THERMAL HYDRAULICS WITHIN 7 PIN BUNDLE

4.0 INTRODUCTION

The development of transverse velocity in the 7 pin bundle and its variation with helical pitch, friction factor of the 7 pin bundle, sodium temperature development in the 7 pin bundle and the thermal benefits of the transverse velocity are presented in this chapter.

4.1 DEVELOPMENT OF TRANSVERSE VELOCITY

The Reynolds number for this simulation is 100,000 with an axial velocity of 7.53 m/s. The heat flux on the clad surface is 1.85 MW/m². The inlet temperature of sodium to the pin bundle is 670 K. The nominal helical wire diameter is 1.65 mm and the nominal helical pitch is 200 mm. The distribution of cross-stream velocity at the various elevations of the bundle is presented in Figs. 4.1 (a) - 4.1 (g). The magnitude of cross stream velocity is typically about 0.77 m/s. The activity of the secondary flow is maximum in the vicinity of the spacer wire. This swirl flow occurring at the peripheral sub-channels is found to be periodic and is found to be a function of wire position. As we move upwards in the axial direction, the wire moves anti-clockwise. As a consequence of this, the circumferential flow is developed in anti-clockwise direction. The velocity is maximum in the peripheral sub-channels which are diametrically opposite to the channels where a spacer wire blocks the sub-channel. This flow developed due to the helical wire is very important from the thermal hydraulics point of view, as it enhances mixing of the coolant which is required to obtain a fairly uniform coolant temperature at the exit of the bundle. It also increases the level of turbulence which promotes good mixing of the coolant and better uniformity of the temperatures. Also, it is seen that the flow has got developed within 33 mm from the inlet of the bundle after which the changes in the flow is marginal.
Fig. 4.1 (a) Transverse velocity field at 33 mm from the inlet of helical wire wrap 7 pin bundle

Fig. 4.1 (b) Transverse velocity field at 66 mm from the inlet of helical wire wrap 7 pin bundle
Fig. 4.1 (c) Transverse velocity field at the 99 mm from the inlet of helical wire wrap 7 pin bundle

Fig. 4.1 (d) Transverse velocity field at the 133 mm from the inlet of helical wire wrap 7 pin bundle
Fig. 4.1 (e) Transverse velocity field at the 166 mm from the inlet of helical wire wrap 7 pin bundle

Fig. 4.1 (f) Transverse velocity field at the exit of helical wire wrap 7 pin bundle
4.1 Close-up view of transverse velocity field at the exit of helical wire wrap 7 pin bundle in X-Y plane.

4.2 **VARIATION OF TRANSVERSE VELOCITY WITH HELICAL PITCH**

The local transverse velocity is defined as,

\[ V_T = \sqrt{V_x^2 + V_y^2} \]

The mass averaged transverse velocity is defined as,

\[ \overline{V_T} = \frac{\int V_x V_T \, dA}{\int V_x \, dA} \]

Where \( V_T \) = local transverse velocity, \( V_x \) – component of velocity in the x- direction, \( V_y \) – component of velocity in the y- direction, \( V_z \) – component of velocity in the z- direction, \( \overline{V_T} \) – mass averaged transverse velocity, dA- elemental flow area.
The variation of mass weighted average transverse velocity with helical pitch of the wire is presented in Fig. 4.2 (a). It is seen that the transverse velocity drastically reduces and becomes negligible when helical pitch increases to 1500 mm as it approaches that of the straight wire pin bundle where no transverse velocity is possible. The ratio of maximum axial velocity \( V_z = 7.53 \text{ m/s} \) to the transverse velocity (Average \( V_T = 0.77 \text{ m/s} \)) is about 9.8 for the geometry under study. This is nearly equal to the tangent of the rolling up angle \( (\theta = 85^\circ) \) of the helical wire. That is,

\[
Tan \ (\theta) = \frac{V_z}{V_T} = \frac{H/2}{(D + d)}
\]

The variation of rolling up angle of the wire with helical pitch is presented in the Fig. 4.2(b). It is seen that when the helical pitch becomes 1500 mm, the rolling up angle becomes nearly equal to 90° which is a straight wire.

![Fig. 4.2 (a) Variation of transverse velocity with helical pitch of the spacer wire.](image)
The ratio of axial velocity to transverse velocity for various helical pitches and the corresponding rolling up angle of the helical wire are presented in Table 4.1. It is seen from the table that the ratio of axial velocity to transverse velocity is nearly equal to the tangent of the rolling up angle of the helical wire. The Table 4.1 shows that for higher value of helical pitch, the rolling up angle becomes very close to 90° for which the ratio of transverse velocity to axial velocity becomes infinity as the transverse flow becomes negligible for straight wire case.

