CHAPTER - 7
EFFECT OF HELICAL WIRE PARAMETERS IN 217 PIN BUNDLE

7.0 INTRODUCTION

Since the helical wire increases the friction factor and Nusselt number in the pin bundle by inducing transverse velocity, it is very essential to estimate its effect for various helical wire parameters like its helical pitch and wire diameter. Towards this, the helical wire pitch is varied in the range of 100 – 300 mm. Similarly, the wire diameter is varied in the range of 1.25 – 2.0 mm. Based on detailed parametric studies, correlations for Nusselt number are proposed.

7.1 DEPENDENCE OF TRANSVERSE VELOCITY ON HELICAL PITCH

The distribution of cross-stream velocity fields and an enlarge view of velocity vectors at the bundle exit for the cases of 100, 200 and 300 mm helical pitch are presented in Figs. 7.1 (a) – 7.1 (f) respectively. These results are for an axial entry velocity of 8 m/s and the corresponding Reynolds number is 100,000. It is seen that the transverse velocity decreases with increase in helical pitch. The values of transverse velocity as function of helical wire pitch are presented in Table 7.1. It is seen that the transverse velocity is highest for 100 mm helical pitch and the values decrease with increase in the helical pitch. The transversal flow induced by the helical wire in the 217 fuel pin bundle is dependent upon the helical pitch and is inversely proportional to it. Thus, the intensity of transverse velocity is more with shorter helical pitch. The ratio of transverse velocity to axial velocity is higher for shorter helical pitch.
Fig. 7.1 (a) The transverse velocity field at the exit of 100 mm helical pitch wire wrap 217 pin bundle.

Fig. 7.1 (b) Close-up view of the transverse velocity field at exit of 100 mm helical pitch wire wrapped 217 pin bundle in X-Y plane.
Fig. 7.1 (c) Transverse velocity field at the exit of 200 mm helical pitch wire wrap 217 pin bundle

Fig. 7.1 (d) Close-up view of the transverse velocity field at exit of 200 mm helical pitch wire wrapped 217 pin bundle in X-Y plane.
Fig. 7.1 (e)  The transverse velocity field at the exit of 300 mm helical pitch wire wrap 217 pin bundle

Fig. 7.1 (f)  Close-up view of the transverse velocity field at exit of 300 mm helical pitch wire wrap 217 pin bundle in X-Y plane.
Table 7.1 Transverse velocity as a function of helical pitch for Re =100,000

<table>
<thead>
<tr>
<th>Helical pitch, mm</th>
<th>Average transverse velocity, m/s</th>
<th>Maximum transverse velocity, m/s</th>
<th>Ratio of Transverse velocity to Average axial velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.47</td>
<td>4.0</td>
<td>0.18</td>
</tr>
<tr>
<td>200</td>
<td>0.68</td>
<td>2.2</td>
<td>0.08</td>
</tr>
<tr>
<td>300</td>
<td>0.42</td>
<td>1.7</td>
<td>0.05</td>
</tr>
</tbody>
</table>

7.2 DEPENDENCE OF TRANSVERSE VELOCITY ON HELICAL WIRE DIAMETERS

In order to compare the velocity vector field for different wire diameters, the velocity vector fields at the bundle exit for the same Reynolds number of 100,000 is presented in Figs. 7.2 (a) – 7.2 (f) for wire diameters of 1.25, 1.65 and 2.0 mm respectively. The values of transverse velocity as function of wire wrap parameters are presented in Table 7.2. The cross–stream velocity appears to be nearly insensitive to the wire diameter for identical Reynolds number. When the wire diameter changes, the flow area occupied by the wire also changes. But, the change in flow area due to change in size of the hexagonal sheath is significant. Hence, the equivalent diameter increases with wire diameter due to the cumulative changes in wire area and the cross sectional area of hexagonal sheath. Hence, the inlet velocity is more for smaller wire diameter as its equivalent diameter is small. Consequently, the ratio of cross stream velocity to mean axial velocity is less for small wire diameter, due to larger cross flow resistance.
Fig. 7.2 (a)  The transverse velocity field at the bundle exit of 1.25 mm diameter helical wire wrap 217 pin bundle

Fig. 7.2 (b)  Close-up view of transverse velocity field at the bundle exit of 1.25 mm diameter helical wire wrap 217 pin bundle in X-Y plane.
Fig. 7.2 (c) The transverse velocity field at the bundle exit of 1.65 mm diameter helical wire wrap 217 pin bundle.

Fig. 7.2 (d) Close-up view of the transverse velocity field at the bundle exit of 1.65 mm diameter helical wire wrap 217 pin bundle in X-Y plane.
Fig. 7.2 (e) The transverse velocity field at the bundle exit of 2.0 mm diameter helical wire wrap 217 pin bundle.

