis

The predicted temperature distributions and velocity profiles for three case studies are found in Figs. 7–9. Notice, as the blinds become open (7° slats — Fig. 9) the velocity increases in the horizontal direction (across the air space). It can be seen from the temperature distributions that this fluid flow increases the rate of temperature change, thus increasing the convective heat transfer. When the blinds are in the closed position (78° slats — Fig. 8), the temperature distribution and velocity profile are similar to that of a window without slats (no slats — Fig. 7), so the convective heat transfer values in the two windows are approximately equal. However, the closed blinds do contain a thin region in the center where the air does not move as well. This air pocket is responsible for a very small decrease in the convective heat transfer.

The values of heat flux for a 1 m² window were also calculated using the Ansys code. The results are given in Table 2. The bottom row of the table compares the convective heat transfer of a window with slats at four different angles to one without slats. Notice the heat transfer increases as the slats approach the horizontal position, just as was predicted by the velocity profiles discussed above. This result also agrees with analytical predictions done by Batchelor [8].

![Image](image_url)

Fig. 7. Temperature distribution and velocity profile of windows without slats.
Table 2
Convective heat flux for a window with a 20 K temperature difference

<table>
<thead>
<tr>
<th>Angle from Horizontal (α)</th>
<th>No slats</th>
<th>78°</th>
<th>45°</th>
<th>26.5°</th>
<th>6.9°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat flux (q)</td>
<td>26.6 W/m²</td>
<td>26.2 W/m²</td>
<td>29.1 W/m²</td>
<td>35.9 W/m²</td>
<td>40.0 W/m²</td>
</tr>
<tr>
<td>q/\dot{q}_{nat}</td>
<td>-1.5%</td>
<td>9.5%</td>
<td>34.9%</td>
<td>50.3%</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 10. Convective heat flux at different slat angles.

Fig. 10 is a plot showing the convective heat flux values. Notice that the increase in heat flux is most dramatic at angles less than 20° from the horizontal. At angles greater than 60° the slats do not have much of an effect on the convective heat flux. This figure reveals that, when the slats are open, the convective heat transfer is noticeably greater than for a window without blinds. When the blinds are closed the convective heat transfers are nearly identical but slightly lower if the blinds are completely closed.

5. Conclusions

Electromechanical analysis demonstrates how well the electrostatic governing equations can be applied to a physical system and quantifies the voltage necessary to achieve desired blind slat angles. The window model accurately predicts, to the accuracy of the experimental measurement, the position of the slats at five different applied voltages. The agreement between the predictions and the measurements also
Eq. (A.1) implies that the voltage of the $e$th region is given by

$$V_{(e,0)} = \sum_{f=1}^{n} \sum_{h=1}^{n_e} P_{(e,0)(f,h)} Q_{(f,h)} + \sum_{h=1}^{n_e} P_{(e,0)(e,h)} Q_{(e,h)}, \quad (A.2)$$

where the first term is the voltage at particle $g$, in region $e$, arising from charge in regions other than region $e$, and the second term is the voltage arising from charge within region $e$ itself (apart from the charge on particle $g$).

Because each of the charges within a given region are equal in magnitude, they have equal repulsion forces and are assumed to be uniformly distributed. Consequently, in this case we let $Q_{(e,0)} = Q_{(e)}$ where $Q_{(e)}$ is the charge corresponding to any element in region $e$, and the region has been divided up uniformly into a certain number of elements $n_e$. In addition, in two distinct regions $e$ and $f$, the distance between points $g$ in region $e$ and $h$ in region $f$ is approximated as the distance between region centers. That is to say we let the subscript $(e,0)$ represent the center of region $e$, and assuming uniformly distributed charges Eq. (A.2) becomes

$$V_{(e,0)} = \sum_{f=1}^{n} \left( \sum_{h=1}^{n_e} P_{(e,0)(f,h)} \right) Q_{(f)} + \left( \sum_{h=1}^{n_e} P_{(e,0)(e,h)} \right) Q_{(e)}. \quad (A.3)$$

Noticing that the terms in Eq. (A.3) contained in parenthesis do not contain the summation index $h$, the terms can be rewritten as

$$\sum_{h=1}^{n_e} P_{(e,0)(f,0)} = n_f P_{(e,0)(f,0)}, \quad (A.4)$$

and Eq. (A.3) is then rewritten as

$$V_e = \sum_{f=1}^{n} P_{ej} Q_j \quad (A.5)$$
Glass

\[
\begin{align*}
X_i &= d_3 \\
Y_i &= (i - n_s - 1/2)(d_3/n_y) - \frac{d_5}{2} \\
i &= (n_s + 1)\{(n_s + 2)\cdots(n_s + n_y)\}
\end{align*}
\]

(A.9)

in which the window dimensions are given by \(d_1, d_2, d_3, d_5, \theta\) is the slat angle, \(n_s\) is the number of charge regions along the slat widths, \(n_y\) is the number of slat regions along the glass, and the origin is set at the axis of rotation (see Figs. 2 & A.2). Notice that \((d_1 + d_2)/n_s\) is the length of each conductive region in the direction of the slat width.

