CHAPTER-5
EXPERIMENTAL RESULTS OF
CONDENSATE RETENTION REDUCTION STUDY

During condensation over HIF tubes, though the surface tension forces play a
major role in the heat transfer enhancement process in the unflooded upper region of
the tube, the surface tension shows its adverse effect in the form of condensate
retention at the tube bottom. As discussed in section 2.3, attempts have been made by
earlier investigators to reduce the condensate retention by attaching either solid or
porous drainage strips at the tube bottom. It has proved to be worthy in single tube
experiments. The only question is how to use such drainage strips in practical
condensers where bank of tubes is common. 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
without 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. This chapter presents these details.

5.1 THE CONDENSATE RETENTION REDUCTION TECHNIQUE

When the 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. In case of porous drainage strips with smaller pore
diameters (Honda et al, 1983), it is observed that the capillary suction created by the
pores suck the condensate into the pores from the bottom of the tube. The Darcy’s law governs the further drainage of the condensate inside the porous strip. The condensate finally drains from the bottom of the porous strip by gravity. It has given a fair idea that 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. It was thought that by making a longitudinal slot at the bottom of the tube would provide a room for the collection of the condensate. Keeping the tube slightly inclined will enable the gravity force to move the condensate along the slot axially. This may reduce the condensate flooding significantly. Hence, such an idea has been implemented and condensate-flooding angles are measured using a setup made for this purpose. The slot width and the inclination of the tube are the parameters that decide the level of flooding under such circumstances. Hence, the HIF tubes with similar fin geometry, but with different slot 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.

5.2 TUBE DETAILS

The commercially available copper tubes having 18.0 mm inner diameter and 3.0 mm wall thickness are employed. Rectangular circumferential fins having 1.0 mm thickness and 1.0 mm fin height with a fin spacing of 1.3 mm are precisely machined. It results in HIF tubes with 22.0 mm diameter at fin root. The finned length is kept as 240 mm for condensate retention measurements, as this is the minimum length needed for fixing the tube in the condenser setup for heat transfer measurements. As the heat transfer measurements are carried out using the experimental setup described earlier for the fin height study, the finned length has been reduced to 120 mm (during heat transfer measurements) by machining the fins at both the ends of the tubes after
condensate retention measurements. Four such HIF tubes are made. A Longitudinal slot of 1.0, 2.0 and 3.0 mm width are machined at the bottom of the three tubes and are referred as tube-A, B and C respectively. The fourth tube is left as it is, i.e., without any slot for comparison purpose and is referred as tube-D. The tube inclinations are varied in the range of 0° to 5° with respect to horizontal in order to study the effect of tube inclination.

5.3 EXPERIMENTAL SETUP FOR THE LIQUID RETENTION MEASUREMENTS

The experimental set up used for liquid retention (flooding angle) measurement is similar to the one described in Yau et al (1986). This simple apparatus is shown in Fig.5.1. The apparatus consists of a tank (to supply the distilled water), a supply pipe with holes at the top and a soft cloth (to distribute water uniformly), a horizontally supported HIF tube (on which the liquid retention measurements are to be made), and a Vernier height gauge with an accuracy to measure 0.01 mm fitted with a travelling microscope having 10X magnification with cross wires (to measure the level of flooding with respect to the tube bottom).

Water is drained slowly and uniformly from the cloth 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 height gauge. In addition to the position of the holdup line, the positions of the tube top and bottom level are also measured to compute the flooding angle as shown in Fig.5.2. 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 supply pipe is used for obtaining the properties of water. Flooding angle is measured with and without simulated water flow over the tube. No appreciable change in the liquid retention level is noticed between these two cases. Rudy and Webb (1985) and Yau et al (1986) have also reported similar observations. Condensate drainage patterns are also observed under various condensate loading conditions by varying the water flow rate.
1. Supports
2. Tank
3. Flow control valve
4. Supply tube with holes
5. Fine mesh cotton cloth
6. Vernier height gauge
7. Magnification lens (10X)
8. HIF tube supports
9. Slip gauge arrangement
10. Surface plate

(Figure is not to scale)