Fig. 7.2 (f) Close-up view of transverse velocity field at the bundle exit of 2.0 mm diameter helical wire wrap 217 pin bundle in X-Y plane.
Table 7.2 Transverse velocity as a function of helical wire diameter for Re = 100,000

<table>
<thead>
<tr>
<th>Helical wire diameter, mm</th>
<th>Average transverse velocity, m/s</th>
<th>Maximum transverse velocity, m/s</th>
<th>Ratio of Transverse velocity to Average axial velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>0.66</td>
<td>2.13</td>
<td>0.07</td>
</tr>
<tr>
<td>1.65</td>
<td>0.68</td>
<td>2.2</td>
<td>0.08</td>
</tr>
<tr>
<td>2.0</td>
<td>0.69</td>
<td>2.27</td>
<td>0.098</td>
</tr>
</tbody>
</table>

7.3 DEPENDENCE OF AXIAL VELOCITY ON HELICAL PITCH

The contours of axial velocity for 100, 200 and 300 mm helical pitch models with a fixed wire diameter of 1.65 mm and with a ratio of the triangular pitch distance to pin diameter (P/D) of 1.255 are presented at the bundle exit in Figs.7.3 (a) - 7.3 (c). These results are for an axial entry velocity of 8 m/s and the corresponding Reynolds number is 100,000. The values of axial velocity at the bundle exit as function of helical wire pitch are presented in Table 7.3. The equivalent diameter of the pin bundle and the average velocity are same for all values of helical pitch. But, maximum values are higher for shorter helical pitches due to distortion by the transverse velocity.

7.4 DEPENDENCE OF AXIAL VELOCITY ON HELICAL WIRE DIAMETERS

In order to compare the velocity field for 1.25, 1.65 and 2.0 mm diameter pins (the P/D ratios are 1.307, 1.255 and 1.194) for a fixed 200 mm helical pitch, the axial velocity fields at the bundle exit for the same Reynolds number are presented in the Figs. 7.4 (a) – 7.4 (c).
Fig. 7.3 (a) The axial velocity field at the bundle exit of 100 mm helical pitch wire wrap 217 pin bundle

Fig. 7.3 (b) The axial velocity field at the bundle exit of 200 mm helical pitch wire wrap 217 pin bundle
Table 7.3 Axial velocity as a function of helical pitch for Re = 100,000

<table>
<thead>
<tr>
<th>Helical pitch, mm</th>
<th>Average axial velocity, m/s</th>
<th>Maximum axial velocity, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>8.0</td>
<td>11.6</td>
</tr>
<tr>
<td>200</td>
<td>8.0</td>
<td>10.8</td>
</tr>
<tr>
<td>300</td>
<td>8.0</td>
<td>10.4</td>
</tr>
</tbody>
</table>

The values of axial velocity as function of wire wrap parameters are presented in Table 7.4. As the wire diameter increases, the equivalent diameter of the bundle increases. So, the axial flow velocity is correspondingly reduced to keep the Reynolds number same. It is seen that the average and maximum values of axial velocity decrease with increase in wire diameter.
Fig. 7.4 (a)  The axial velocity field at the bundle exit of 1.25 mm diameter helical wire wrap 217 pin bundle

Fig. 7.4 (b)  The axial velocity field at the bundle exit of 1.65 mm diameter helical wire wrap 217 pin bundle
Fig. 7.4 (c) The axial velocity field at the bundle exit of 2.0 mm diameter helical wire warpped 217 pin bundle

Table 7.4 Axial velocity as a function of helical wire diameter for Re = 100,000

<table>
<thead>
<tr>
<th>Helical wire diameter, mm</th>
<th>Average axial velocity, m/s</th>
<th>Maximum axial velocity, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>9.5</td>
<td>12.4</td>
</tr>
<tr>
<td>1.65</td>
<td>8.0</td>
<td>10.9</td>
</tr>
<tr>
<td>2.0</td>
<td>7.03</td>
<td>9.47</td>
</tr>
</tbody>
</table>

### 7.5 INFLUENCE OF HELICAL PITCH ON FRICTION FACTOR

The dependence of friction factor on helical pitch is depicted in Fig. 7.5 (a) for Re = 100,000. It is seen that friction factor decreases from 0.03 for 100 mm helical pitch and approaches a constant value of 0.0175 for helical pitches 600 mm and above. When the length of the helical pitch increases, the friction factor approaches as that of Blasius correlation for internal flow, as expected.
Fig. 7.5 (a) Variation of friction factor of 217 pin bundle with helical pitch

Fig. 7.5 (b) Dependence of friction factor of 217 bundle on helical pitch for various Reynolds number
The dependence of friction factor on helical pitch for various Reynolds numbers, both in the laminar and turbulent regimes is depicted in Fig. 7.5 (b). It is seen that the friction factor is inversely proportional to the Reynolds number for all values of helical pitch, as in any internal flow. Also, as the helical pitch decreases, the friction factor increases due to enhancement in cross flow induced by short helical pitches.

