CHAPTER 5

STUDY ON THE USE OF CIRCUMFERENTIAL DRAINAGE RINGS TO REDUCE CONDENSATE FLOODING

5.1 CONDENSATE RETENTION

During film condensation of vapour over HIF tubes, the surface tension force acts to drain the condensate towards the fin-root. This condensate moves along the fin root circumferentially from the top to the bottom of the tube and drains at the tube bottom. This causes the condensate to be retained between the fins at the bottom of the tube. This phenomenon is known as condensate ‘hold-up’, ‘retention’ or ‘flooding’. Though the surface tension enhances the heat transfer in the un-flooded upper region of the tube, it shows its adverse effect in the form of condensate retention at the tube bottom by reducing the effective surface area which in-turn reduces the heat transfer rate. As discussed in section 2.4, attempts have been made by earlier investigators to reduce the condensate retention by attaching either solid or porous drainage strips at the tube bottom or by electro hydro dynamic technique. It has proved to be worthy in single tube experiments but in practical condensers where bank of tubes is common, it is difficult to implement. The major drawbacks while using such drainage strips are (i) the use of such strips in tube banks increases the vertical clearance between the tubes which increases the size of the condenser shell; (ii) the vapour shear on such strips will increase the vapour-side pressure drop which is not desirable
in most of the applications. Thus, such drainage strips are not practically used (Webb (1994)). Hence, there exists a need for reducing the condensate retention by overcoming these adverse effects. One such technique has been identified and is experimentally proved for its condensate retention reduction and the consequent heat transfer enhancement capabilities. Further, the flow patterns are studied under various conditions. This chapter presents these details.

5.2 THE CONDENSATE RETENTION REDUCTION TECHNIQUE

When solid drainage strips are attached to the tube bottom (to reduce the condensate flooding level), it is found (Trela and Butrymowicz (1999)) that the strip alters the curvature of the condensate from convex to concave (at the meeting point between the strip and the tube). The action of surface tension forces due to such change in the curvature of the condensate creates a suction effect and pulls the condensate onto the drainage strip. The further movement of the condensate over the drainage strip is by gravity. Experimental investigation with steam condensing on finned tubes with solid drainage strips has shown a maximum increase of heat transfer coefficient by 35% when compared to tubes without a strip (Marto et al (1988)). The condensate must be effectively collected first from the bottom of the tube and it must be immediately moved away by some means in order to reduce the condensate flooding. According to Srinivasan (2001) a longitudinal slot at the bottom of the tube, would provide room for the collection of the condensate and slight tube inclination enables the gravity force to move the condensate along the slot axially. In the present investigation HIF tubes with bottom groove are employed along with circumferential drainage rings at predetermined locations. Condensate drainage on this tube is studied by varying the inclination of the tube which may help to position circumferential
drainage rings. The rings may be placed in limited locations there by the disadvantage of using continuous strips is avoided. This may reduce the condensate flooding significantly. Hence, such an idea has been implemented and condensate flooding angles are measured using an experimental setup made for this purpose. The groove width, circumferential ring height and the inclination of the tube are the main parameters that decide the level of flooding for such cases. Hence, HIF tubes with similar fin geometry, but with different groove widths are manufactured and tested by keeping them at different tube inclinations to find their ability to reduce the condensate flooding and the corresponding increase in the heat transfer performance. The effect of condensate flooding is more pronounced for high surface tension fluids. The use of a high surface tension fluid would make the measurements easier with lower measurement errors. Hence, water is used as a working fluid in the present experiments.

5.3 TUBE DETAILS

The commercially available copper tubes with 25.4 mm outer diameter and 3.0mm wall thickness are employed. Rectangular circumferential fins having 1.0 mm thickness and 1.0 mm fin height with a fin spacing of 1.2 mm are precisely machined. It results in HIF tubes with 23.4 mm diameter at fin root. The finned length is kept as 500 mm for condensate retention measurements. Four such HIF tubes are made. A tube is kept without bottom groove which is referred as tube-A. A Longitudinal groove of 0.5, 1.0 and 1.5 mm width are machined at the bottom of the remaining three tubes and are referred as tube-B, C and D respectively. The tube inclinations are varied in the range of 0° to 6° with respect to horizontal in order to study the effect of tube inclination. The cross section of the tube is shown in Figure 5.1.
$D_o = 25.4 \text{ mm}, D_i = 19.4 \text{ mm}, b = 1.2 \text{ mm}, t = 1.0 \text{ mm}, e = 1.0 \text{ mm} \text{ and } L = 500 \text{ mm}$