Fig. 5.1. Apparatus for liquid retention measurement

Fig. 5.2. Method of measurement of flooding angle
The horizontal distance between the two supporting points of the test tube is 260 mm whereas the finned length of the tube is 240 mm. Enough care has been taken to keep the slot exactly at the tube bottom. The entire setup is placed over the surface plate for perfect flatness and the surface plate is kept perfectly horizontal. Provisions are made at one of the tube supports such that its height can be adjusted by placing the slip gauges (having an accuracy of 1.0 \( \mu \text{m} \)) under it, in order to provide necessary tube inclination (0 to 5° with the horizontal). The tube inclination is also cross verified by measuring the rise in level of the tube top surface over a fixed horizontal distance of 200 mm. The travelling microscope fitted in the Vernier height gauge can be rotated with respect to its axis so that the cross wires can be aligned over the condensate retention line. This makes the condensate retention measurements easier when the tube is kept inclined. The travelling microscope has 10X magnification which helps in viewing the flooded and unflooded zones of the tube clearly. 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 unflooded region of the tube. Such liquid wedges are clearly noticed in the present investigations as well. However they are not quantified because the present objectives are different. For tubes with inclination, both axial location and the respective flooding angle are measured to calculate the average flooding angle.

5.4 RESULTS OF CONDENSATE RETENTION STUDY

Three categories of measurements are carried out. First the tubes are kept horizontal and flooding angles are measured. Then, pin-type drainage strips of various heights are placed within the slot of tube-C and the flooding angles are measured to study the effect of strip height on condensation retention. Finally, the tubes (without any drainage strips) are kept little inclined (about 1 – 5° with respect
to horizontal) and the effect of tube inclination on condensate retention is studied. The results are presented and discussed here.

5.4.1 Effect of slot width on flooding angle (when the tubes are in horizontal position)

The tubes are kept perfectly horizontal and flooding angles are measured at various axial locations and then averaged. In case of Tube-D, which has no bottom slot, 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 slot (Tube-A to C), uniform condensate level is observed as the condensate level gets equalized through the bottom slot. Fig. 5.3 presents the measured flooding angles against the slot width. The flooding angle obtained with tube-D is 77.54°. The flooding angle for this tube geometry has been calculated using the Rudy and Webb (1985) or Honda et al (1983) relation (chapter 2, Eqn. 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 3.0%.

The effect of slot width on flooding angle is marginal when the tubes are kept horizontally. The flooding angles measured with tube-A (1.0 mm slot), tube-B (2.0 mm slot), and tube-C (3.0 mm slot) are 73.51, 76.34 and 76.9° respectively. The drop in flooding angles are about 5.2 %, 1.5 % and 0.8 % for tubes A, B and C respectively when compared to the tube-D. However, an interesting phenomenon is observed. The flooding angle obtained for the tube-A (which has the lowest slot width) is the lowest. The flooding angle increases with the increase in slot width and tends to attain the value of the tube-D which has no slot.
Fig. 5.3. Effect of slot width on flooding angle (for horizontal tube orientation)

Fig. 5.4. Effect of drainage strip height on flooding angle (for tube C with horizontal orientation)
When the flooding angle data obtained with the tubes A to C are correlated in a second order polynomial form: $\phi_f = a_1(w)^2 + a_2(w) + a_3$ (where $\phi_f$ in degree and $a_1$, $a_2$ and $a_3$ are the correlation constants), an exact fit with the correlation coefficient $R^2 = 1$ is obtained. The values of the constants obtained are $a_1 = -1.135$, $a_2 = 6.245$ and $a_3 = 68.39$. When this relation is differentiated with respect to 'w' and equated to zero, the magnitude of slot width obtained is 2.75 mm. It indicates that when the slot widths are beyond 2.75 mm, the impact of slot width on the condensate-flooding angle can be neglected.

While studying the condensate drainage patterns, the condensate is found to drain drop by drop when the simulated water flow rates are lower. The droplets originate at different axial location at different times and do not follow any definite pattern. When the flow rate is increased, the water is found to drain as columns at distinct axial locations. When the flow rate is increased further, the number of column increases and the columns tend to merge and form the column and sheet mode. Further increase in water flow rate results in sheet mode drainage (of the condensate). Similar observations are reported by Honda et al (1989) as well.