The average percentage increase in friction factor when the helical pitch decreased from 200 mm to 100 mm is around 50 % whereas it is only 5 % when the helical pitch is decreased from 300 mm to 200 mm. From the Chen and Todreas correlation for friction factor with different helical pitch, it is seen that the friction factor is higher for shorter helical pitch with which the present CFD results agree well.

7.6 INFLUENCE OF HELICAL WIRE DIAMETER ON FRICTION FACTOR

The predicted dependence of friction factor on P/D is depicted in Fig. 7.6 for various values of Reynolds number. The friction factor is seen to increase with P/D. Due to change in diameter of the helical wire, the triangular pitch distance between the fuel pins will get changed but velocity of flow is correspondingly changed to keep the Reynolds number same as that of the bundle with wire diameter 1.65 mm. When the wire diameter is reduced, the resistance to cross flow is increased. As a result of this, the relative magnitude of cross flow reduces leading to reduction in friction factor in small wire diameter bundles. The friction factor is seen to be a weak function of P/D for the pin bundle dimensions considered. The average percentage increase in friction factor when the helical wire diameter decreased from 1.65 mm to 1.25 mm is around 5 % whereas it is only 3 % when it is decreased from 2.0 mm to 1.65 mm. From the Chen et al (2014) correlation for friction factor with different
helical wire diameter, it is observed that the friction factor is higher for larger P/D ratio (i.e. for larger helical wire diameter) with which the present CFD results for 217 pin bundle agree.

Fig. 7.6 Dependence of friction factor of 217 bundle on helical wire diameter for various Reynolds number

7.7 INFLUENCE OF HELICAL PITCH ON TEMPERATURE DISTRIBUTION

The temperature fields for a fixed Reynolds number of ~100000 in a 217 pin bundle with 100, 200 and 300 mm helical pitch values are presented at a distance of 100 mm from the bundle entry in Figs. 7.7 (a) – 7.7 (c). While the average sodium temperature at the exit of 100 mm is same (686.2 K) for all the cases, the average clad temperature is 694.4 K, 694.9 K and 695.4 K respectively for 100, 200 and 300 mm helical pitch pin bundles. Hence, it is seen that the clad temperature is lower for 100 mm helical pitch and higher for 300 mm
helical pitch. It is also seen that the maximum temperature occurs in different regions of the bundle, as the helical wire completes one full turn for 100 mm helical pitch, half turn for 200 mm and one third turn for 300 mm helical pitch pin bundles.

Fig. 7.7 (a)   Temperature field at 100 mm elevation for 100 mm helical pitch wire wrap 217 pin bundle

Fig. 7.7 (b)   Temperature field at 100 mm elevation for 200 mm helical pitch wire wrap 217 pin bundle
Table 7.5 Effect of helical pitch on clad to sodium temperature difference

<table>
<thead>
<tr>
<th>Helical pitch (mm)</th>
<th>Clad temperature, K</th>
<th>Sodium temperature, K</th>
<th>Clad to Sodium temperature difference, (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Minimum,</td>
<td>Maximum</td>
</tr>
<tr>
<td>100</td>
<td>699</td>
<td>691</td>
<td>692</td>
</tr>
<tr>
<td>200</td>
<td>699</td>
<td>691</td>
<td>691</td>
</tr>
<tr>
<td>300</td>
<td>699</td>
<td>692</td>
<td>689</td>
</tr>
</tbody>
</table>

The effect of helical pitch on clad to sodium temperature difference is presented in Table 7.5. It is seen that the hot spot location is only about 6 - 8 K higher than the local bulk temperature for nominal helical pitch of 200 mm. In other words, the clad temperature is fairly uniform in the circumferential direction due to the circulating fluid flow created by the
helical wires. The coolant is made to impinge and sweep the corners formed by the junction of the pin and spacer wire. Hence, wire wrap promotes cross stream flow to prevent excessively high temperature around the wire wrap.

### 7.8 INFLUENCE OF HELICAL WIRE DIAMETER ON TEMPERATURE DISTRIBUTION

The sodium temperature field for 217 pin bundle at a Reynolds number of \( \sim 100000 \) with different helical wire diameters of 1.25, 1.65 and 2.0 mm at the bundle exit of 200 mm travel in the bundle is presented in Fig. 7.8 (a) – 7.8 (c). The temperature field contains both the clad and sodium temperatures. It is seen that the temperature is lower for smaller wire diameter as the heat flux is kept lower to obtain a fixed sodium outlet temperature of 702 K. The temperature distribution becomes more uniform when wire diameter increases.