**Figure 5.1 Tube details**

### 5.4 EXPERIMENTAL SETUP FOR THE CONDENSATE RETENTION MEASUREMENTS

The experimental set up used for condensate retention (flooding angle) measurement is similar to the one described in Yau et al (1986). The experimental set up shown in Figure 5.2 consists of a constant head tank (to supply the distilled water), a condensate feeding tube with holes at the top and soft threads over each hole (to distribute water uniformly), a horizontally supported HIF tube (on which the condensate retention measurements are to be made) and a theodalite with an accuracy to measure 0.01” of angle (to measure the level of flooding with respect to the tube bottom).

The horizontal distance between the two supporting points of the test tube is 600 mm whereas the finned length of the tube is 500 mm, enough care has been taken to keep the groove exactly at the tube bottom. Provisions are made at one of the tube supports such that its height can be adjusted by providing holes at specific places to provide necessary tube inclination (0°, 3° and 6° with the horizontal).

Water is drained slowly and uniformly from the soft threads onto the horizontally supported HIF tube so that the whole of the tube is wetted. The position at which the water filled the inter-fin space (‘holdup line’ or ‘retention level’) is measured using the theodalite. In addition to the position
of the holdup line, the positions of the tube top and bottom are also measured to compute the flooding angle as shown in Figure 5.3. Measurements are made under static conditions (i.e., under non-condensing conditions) at atmospheric pressure. As the evaporation of water is not so significant at room, the measured water temperature at the condensate feeding tube is used for obtaining the properties of water. The locations of circumferential drainage ring are identified by continuously visualizing the drainage flow under various loading conditions and inclinations. Condensate drainage patterns are also observed by varying the condensate drainage rate.

![Figure 5.2 Schematic of experimental setup](image-url)

1 - Constant Head Tank
2 - Flow Control Valve
3 - Supports
4 - Condensate Feeding Tube
5 - Smooth Cotton Thread
6 - HIF Tube
7 - Condensate Collection Pan
Masuda and Rose (1987) have made extensive studies on the condensate retention over HIF tubes. They reported that the condensate is not only retained at the tube bottom but also retained in the form of ‘Liquid Wedges’ at the inter-fin space in the un-flooded region of the tube. Such liquid wedges are noticed in the present investigations as well.

5.5 RESULTS OF CONDENSATE RETENTION STUDY

Measurement of condensate retention is carried out in four different categories. First the tubes are kept horizontal and flooding angles are measured for the tubes without bottom groove and with different groove width. Then, circumferential drainage rings of various heights are inserted into tube-with optimum groove width and the flooding angles are measured to study the effect of ring height on condensate retention. Third, the tubes are kept little inclined (3° and 6° with respect to horizontal) and the effect of tube inclination on condensate retention is studied by varying the condensate loading condition. Fourth, circumferential drainage rings of optimum height are placed at suitable locations and the effect of inclination on condensate retention is studied.
retention is studied. The results of these categories are presented and discussed in the following sections.

5.5.1 Effect of Groove Width on Flooding Angle for Horizontal Tube Position

The tubes are kept perfectly horizontal and flooding angles are measured at various axial locations and then averaged. In case of tube-A, which has no bottom groove, the measured flooding angles at various axial locations differed less than one percent. It has demonstrated that the fins machined over the tube are of sufficient accuracy. In case of tubes with bottom groove (tube B to D), uniform condensate level is observed as the condensate level gets equalized through the bottom groove. Figure 5.4 presents the measured flooding angles against the groove width. The flooding angle obtained with tube-A is $80.65^\circ$. The flooding angle for this tube geometry has been calculated using the Rudy and Webb (1985) or Honda et al (1983) relation (chapter 2, equation (2.1)) by taking the properties of water at the temperature measured during the studies. It is observed that both the (measured and calculated) values agreed within 2%.