![Graph showing the variation of rolling up angle with helical pitch](image)

Fig. 4.2 (b) Variation of rolling up angle with helical pitch of the spacer wire

### 4.3 VARIATION OF AXIAL VELOCITY

The contours of axial velocity at various axial planes along the flow direction are depicted in Figs. 4.3 (a) – 4.3 (f). The uniform axial velocity after entering the pin bundle distorts significantly. The distortion is such that the velocity is high in the peripheral sub channels. Among the various peripheral sub channels, the velocity is high in the sub channels having spacer wire. This is true especially close to the entrance within half helical pitch length. Further, the position of the sub channel (with peak axial velocity) changes along the flow direction. In fact, it rotates anti-clockwise as the flow moves upwards. The ratio of maximum velocity to average velocity increases from unity at the entry and reaches 1.2 at the exit.
Table 4.1 The ratio of axial velocity to transverse velocity transverse velocity and the rolling up angle for various helical pitches

<table>
<thead>
<tr>
<th>Helical pitch</th>
<th>Transverse velocity</th>
<th>Ratio of axial velocity to Transverse velocity (a)</th>
<th>Rolling up angle of the helical wire # (b)</th>
<th>Tan⁻¹(a)</th>
<th>Tan⁻¹(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.42</td>
<td>5.30</td>
<td>6.73</td>
<td>79.3</td>
<td>81</td>
</tr>
<tr>
<td>200</td>
<td>0.77</td>
<td>9.78</td>
<td>13.46</td>
<td>84</td>
<td>85</td>
</tr>
<tr>
<td>300</td>
<td>0.49</td>
<td>15.36</td>
<td>20.20</td>
<td>86</td>
<td>87</td>
</tr>
<tr>
<td>600</td>
<td>0.21</td>
<td>35.85</td>
<td>40.40</td>
<td>88</td>
<td>88.5</td>
</tr>
<tr>
<td>1000</td>
<td>0.11</td>
<td>68.45</td>
<td>67.34</td>
<td>89</td>
<td>89</td>
</tr>
<tr>
<td>1500</td>
<td>0.07</td>
<td>107.6</td>
<td>90.90</td>
<td>89.5</td>
<td>89.5</td>
</tr>
</tbody>
</table>

# Ratio of half of helical pitch to sum of pin diameter and wire diameter.

Fig. 4.3 (a) Axial velocity field at 33 mm from the inlet of helical wire wrap 7 pin bundle
Fig. 4.3 (b) Axial velocity field at 66 mm from the inlet of helical wire wrap 7 pin bundle

Fig. 4.3 (c) Axial velocity field at 99 mm from the inlet of helical wire wrap 7 pin bundle
Fig. 4.3 (d)  Axial velocity field at 133 mm from the inlet of helical wire wrap 7 pin bundle

Fig. 4.3 (e)  Axial velocity field at 166 mm from the inlet of helical wire wrap 7 pin bundle
4.4 VELOCITY DISTRIBUTION IN STRAIGHT WIRE PIN BUNDLE

The velocity distribution in straight wire pin bundle is marked by the insignificant transverse flow, Fig.4.4 (a). The mass average transverse velocity is 5 mm/s. This indicates that there is no cross flow within the bundle. The outlet axial velocity distribution for this case is presented in Fig. 4.4 (b). The velocity in the gap between wire and pin is 0.08 m/s whereas the same is 4.15 m/s in the case of helical wire. This shows that the velocity field is stagnant in this gap between wire and pin but the same is active in the case of helical wire which can enhance heat transfer in this gap and reduces the hotspot.

4.5 FRICTION FACTOR IN 7 PIN BUNDLE

One of the engineering parameters of interest is the friction factor. The value of friction factor predicted in the present study for 7 pin bundle with helical wire for various Reynolds number is compared with Chen et al (2014) correlation in Fig. 4.5 (a). It is seen that the agreement is very good with a maximum deviation of 15 %. The CFD model is seen to
over predict the friction factor in the laminar regime while the same is under predicted in the turbulent regime.

Fig. 4.4 (a) Transverse velocity field in straight wire wrap 7 pin bundle

Fig. 4.4 (b) Axial velocity field in straight wire wrap 7 pin bundle
Comparison of friction factor with helical spacer wire and straight spacer wire is presented in Fig. 4.5 (b). It is seen that the friction factor with helical spacer wire is higher than that of straight spacer wire. The value of friction factor for straight wire smooth pin bundle is 0.018 from Blasius correlation (1913).

The variation of friction factor with helical pitch is plotted and presented in the Fig. 4.5 (c). It is seen that friction factor drastically reduces from 0.033 for 100 mm helical pitch to 0.0175 for 600 mm helical pitch.
Fig. 4.5 (b) Comparison of friction factor of helical and straight wire pin bundle with Blasius correlation

Fig. 4.5 (c) Variation of friction factor with helical pitch length for 7 pin bundle
4.6 SODIUM TEMPERATURE DISTRIBUTION WITH HELICAL WIRE 7 PIN BUNLDE

The sodium temperature distribution in the pin bundle with spacer wire is depicted in Figs. 4.6 (a) – 4.6 (f) in the form of contours at various axial planes. These results are for an axial entry velocity of 7.53 m/s and Reynolds number 100,000. It is observed that the sodium temperature increase is higher in the central sub-channels, as sodium flowing in these sub-channels is heated all-around, because these channels are formed by fuel pins. The sodium temperature increase is less in the peripheral sub-channels since the heat input per unit length in these channels are less due to the presence of hexagonal sheath which is adiabatic. The bulk temperature increase of sodium between the inlet and the outlet is 32 K, satisfying the heat balance requirement. The temperature field at any elevation depends on the wire position. The temperature is maximum at the outlet where wire position is facing the hexagonal sheath. The temperature is minimum in the position which is diametrically opposite to the maximum temperature region.