The second step in calculating the position vectors includes the third dimension. To minimize the error caused by assuming all charges act at one point in each region, the electrostatic system is divided into regions that are as square as possible [7]. To this end, the number of regions \(n_l\) along the length of the slats is calculated using

\[
n_l = \text{integer}\left[\frac{L}{(d_1 + d_2)/n_s}\right].
\]

(A.10)

where \(L\) is the total length of each slat, and \(n_l\) is rounded to the nearest integer. Then, the complete three-dimensional position vector of the \((i,j,k)\) point is given by

\[
r_{ijk} = \left( X_i, Y_i + (j - 1)d_3, \left( k - 1\right)\left( \frac{L}{n_l}\right) \right),
\]

\[
j = 1, 2, 3, \ldots, n_h, \quad k = 1, 2, 3, \ldots, n_l,
\]

(A.11)

where the origin is set at the end of the axis of rotation of the bottom slat (see Fig. A.2). Using Eq. (A.11), the values of \(P_{ijk}(abc)\) in Eq. (A.7) can now be calculated.

As seen in work done by Park [14], for the special case of \((ijk) = (abc)\) the coefficient of potential \(P_{ijk}(abc)\) becomes

\[
P_{ijk}(abc) = k\left[\frac{1}{l} \ln\left(\frac{l + \sqrt{w^2 + l^2}}{l - \sqrt{w^2 + l^2}}\right) + \frac{1}{w} \ln\left(\frac{w + \sqrt{w^2 + l^2}}{w - \sqrt{w^2 + l^2}}\right)\right].
\]

(A.12)

where \(l\) and \(w\) are the length and width of the \((ijk)\) region, or more simply stated

\[
P_{ijk}(abc) = 2k\left[\frac{1}{l} \ln\left(\frac{l + \sqrt{w^2 + l^2}}{w}\right) + \frac{1}{w} \ln\left(\frac{w + \sqrt{w^2 + l^2}}{l}\right)\right].
\]

(A.13)

We could now apply Eqs. (A.7) and (A.8) directly to the powerblind. However, before applying these equations, we will reduce number of calculations necessary by recognizing certain patterns associated with the charge distributions. First, we recognize that the distance from \((ijk)\) to \((abc)\) is the same as the distance from \((abc)\) to \((ijk)\). Consequently, the terms in \(P_{ijk}(abc)\) are symmetric, or

\[
P_{ijk}(abc) = P_{(abc)(ijk)}.
\]

(A.14)
Nomenclature

$abc, ijk$ counters for regions in three dimensions
$d_1, d_2, d_3, d_5$ window dimensions
$e_f$ counter for charge regions
$(e,0)$ subscript representing the center of region $e$
$F_{ij(k)}$ force vector acting on region $ijk$
$g,h$ counter for charges within each region
$G$ acceleration due to gravity
$i,j$ counter for particle charges
$k$ $(1/4\pi\varepsilon_0)$ electrostatic constant where $\varepsilon_0$ is the permittivity of free space
$l$ length of charge regions
$L$ total length of each slit
$M_{\text{elect}}$ moment caused by electrostatic forces
$M_{\text{grav}}$ moment caused by gravitational forces
$n$ number of charge regions in the entire system
$n_e$ number of particle charges in region $e$
$n_f$ number of particle charges in region $f$
$n_y$ number of divisions along the glass for each slat region (vertical direction)
$n_h$ total number of slats
$n_i$ number of divisions along the length of the slats (and corresponding region of glass)
$n_w$ number of divisions along the width of the slats
$p$ air pressure
$P_{ij}$ coefficient of potential between the $i$th and $j$th particle
$P_{(e,g)(f,h)}$ coefficient of potential between the charges $g$ and $h$ in regions $e$ and $f$
$P_{(ijk)(abc)}$ coefficient of potential between the $ijk$ and $abc$ regions
$q$ heat flux in the horizontal direction of window with slats
$q_{\text{no-slat}}$ heat flux in the horizontal direction of window without slats
$Q_e$ charge of the $e$th region due to particle charge $g$
$Q_{(ijk)}$ charge of region $ijk$
$r_{ij}$ distance between the $i$th and $j$th particle
$r_{(ijk)(abc)}$ distance between the center of the $ijk$ and $abc$ regions
$r_{(ijk)}$ position vector used to denote global position of each region
of each slat
$T$ temperature
$u$ air velocity in the $x$-direction
$v$ air velocity in the $y$-direction
$V$ voltage applied to the window slats
$V_i$ voltage of the $i$th particle
$V_{(e,g)}$ voltage of the $e$th region due to the particle charge $g$
$V_{(ijk)}$ voltage of charge region $ijk$