The effect of groove width on flooding angle is marginal when the tubes are kept horizontally. The flooding angles measured with tube-B (0.5 mm groove), tube-C (1.0 mm groove), and tube-D (1.5 mm groove) are 79.0°, 76.87° and 78.0° respectively. The drop in flooding angle is about 2%, 4.7% and 3.3% for tubes B, C and D respectively when compared to the tube-A. However, an interesting phenomenon is observed. Tube-B with 0.5 mm groove does not exhibit proper collection of condensate and the flooding angle is also slightly higher. The flooding angle obtained for the tube-C (1.0 mm groove width) is the lowest. Further increase in groove width increases the flooding angle. Hence the optimum groove width is 1.0 mm.
5.5.2 Effect of Circumferential Drainage Ring Height on Flooding Angle

As mentioned above, simply making groove at the bottom of the HIF tube does not help much in reducing the flooding level. Yau et al (1986), Sreepathi and Sukhatme (1991) have shown that the flooding level is found to drop with the increase in solid/porous longitudinal drainage strip height up to a certain maximum and any further increase in strip height has no impact on flooding. To overcome the difficulties of flat continuous strips and solid pin-type strips, circumferential drainage rings are tested in this investigation. Unlike the continuous solid or porous drainage strips, circumferential drainage rings may be positioned at any specified locations in the HIF tube. Effect of ring height on condensate flooding is studied. When the ring height is increased, the flooding angle decreases to a certain extent and then stays constant indicating that there exists an optimum ring height as shown in Figure 5.5. While testing with circumferential drainage rings of height less than 8 mm the drained condensate flows over the ring and passes to the next
region during higher flow rates. Flooding angle remains constant when the circumferential ring height is greater than 8.0 mm. So, for the present HIF tube-C, the optimum ring height is 8.0 mm. At this ring height, the drop in flooding angle is about 14.7% when compared to the tube without such rings. The condensate is found to drain from the bottom of the rings as droplets for lower water flow rates and as columns at higher flow rates.

![Figure 5.5 Effect of circumferential drainage ring height on flooding angle](image)

**Figure 5.5 Effect of circumferential drainage ring height on flooding angle**

5.5.3 **Effect of Tube Inclination on Flooding Angle**

Since both the above mentioned methods do not yield the expected results in reducing the condensate flooding, alternate means are explored. It is thought that when the finned tube having an axial groove of 1 mm at the bottom is kept little inclined, the condensate may flow along the groove and drain at the lower end. Such a technique may drain the condensate better and provide lower average flooding angle. Hence, the condensate retention measurements are carried out for all the four tubes with tube-inclinations ($\beta$)
ranging from $0^\circ$ to $6^\circ$. When the tube is kept inclined, one end of the tube will be at a lower elevation when compared to the other end. The location where the fins start at the upper end of the tube is referred as $x = 0$ and correspondingly the other end at the lower elevation is $x = L$ (where $L = 500.0$ mm in the present study).

The average flooding angle is calculated from the measured axial distribution of the local flooding angle. The variation of average flooding angle with tube inclination for each tube is shown in Figure 5.6. For the tube without slot (tube-A), average flooding angle stays constant with the tube inclination. The average flooding angle decreases almost linearly with the tube inclination for the tubes B, C and D. It is solely due to the drainage of the condensate along the bottom slot. When the tube inclination increases, the component of gravity force that moves the condensate along the slot also increases, which in turn drains the condensate better and results in lower average flooding angle.

At $\beta = 3^\circ$, the flooding angle decreases to a maximum of about 8% for tube-C when compared to tube-D. For tubes B and D, the flooding angles obtained are about 4% and 6.5% lower when compared to tube-A. When the tube inclination is increased further ($\beta = 6^\circ$), the tube-C yields the lowest average flooding angle when compared to other tubes. The flooding angles obtained with the tubes B, C and D are about 6, 13, and 10% lower when compared to tube-A for $6^\circ$ tube inclination. For the given tube inclinations, the tube with optimum groove width (1mm) are found to provide lowest flooding angle.
5.5.4 Study of Condensate Flooding Angle

The condensate flooding angle is measured in each case during dynamic conditions, (i.e) during simulated drainage conditions. In case of tubes without circumferential rings the flooding angle is measured at each 50 mm interval leaving the two ends. The variations between the values are minimal and the average is listed in Table 5.1. In case of tubes with drainage rings, the distance between the ring spacing is divided into six equal divisions and the flooding angles are measured at the middle 5 locations and the average values are reported.
Table 5.1 Condensate flooding angle for various tube inclinations