![Temperature field at 33 mm from the inlet of helical wire wrap 7 pin bundle](image)

Fig. 4.6 (a) Temperature field at 33 mm from the inlet of helical wire wrap 7 pin bundle
Fig. 4.6 (b) Temperature field at 66 mm from the inlet of helical wire wrap 7 pin bundle

Fig. 4.6 (c) Temperature field at 99 mm from the inlet of helical wire wrap 7 pin bundle
Fig. 4.6 (d) Temperature field at 133 mm from the inlet of helical wire wrap 7 pin bundle

Fig. 4.6 (e) Temperature field at 166 mm from the inlet of helical wire wrap 7 pin bundle
Fig. 4.6 (f) Temperature field at the exit of helical wire wrap 7 pin bundle

4.7 COMPARISON OF SODIUM TEMPERATURE DISTRIBUTION IN STRAIGHT WIRE PIN BUNDLE WITH HELICAL WIRE PIN BUNDLE

The sodium temperatures at the exit of straight wire and helical wire pin bundle are presented in Figs. 4.7 (a) – 4.7 (b) for comparison. From Fig. 4.7 (a), it is seen that the maximum clad temperature is 765 K and the same for helical wire is 735 K. The maximum clad temperature is higher in the case straight wire bundle due to the absence of transverse flow. The maximum temperature occurs at the location of the gap between pin and wire. The ΔT between the bulk sodium in the central sub-channel and peripheral sub-channel is 38 K for straight wire and the same for helical wire is 22 K. The difference in bulk sodium temperature between the central and peripheral sub-channels is less in the case with helical wire than the case of straight pin bundle due to the presence of secondary flow. Hence, the
outlet temperature is more uniform in the case of helical wire bundle. The helical wire forces the hot sodium from the central sub-channels to move out to peripheral sub-channels to mix with the relatively cold sodium and direct the relatively cold sodium at the periphery towards the center. These inward and outward flows create good mixing of the hot sodium at the central sub-channels with the relatively colder sodium at the periphery, rendering a more uniform temperature profile across the pin bundle and reduced hot spot on the pin. The average sodium temperature at the outlet in both the cases is 702 K. The bulk temperature increase of sodium between the inlet and the outlet is 32 K satisfying the heat balance requirement.

Fig. 4.7 (a) Temperature field at the exit of straight wire 7 pin bundle
Fig. 4.7 (b) Temperature field at the exit of helical wire 7 pin bundle

4.8 NUSSELT NUMBER IN HELICAL AND STRAIGHT WIRE BUNDLE

The Nusselt number at the exit of helical wire wrapped and straight wire 7 pin bundle for Re = 100, 000 is presented in Fig. 4.8 along with the correlation based on experimental data. It is seen that the Nusselt for helical wire wrapped bundle is 15% higher than that of the straight wire bundle in the turbulent regime (Re > 4000) and nearly equal in the laminar regime (Re < 2500). It is also seen that the Nusselt number predicted by the present CFD study is higher than the experimental data in the turbulent regime. This is due to the increased heat transfer coefficient due to helical wire which is probably not considered in the experimental correlation.
4.9 THERMAL BENEFITS OF TRANSVERSAL FLOW DUE TO HELICAL WIRE

There are three advantages realized due to the transversal flow created by helical spacer wire. One is the sodium outlet temperature has become more uniform due to the fact that the temperature difference ($\Delta T$) between sodium in the central sub-channels and in the periphery sub-channels is reduced. The low value of $\Delta T$ leads to lower levels of fluctuation in the readings of core monitoring thermocouples which is essential for online monitoring. The second advantage is that the clad temperature has become more uniform in the circumferential direction due to the circulating flow created by helical wire. The coolant is made to impinge and sweep the corners formed by the junction of the pin and spacer wire. This sweeping prevents possible hot spot beneath the wire wrap. The third advantage is that
the fuel subassembly can be designed to generate a larger power without exceeding the temperature limits of clad and sodium.

4.10 CLOSURE

The friction factor of the pin bundle with helical wire and straight wire obtained from the present study is seen to agree well with the reported experimental data. It is observed that the helical wire induces a secondary swirl in the pin bundle which promotes cross stream mixing of the coolant to make its temperature more uniform. The transverse flow reduces the sodium temperature difference between the inner and outer sub-channels to 22 K (in the case of helical wire pin bundle) from 38 K (in the case of straight wire pin bundle).