5.4.2 Effect of (pin-type) drainage strip height on flooding angle

As mentioned above, simply making the slot at the bottom of the HIF tube does not help much in reducing the flooding level. Yau et al (1986) and Sreepathi and Sukhatme (1991) have shown that the use of flat solid drainage strips can reduce flooding considerably. The flooding level is found to drop with the increase in strip height upto a certain maximum and any further increase in strip height has no impact on flooding. Instead of flat continuous strips, the solid pin-type strips are tested in this investigation. The strips are cut from a 3.0 mm diameter copper wire. These pin-type strips are placed vertically downwards at the bottom slot of the tube-C. Effect of strip spacing (i.e., the axial distance between the strips) and strip height on condensate flooding are studied. The strip spacing is varied as 10, 20, and 30 mm. For the given strip height, the flooding angles observed with the three strip spacing are almost the
same, i.e., the strip spacing does not influence flooding angle. When the strip height is increased, the flooding angle decreases to a certain extent and then stays constant indicating that there exists an optimum strip height as shown in Fig.5.4. For the present HIF tube-C, the optimum strip height is 20.0 mm. At this strip height, the drop in flooding angle is about 5.0 % when compared to the tube without such strips. The condensate is found to drain from the bottom of the strips as droplets for lower water flow rates and as columns at higher flow rates.

5.4.3 Axial variation of flooding angle with tube inclination

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 slot at the bottom is kept little inclined, the condensate may flow along the slot 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 (β) ranging from 0 to 5°. 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 lower end of the tube is referred as x = 0 and correspondingly the other end at the higher elevation is x = L (where L = 240.0 mm in the present study). Fig.5.5 shows the axial variation of the flooding angle, obtained with Tube-A, for various tube inclinations.

When the tube is kept horizontal (β = 0°), there is no axial variation of the flooding angle. As expected, significant reduction in the flooding level has been obtained when the tube is kept inclined. The flooding level is found to vary almost linearly along the axial distance. The condensate near the higher end (x/L = 1.0) is found to drain along the slot axially resulting in lower flooding levels there. The
Fig. 5.5. Axial variation of flooding angle with tube inclination for tube-A

Fig. 5.6. Variation of average flooding angle with tube inclination
flooding angle obtained at the lower end \((x/L = 0)\) are also lower than that obtained with the horizontal orientation of the tube. Both these aspects have ultimately resulted in lower average flooding angle. The flooding angle at any given axial location decreases with the increase in tube-inclination. Similar behaviour is observed for tube-B and C.

5.4.4 Effect of tube inclination on average flooding angle

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 Fig.5.6. For the tube without slot (tube-D), average flooding angle stays constant with the tube inclination. The average flooding angle decreases almost linearly with the tube-inclination for the tubes A, B, and C. 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 increases, which in turn drains the condensate better and results in lower average flooding angle.

At \(\beta = 1^\circ\), the flooding angle decreases by about 18 % for all the three tubes when compared to the tube-D. When the tube inclination is increased further, the rate of decrease in average flooding angle for the three tubes differ considerably. The tube with 1.0 mm slot (tube-A) yields the lowest average flooding angle when compared to the rest of the two. For the given tube inclination, the tube with the lowest slot width is found to provide lowest flooding angle. The average flooding angle is found to increase with the increase in slot width over the range of slot widths studied. At \(\beta = 5^\circ\), the flooding angles obtained with the tubes A, B, and C are about 40, 36, and 32 % lower when compared to tube-D.

It is generally known from the (gravity driven) open channel flow that when the width of the channel is larger, drainage will be better as the resistance to flow is less.
In the present investigation, exactly opposite phenomenon is observed. It provides a room to think that some other force(s) assists in moving the condensate along the bottom slot in addition to gravity when the tube is kept inclined. It is to be remembered that the capillary rise in the space between the fins due to surface tension is responsible for condensate retention. The extent of flooding increases with the decrease in the fin spacing. The present condensate retention measurements obtained with the tubes A to C (when kept inclined) also show a similar aspect, i.e. for a given tube inclination when the slot width decreases, the drainage is better and hence the flooding angle decreases. It casts that the additional force could be due to the surface tension effect.

When a solid drainage strip is attached to the bottom of the finned tube, the curvature of the condensate is changed from convex to concave at the meeting line (between the tube and strip). It disturbs the force balance between the surface tension and gravity forces which establishes the flooding angle favourably to yield lower flooding angle. The slot machined at the tube bottom appears to serve as a source of such disturbance in case of the tubes A to C. It is observed from the Fig.5.3 that though the slot makes certain impact on the flooding angle, it is not so significant when the tubes are kept horizontally. The reason for which is that there exists no mechanism that will remove the condensate continuously once it fills the slot. When the tubes are kept inclined, the component of gravity force parallel to the tube axis does this job, i.e., it continuously drains the condensate along the slot. With the increase in tube inclination, the component of gravity that moves the condensate along the slot increases which results in better drainage. Thus, for the given slot width, the average flooding angle decreases with increase in tube inclination as shown in Fig.5.6. Once the condensate entered into the slot is removed, the slot tends to become empty, wherein significant change in condensate film curvature takes place. This reduces the net upward surface tension force and results in lower flooding level. For the tubes with narrow slot, the rate of change of film curvatures is more and hence, the larger reduction in the condensate retention level is obtained. Thus, for the
given tube inclination, the average flooding angle decreases with the decrease in slot width as shown in Fig.5.6.