<table>
<thead>
<tr>
<th>Tube inclination</th>
<th>Circumferential drainage ring spacing, mm</th>
<th>Condensate flow rate, lpm*</th>
<th>Average flooding angle, degrees</th>
<th>% Reduction in flooding angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° without groove</td>
<td>-</td>
<td>0.2 – 0.8</td>
<td>80.65</td>
<td>-</td>
</tr>
<tr>
<td>0° with groove</td>
<td>-</td>
<td>0.2 – 0.8</td>
<td>76.87</td>
<td>4.7</td>
</tr>
<tr>
<td>3°</td>
<td>-</td>
<td>0.2 – 0.8</td>
<td>71.31</td>
<td>11.6</td>
</tr>
<tr>
<td>6°</td>
<td>-</td>
<td>0.2 – 0.8</td>
<td>70.12</td>
<td>13.0</td>
</tr>
<tr>
<td>3°</td>
<td>100</td>
<td>0.2 – 0.8</td>
<td>69.9</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>0.2 – 0.8</td>
<td>70.14</td>
<td>13.0</td>
</tr>
<tr>
<td>6°</td>
<td>100</td>
<td>0.2 – 0.8</td>
<td>68.54</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>0.2 – 0.8</td>
<td>68.78</td>
<td>14.7</td>
</tr>
</tbody>
</table>

* liters per minute

When the tube is horizontal, making a longitudinal groove tends to reduce the flooding angle by about 4.7%. When this grooved tube is kept inclined by 3° and 6°, the drop in flooding angle is 11.6% and 13.0% respectively. However, when drainage rings are added, with ring spacing of 100 mm and 125 mm, at 3° tube inclinations the drop in flooding angle is 13.2% and 13% respectively. Similarly with ring spacing of 100 mm and 125 mm and at 6° tube inclination the drop in flooding angle is 15.0% and 14.7% respectively. It is clearly evident that providing the circumferential rings not only control the drainage locations, it also results in reduction of flooding angle in-turn will enhance the heat transfer rate.

5.6 HEAT TRANSFER PERFORMANCE

Flooding angle measurements under simulated non-condensing conditions presented in the previous section has indicated that it is possible to reduce the condensate flooding by 15% with the present technique. However, the ability of the tubes under condensing conditions is predicted by using the
model developed in chapter 3. The prediction model has been developed based on empirical correlation of the available data. The model is validated against a wide range of experimental data and found to predict with in ±20% of the reliable data. A modification has been done in the model such that the measured flooding angles are used in case of the grooved tube and tubes with drainage rings for predicting the heat transfer coefficient. The results are presented in the following sections.

5.6.1 Prediction of Condensation Heat Transfer Coefficient

Heat transfer performance of the tube is predicted at horizontal orientation without groove, horizontal orientation with groove and grooved tube with 3°, 6° inclinations with horizontal provided with 4 and 5 circumferential rings. The predictions of the model for different cases are shown in Figure 5.7. The predicted heat transfer coefficient values are plotted in the form of \( h_p \) versus condensing side temperature difference (\( \Delta T \)).

For all the cases mentioned above, the heat transfer coefficient decreases with increase in condensing side temperature difference. The heat transfer coefficient and its percentage improvement are presented in the Table 5.2 for the different conditions investigated. The predictions of the model are shown in Figure 5.7.

At \( \Delta T=20 \text{ K} \), the heat transfer coefficient value of 45.73 kW/m²K is obtained in case of ordinary HIF tube. With the addition of longitudinal groove at the tube bottom, \( h = 47.45 \text{ kW/m}^2\text{K} \) (about 3.76% higher) is observed. With the addition of 4 circumferential rings (125mm ring spacing) and tube inclination the drainage is better, the tube flooding is reduced and the heat transfer coefficient values 50.51 kW/m²K and 51.13 kW/m²K are predicted, when the tube inclination is 3° and 6° respectively. Similarly on reducing the circumferential ring spacing to 100 mm the predicted heat
transfer coefficient for $3^\circ$ and $6^\circ$ tube inclination are $50.58 \text{ kW/m}^2\text{K}$ and $51.24 \text{ kW/m}^2\text{K}$ respectively. Hence, with 1 mm groove width, 100 mm ring spacing and $6^\circ$ tube inclination to the horizontal has produced 12.06% improvement in heat transfer coefficient.