![Fig. 7.8 (a) Temperature field at the exit of 1.25 mm diameter helical wire wrap 217 pin bundle](image)

Fig. 7.8 (a) Temperature field at the exit of 1.25 mm diameter helical wire wrap 217 pin bundle
Fig. 7.8 (b)  Temperature field at the exit of 1.65 mm diameter helical wire wrap 217 pin bundle

Fig. 7.8 (c)  Temperature field at the exit of 2.0 mm diameter helical wire wrap 217 pin bundle
7.9 INFLUENCE OF HELICAL PITCH ON NUSSELT NUMBER

It is found that the temperature difference between the clad and coolant increases with helical pitch suggesting lower values of Nusselt number for longer helical pitches. This is due to the fact that when the helical pitch is increased, the helical wire induced cross flow decreases. The predicted dependence of Nusselt number on helical pitch is depicted in Fig. 7.9 for various values of Reynolds number. In the turbulent regime, the Nusselt number is higher if the helical pitch is shorter. This trend is in line with the dependence of friction factor on helical pitch as expected. However, in the laminar regime, the Nusselt number does not exhibit any perceptible dependence on helical pitch.

![Graph showing the dependence of Nusselt number on Reynolds number for different helical pitches](image)

Fig. 7.9 Comparison of Nusselt number at 100 mm from the inlet of 217 fuel pin bundle for various helical pitch
7.10 INFLUENCE OF HELICAL WIRE DIAMETER ON NUSSELT NUMBER

When the wire diameter increases, the axial velocity of flowing fluid decreases and heat flux is increased to keep the Reynolds number and outlet temperature constant. It is found that the temperature difference between the clad and coolant increases with helical wire diameter indicating lower values of heat transfer coefficient for larger wire diameter. This is due to the fact that when wire diameter increases, the axial velocity of sodium decreases though the relative cross flow velocity increases. As a consequence of this, as well as increase in hydraulic diameter, the Nusselt number increases with wire diameter. This is in line with dependence of friction factor on wire diameter. The estimated variation of Nusselt number with respect to diameter is depicted in Fig. 7.10 for various values of Reynolds number. It is seen that larger the helical wire diameter, larger is the Nusselt number.

7.11 DEVELOPMENT OF NUSSELT NUMBER CORRELATIONS

Correlations for Nusselt number at the bundle exit based on CFD study are proposed for 217 pin bundle with different helical pitches and helical wire diameter and for a range of Reynolds number.

7.11.1 For Various Helical Pitches

The following empirical correlation is valid for a pin diameter of 6.6 mm, helical pitch from 100 to 300 mm and constant wire diameter of 1.65 mm. The sodium flow should be in turbulent regime with Reynolds number in the range of 20000 to 100000 and Peclet number from 100 to 500 respectively.
Fig. 7.10 Comparison of Nusselt number at the exit of 217 fuel pin bundle for various helical wire diameter

\[ Nu = 2.29 \times \left( \frac{H}{D} \right)^{-0.05} \times (Pe)^{0.28} \]

The following correlation is valid for Reynolds number 2000 to 20000 and Peclet number from 10 to 100 respectively.

\[ Nu = 3.24 \times \left( \frac{H}{D} \right)^{-0.05} \times (Pe)^{0.201} \]

7.11.2 For Various Helical Wire Diameter

The following correlation is valid for a pin diameter of 6.6 mm, constant helical pitch of 200 mm and wire diameter from 1.25 to 2.0 mm. The Reynolds number range is 20000 to 100000 and Peclet number from 100 to 500 respectively.
\[ Nu = 2.133 \times \left( \frac{d}{D} \right)^{0.28} \times (Pe)^{0.315} \]

The following correlation is valid for Reynolds number from 2000 to 20000 and Peclet number ranges from 10 to 100 respectively.

\[ Nu = 5.893 \times \left( \frac{d}{D} \right)^{0.224} \times (Pe)^{0.065} \]

Where \( d \) - diameter of the wire, \( D \) – diameter of the pin, \( H \) – Helical pitch of the wire.

The method of deducing the constants and exponents of the proposed correlations and the analysis of data scatter and the estimation maximum possible error in the proposed correlations is presented in Appendix B. It is seen that the proposed correlations are best fitted against the actual values of Nusselt number obtained from the CFD study. The maximum possible error is 10 %.

### 7.12 CLOSURE

The intensity of transverse velocity is found to be inversely proportional to the helical pitch. Hence, the values of friction factor and Nusselt number are larger for shorter helical pitch for all values of Reynolds number. As the wire diameter increases, the equivalent diameter of the whole bundle increases. The relative transverse velocity is found to be directly proportional to the wire diameter and the values of friction factor are smaller for smaller values of helical wire diameter. The Nusselt number is seen to increase with increase in wire diameter. Based on parametric study, correlations for Nusselt number at the bundle exit are proposed for 217 pin bundle with different helical pitches and helical wire diameter as a function of Peclet number.