In general, the action of surface tension force is responsible for the condensate flooding at the bottom of the tube. By making a narrow longitudinal slot and by keeping the tube little inclined (about 5° with the horizontal), the same surface tension force is effectively used for the better drainage of condensate along the slot, which ultimately reduces the condensate flooding.

Condensate drainage patterns for various simulated condensation rates are studied. As discussed earlier, the condensate drains at various intermediate locations, when the tubes are kept horizontally. The condensate drained as droplets, columns, column and sheets or as a sheet depending upon the simulated flow rate maintained over the tube. When the tube with the slot is kept inclined, for all the condensate loading conditions tested, the condensate drains only as columns and neither the droplet mode nor the sheet mode is observed. A column of drainage is observed at the lower end of the tube (i.e. at x/L=0) for all the flow rates tested. At lower flow rates, only this column is observed.

When the water flow rate is increased, the condensate drainage starts after a considerable distance from the upper end (x/L = 1.0) of the tube as a new column. Then the column travels along the tube bottom axially up to the x/L = 0 and merges with the column already exists there. The distance between the upper end of the tube and the place of origin of the new column decreases with the increase in the rate condensate loading. The number of columns originate, travel and merge, and the number of columns present at any given instant of time, increases with the increase in condensate loading. The number of columns at any given instant varied from 1 to 3 depending upon the simulated flow rate maintained over the present tube length of 240.0 mm. The number that will exist at the given instant may be larger for practical condensers where the tube lengths are longer.
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, importance was given to understand how the condensate drains and what is their 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.

Mori et al (1981), while focussing on the vertical fluted tubes, suggested that circumferential discs could be placed horizontally at regular heights for effective removal of the condensate. Such discs 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 slot at the tube bottom when kept little inclined (as used in the present investigation), it is possible to place such circumferential disc at predetermined axial locations and condensate can be made to drain at these locations. In case of bank of tubes, the designer can use this concept 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 and reduce the size of horizontal surface condensers significantly. However, more researches need to be done to properly quantify these aspects.

5.5 RESULTS OF THE HEAT TRANSFER STUDY

Flooding angle measurements under simulated, non-condensing conditions has indicated that it is possible to reduce the condensate flooding by 30 ~ 40 % with the
present method. However, the ability of the tubes under real condensing conditions is to be tested. It has been carried out using the same experimental setup (discussed in chapter-3) that was fabricated to study the effect of the fin height. The experimental observations and the results obtained after data reduction are listed in Appendix-II. These results are presented and discussed here.

5.5.1 Variation of condensation heat transfer coefficient with $\Delta T_v$

Heat transfer performance of each tube is tested at horizontal orientation and with $\beta = 1, 3$ and $5^\circ$. Enough care has been exercised for keeping the slot exactly at the tube bottom. The tubes are mounted co-axially in the shell and by tilting the shell, necessary tube inclination is provided. Five readings are taken for each case covering the $\Delta T_v$ range of 10 to 30 °C. The heat transfer results are plotted in the form of $h_e$ against $\Delta T_v$ for tube-A, B, and C in the Fig.5.7, Fig.5.8 and Fig.5.9 respectively. In case of tube-D, the heat transfer results obtained are essentially the same for all the tube inclinations. The tube-D data are also presented in these figures for comparison purposes. The value of $h_e$ decreases with $\Delta T_v$ for all the tubes. The trends of variation are almost similar for all the tube inclinations tested.

The values of the condensing-side heat transfer coefficient varied in the range of $36 \sim 46$ kW/m$^2$K for the $\Delta T_v$ range of 10 $\sim$ 30 K in case of tube-D which is the lowest performer among the tubes tested. The tube-A with $\beta = 5^\circ$ gives the best performance for which $h_e$ varied in the range of $50 \sim 62$ kW/m$^2$K over the same $\Delta T_v$ range. The highest condensation heat transfer coefficient of $62,124$ W/m$^2$K (at $\Delta T_v = 11.2$ K) is obtained with tube-A when provided with a tube inclination of $\beta = 5^\circ$.