**Figure 5.7** Prediction of the present general model for different cases

**Table 5.2** Predicted heat transfer coefficient and its percentage improvement

<table>
<thead>
<tr>
<th>Tube inclination</th>
<th>Drainage ring spacing, mm</th>
<th>Condensate flow rate, lpm</th>
<th>$h$, kW/m$^2$K at $\Delta T = 20$K</th>
<th>% Improvement in heat transfer coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ$ without slot</td>
<td>-</td>
<td>0.2 – 0.8</td>
<td>45.73</td>
<td>-</td>
</tr>
<tr>
<td>$0^\circ$ with slot</td>
<td>-</td>
<td>0.2 – 0.8</td>
<td>47.45</td>
<td>3.76</td>
</tr>
<tr>
<td>$3^\circ$</td>
<td>-</td>
<td>0.2 – 0.8</td>
<td>49.98</td>
<td>9.3</td>
</tr>
<tr>
<td>$6^\circ$</td>
<td>-</td>
<td>0.2 – 0.8</td>
<td>50.52</td>
<td>10.48</td>
</tr>
<tr>
<td>$3^\circ$</td>
<td>100</td>
<td>0.2 – 0.8</td>
<td>50.58</td>
<td>10.61</td>
</tr>
<tr>
<td>$3^\circ$</td>
<td>125</td>
<td>0.2 – 0.8</td>
<td>50.51</td>
<td>10.46</td>
</tr>
<tr>
<td>$6^\circ$</td>
<td>100</td>
<td>0.2 – 0.8</td>
<td>51.24</td>
<td>12.06</td>
</tr>
<tr>
<td>$6^\circ$</td>
<td>125</td>
<td>0.2 – 0.8</td>
<td>51.13</td>
<td>11.82</td>
</tr>
</tbody>
</table>
5.6.2 Effect of Tube Inclination on Surface Heat Transfer Coefficient Enhancement and Surface Heat Transfer Coefficient Augmentation

The effect of tube inclination on the heat transfer enhancement ratio ($\varepsilon_{\Delta T}$) at $\Delta T = 20$ K is shown in Figure 5.8. The heat transfer enhancement ratios are calculated when compared to the plain tube (of 23.4 mm outer diameter) data obtained using the Nusselt equation (equation (5.1)) at $\Delta T = 20$ K. The heat transfer enhancement ratio obtained with the tube-A is about 4.24 and remains constant for all the tube inclinations. In case of other tubes, as the groove drains the condensate better, the heat transfer enhancement ratio increases with increase in tube inclination. The HIF tube with bottom groove and five circumferential drainage rings give the highest heat transfer enhancement ratio of 4.75 when the tube inclination is 6°.

$$h = 0.725 \cdot \left[ (\rho^2 g K^3 h_{fg}) / (\mu d \Delta T) \right]^{0.25}$$  \hspace{1cm} (5.1)

**Figure 5.8** Variation of $\varepsilon_{\Delta T}$ with tube inclination at $\Delta T = 20$ K
Variation of heat transfer augmentation (i.e., the heat transfer performance of tubes when compared to tube-A) with tube inclination at $\Delta T = 20$ K is shown in Figure 5.9. The tubes provide significant heat transfer augmentation when they are kept inclined. It is possible to augment the condensation heat transfer rate by about 12% by making an axial groove at the finned tube bottom and keeping the tube inclined by 6° with respect to horizontal. A comparison has been made in Table 5.3 with the heat transfer performance of other drainage mechanisms. It can be noticed that the present technique overcomes the difficulties of solid and porous drainage discs and gives an augmentation greater than 10%.
Table 5.3  Comparison of condensate retention reduction capability of the present technique with other methods

<table>
<thead>
<tr>
<th>S. No</th>
<th>Investigation</th>
<th>Drainage mechanism</th>
<th>Fluid</th>
<th>Fin spacing, mm</th>
<th>Heat transfer augmentation obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Honda et al (1983)</td>
<td>Porous drainage strip, Nickel*, 1.9 mm thick, 16 mm height, 0.8mm effective pore diameter</td>
<td>R113</td>
<td>0.39</td>
<td>36%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Methanol</td>
<td>0.46</td>
<td>108%</td>
</tr>
<tr>
<td>2</td>
<td>Yau et al (1986)</td>
<td>Solid drainage strip, Copper*, 2 mm thick, 8.0 mm height</td>
<td>Water</td>
<td>1.5</td>
<td>25%</td>
</tr>
<tr>
<td>3</td>
<td>Yanzhong and Qinjin (1986)</td>
<td>Solid drainage strip, Copper*, 5 - 8 mm height, 1.0 mm thick</td>
<td>R11</td>
<td>0.68</td>
<td>20%</td>
</tr>
<tr>
<td>4</td>
<td>Sreepathi and Sukhatme (1991)</td>
<td>Solid drainage strip, Copper*, 1.0 mm thick, 8.0 mm height, porous drainage strip, Copper*, 1.5 mm thick, 8.5 mm height, 0.1 mm effective pore diameter</td>
<td>R11</td>
<td>0.30</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R11</td>
<td>0.30</td>
<td>10%</td>
</tr>
<tr>
<td>5</td>
<td>Trela and Butrymowicz (1999)</td>
<td>Brass tube, Solid drainage strip, Copper*, 1.0 mm thick and 4.0 mm height.</td>
<td>R11</td>
<td>0.5</td>
<td>19%</td>
</tr>
<tr>
<td>6</td>
<td>Present study</td>
<td>Circumferential drainage rings of 8mm height, Machining an axial groove of 1 mm width at the bottom of the finned tube and keeping the tube inclined by 6° with the horizontal.</td>
<td>Water</td>
<td>1.2</td>
<td>12%</td>
</tr>
</tbody>
</table>

* Strip material
5.7 STUDY OF CONDENSATE DRAINAGE PATTERN

The condensate drainage patterns recorded with digital camera are shown in Figures 5.10 to 5.37. The experiments are carried out with simulated condensate flow rates of 0.2 lpm, 0.4 lpm, 0.6 lpm and 0.8 lpm, without tube inclinations and with tube inclinations of 3° and 6° to horizontal. In each case, the tube without circumferential drainage rings and with rings are tested.

5.7.1 Drainage Pattern for the Horizontal Tube

In case of horizontal position, at 0.2 lpm flow rate, the condensate mostly drains drop by drop as shown in Figure 5.10. The locations of origination of drops are random. When the flow rate is increased to 0.4 lpm, the condensate drains either as drops or as discontinuous columns. The location of drainage is also at random as shown in Figure 5.11. If the flow rate is increased to 0.6 lpm, the condensate drains as discontinuous columns. The location of each column is random. At 0.8 lpm flow rate, continuous columns at almost regular intervals are observed. The drainage pattern for 0.6 lpm and 0.8 lpm are shown in Figures 5.12 and 5.13 respectively.
Figure 5.10  Drainage pattern on a horizontal tube with condensate flow rate of 0.2 lpm

Figure 5.11  Drainage pattern on a horizontal tube with condensate flow rate of 0.4 lpm
Figure 5.12  Drainage pattern on a horizontal tube with condensate flow rate of 0.6 lpm

Figure 5.13  Drainage pattern on a horizontal tube with condensate flow rate of 0.8 lpm
5.7.2 Drainage Pattern for the Inclined Tube Without Drainage Rings

In horizontal condensers with plain and HIF tubes, considerable efforts (Honda et al (1989), Hu and Jacobi (1996a, b)) were made to understand the condensate drainage behaviour. In these studies, importances were given to understand the condensate drainage and its impact on heat transfer performance. Efforts were made to predict how and where the condensate would drain naturally by itself. No effort has been made to control or dictate where should the condensate drain and how. In real condensers where bank of tubes is the reality, such an approach will provide a direction to reduce condensate inundation effects to a larger extent. As discussed in section 5.5.3 tube inclination has made remarkable contribution in reducing the flooding angle. Hence study of drainage pattern on a grooved tube with 3º and 6º inclination with horizontal under different loading conditions is used to identify the location of drainage.

When the tube is kept at 3º inclination with horizontal, at 0.2 lpm, the drainage is only at lower most end (right end) of inclined tube, as shown in Figure 5.14. When the flow rate is increased to 0.4, 0.6 and 0.8 lpm, the drainage pattern observed are shown in Figures 5.15 to 5.17 respectively. At 0.4 lpm, major portion of the condensate drains at the lower most end of the tube. However, intermittent drop / column mode drainage is seen at random in the other regions. When the flow rate is further increased to 0.6 lpm and 0.8 lpm more and more intermittent condensate locations are observed.
Figure 5.14  Drainage pattern on 3° inclined tube with a condensate flow rate of 0.2 lpm

Figure 5.15  Drainage pattern on 3° inclined tube with a condensate flow rate of 0.4 lpm
Figure 5.16  Drainage pattern on 3° inclined tube with a condensate flow rate of 0.6 lpm

Figure 5.17  Drainage pattern on 3° inclined tube with a condensate flow rate of 0.8 lpm
The tubes are then kept at 6° inclination with horizontal and the experiments are repeated. The drainage patterns are shown in Figures 5.18 to 5.21. At 0.2 lpm, drainage is only at the lower most end of the tube. At 0.4 lpm, the drainage is similar to 0.2 lpm, but few intermediate column mode drainages are also noticed. At 0.6 lpm, apart from column drainage at right end, additional column mode drainage is also observed. At 0.8 lpm more intermediate column mode drainages are noticed.

From the observations, it can be pointed out that when tubes are kept inclined the condensate at the tube bottom moves along the bottom groove from the higher location to the lower location (left to right in the present tube arrangement) by gravity. If the inclination is more, such a movement is also more because of the increased action of gravity force.

![Figure 5.18 Drainage pattern on 6° inclined tube with a condensate flow rate of 0.2 lpm](image_url)
Figure 5.19 Drainage pattern on 6° inclined tube with a condensate flow rate of 0.4 lpm

Figure 5.20 Drainage pattern on 6° inclined tube with a condensate flow rate of 0.6 lpm
5.7.3 Drainage Pattern for the Inclined Tube Fitted with Drainage Rings

Mori et al (1981), while focusing on the vertical fluted tubes, suggested that circumferential drainage rings could be placed horizontally at regular heights for effective removal of the condensate. Such rings would collect the condensate at regular intervals and drains it sideways which in-turn reduces the average condensate thickness over the tube and increases the heat transfer rate. In case of horizontal tubes, such an arrangement is not possible with the conventional HIF or plain tubes. However, for a tube (either plain or integral finned) with a longitudinal groove at the tube bottom when kept little inclined (as used in the present investigation), it is possible to place such circumferential drainage rings at predetermined axial locations and the condensate can be made to drain at these locations. If the spacing between the
rings is suitably adjusted, depending on the condensing conditions, all the condensate formed over the tube surface, between the rings may drain at the ring locations, and thus reduce the condensate flooding portion in the other regions. It may result in increased condensation rates. This may help very much in fixing the drainage locations, and some kind of controls or collection methods may be thought of to reduce the condensate inundation effects in case of tube bundles in real condensers. To understand such effects, experiments are carried out using tubes fitted with circumferential drainage rings.

For the tubes with 3° and 6° inclinations, the drainage rings with spacing of 100 mm (5 rings for 500 mm tube length), 125 mm (4 rings for 500 mm tube length) are tested. Figures 5.22 to 5.25 show the drainage pattern for 3° tube inclinations and 125mm ring spacing. In most of the cases, as pointed out earlier, the condensate is found to drain at the locations where the circumferential rings are provided. These rings found to act as stoppers and block the further movement of the condensate along the bottom groove. Thus the condensate collected between the rings drains at these ring locations. When the flow rate is increased from 0.2 lpm to 0.8 lpm in each case, at the ring locations, the condensate drains as drops, discontinuous columns and as continuous columns. With 3° tube inclinations some intermittent drop mode drainage is also observed due to reduced gravity at less degree of inclination. For 6° tube inclinations, the drainage patterns are shown in Figures 5.26 to 5.29. No drains of condensate are observed at intermittent locations for all the condensate flow rates.
Figure 5.22  Drainage pattern on 3° inclined tube with a condensate flow rate of 0.2 lpm and 125 mm ring spacing

Figure 5.23  Drainage pattern on 3° inclined tube with a condensate flow rate of 0.4 lpm and 125 mm ring spacing
Figure 5.24  Drainage pattern on 3º inclined tube with a condensate flow rate of 0.6 lpm and 125 mm ring spacing

Figure 5.25  Drainage pattern on 3º inclined tube with a condensate flow rate of 0.8 lpm and 125 mm ring spacing
Figure 5.26  Drainage pattern on 6° inclined tube with a condensate flow rate of 0.2 lpm and 125 mm ring spacing

Figure 5.27  Drainage pattern on 6° inclined tube with a condensate flow rate of 0.4 lpm and 125 mm ring spacing
Figure 5.28  Drainage pattern on 6° inclined tube with a condensate flow rate of 0.6 lpm and 125 mm ring spacing

Figure 5.29  Drainage pattern on 6° inclined tube with a condensate flow rate of 0.8 lpm and 125 mm ring spacing
To avoid such intermediate drainages noticed, the spacing between the rings is reduced from 125 mm to 100 mm and the experiments are repeated. The drainage pattern for 100 mm ring spacing with 3° and 6° tube inclinations are shown in Figures 5.30 to 5.33 and Figures 5.34 to 5.37 respectively. As expected, with lower ring spacing, the intermediate drainage is avoided even up to 0.8 lpm condensate feeding rate. With higher tube inclination, it is sufficient to have lower number of rings. From these observations, it is understood that providing such circumferential drainage rings at suitable spacing, over the HIF tubes with bottom longitudinal groove, the condensate drainage locations can be fixed. Such a control of the drainage locations can be used to reduce condensate inundation effects, in actual condensers, where bundle of tubes are used.

![Drainage pattern on 3° inclined tube with a condensate flow rate of 0.2 lpm and 100 mm ring spacing](image)

**Figure 5.30** Drainage pattern on 3° inclined tube with a condensate flow rate of 0.2 lpm and 100 mm ring spacing
Figure 5.31  Drainage pattern on 3° inclined tube with a condensate flow rate of 0.4 lpm and 100 mm ring spacing

Figure 5.32  Drainage pattern on 3° inclined tube with a condensate flow rate of 0.6 lpm and 100 mm ring spacing
Figure 5.33  Drainage pattern on 3° inclined tube with a condensate flow rate of 0.8 lpm and 100 mm ring spacing

Figure 5.34  Drainage pattern on 6° inclined tube with a condensate flow rate of 0.2 lpm and 100 mm ring spacing
Figure 5.35  Drainage pattern on 6° inclined tube with a condensate flow rate of 0.4 lpm and 100 mm ring spacing

Figure 5.36  Drainage pattern on 6° inclined tube with a condensate flow rate of 0.6 lpm and 100 mm ring spacing
Figure 5.37  Drainage pattern on 6° inclined tube with a condensate flow rate of 0.8 lpm and 100 mm ring spacing

5.8 CONCLUDING REMARKS

Though the surface tension provides significant heat transfer enhancement, during condensation over HIF tubes in the un-flooded upper portions of the tube, it adversely affects the heat transfer due to condensate flooding at the tube bottom. The effect of condensate flooding is more significant with high surface tension fluids like water. Thus, it is not possible to use fin spacing below 0.7 mm for steam condensers. Hence, condensate flooding needs to be reduced by suitable means. Some of the previous investigators, have attached either solid or porous drainage discs at the tube bottom and reported heat transfer augmentation of 10 ~ 25% (during condensation of steam) when compared to the tubes without such discs. However, such strips are not used in practical condensers because of three major reasons, viz., (i) use of such strips makes fabrication much complicated, (ii) use of drainage strips increases the vertical distance between
the tubes which makes shell size larger and is not desirable, and (iii) vapour shear over the surfaces of the drainage strips increases the vapour-side pressure drop which is not at all desired as it is one of the critical design parameters in most of the cases.

It has been shown by condensate flooding level measurements that by making an axial groove at the finned tube bottom and keeping the tube inclined by 6° with respect to horizontal, it is possible to reduce condensate flooding by 15%. Heat transfer predictions have shown 12% augmentation when compared to a HIF tube of same dimensions without such groove and tube inclination. In addition, it is evident that by properly placing the circumferential drainage rings at strategic locations, it is possible to control the condensate drainage, by which the condensate inundation effects could be minimized significantly in practical condensers.

In case of bank of tubes, this concept can be used to control the location of condensate drainage. It will leave the other regions of the tubes at the bottom rows unaffected and these regions of the tubes will function as the top row tubes without any condensate inundation effects. This will increase the heat transfer performance to a larger extent. However, more researches need to be done to quantify these aspects properly, with bundle of tubes.