The experimental data are correlated in a dimensional form as $h_e = a (\Delta T_v)^n$ ; where $h_e$ is expressed in W/m$^2$K. The value of the constants ‘a’ and ‘n’ are listed in Table.5.1. It can be noted that the value of index ‘n’ varied in the range 0.22 to 0.27
Fig. 5.7. Variation of $h_e$ with $\Delta T_v$ for various tube inclinations (Tube-A)

Fig. 5.8. Variation of $h_e$ with $\Delta T_v$ for various tube inclinations (Tube-B)
Fig. 5.9. Variation of $h_*$ with $\Delta T_v$ for various tube inclinations (Tube-C)

Fig. 5.10. Variation of $h_e$ with tube inclination at $\Delta T_v = 20$ K
that are almost close to the Nusselt value (n = 0.25) for the plain tubes. It can be noticed that for the tubes used in the fin height study, the index ‘n’ varied near 0.1. Both the experiments were carried out in the same setup under similar conditions. The reasons for these variations are not clear. Similar observations are reported by Briggs et al (1992) wherein the exponent ‘n’ varied widely in the range of 0.05 ~ 0.5.

TABLE-5.1 Correlation of Experimental Results of the Condensate Retention Reduction Study

<table>
<thead>
<tr>
<th>β</th>
<th>Tube-A</th>
<th>Tube-B</th>
<th>Tube-C</th>
<th>Tube-D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>n</td>
<td>a</td>
<td>n</td>
</tr>
<tr>
<td>0°</td>
<td>85567</td>
<td>0.2414</td>
<td>85865</td>
<td>0.2550</td>
</tr>
<tr>
<td>1°</td>
<td>93960</td>
<td>0.2436</td>
<td>96095</td>
<td>0.2555</td>
</tr>
<tr>
<td>3°</td>
<td>95636</td>
<td>0.2255</td>
<td>102320</td>
<td>0.2507</td>
</tr>
<tr>
<td>5°</td>
<td>109210</td>
<td>0.2376</td>
<td>109360</td>
<td>0.2479</td>
</tr>
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</table>

\[ h_e = a (\Delta T_v)^{-n} \quad h_e \text{ in W/m}^2\text{K,} \quad \Delta T_v \text{ in kelvin or } ^\circ\text{C} \quad R^2 = 0.96 \sim 0.99 \]

5.5.2 Effect of tube inclination on condensation heat transfer coefficient

The values of \( h_e \) for various tube inclinations at \( \Delta T_v = 20 \) K are plotted in Fig.5.10. There is no variation of \( h_e \) with ‘β’ incase of tube-D which has no slot. For the tubes with slot (A, B and C), \( h_e \) increases with increase in ‘β’. The rate of increase in \( h_e \) decreases with increase in ‘β’, and becomes almost flat near \( β = 5^\circ \). Thus, the optimum tube inclination appears to be around 5°. When these data (excluding the data at \( β = 0 \)) are correlated in the form of a second order polynomial as: \( h_e = a_1(β)^2 + a_2(β) + a_3 \), (where \( h_e \) in W/m\(^2\)K and \( a_1, a_2, \) and \( a_3 \) are the correlation constants), an exact fit with the correlation coefficient \( R^2 = 1 \) is obtained for all the three tubes. Table.5.2 lists the values of these constants. When this relation is differentiated with respect to \( β \) and equated to zero, the value of the optimum tube inclination (\( β_{opt} \)) for the respective tubes can be obtained. The value of optimum tube
inclination ($\beta_{opt}$) obtained are close to $5^\circ$ and are listed in Table.5.2. Thus, it appears that the little tube inclination of $\beta = 5^\circ$ is sufficient enough to reduce the condensate flooding significantly and to increase the heat transfer performance correspondingly. When the data are fitted in an usual power law form: $h_e = a(\beta)^{n_1}$, where $h_e$ is in W/m²K and ‘a’ and ‘$n_1$’ are the correlation constants, an excellent fit with $R^2$ above 0.98 is obtained. The values of these constants are also included in the Table.5.2. The value of the index ‘$n_1$’ obtained is close to 0.1. It indicates that the tube inclination has a considerable impact over the heat transfer performance of finned tubes with bottom slot when kept inclined.

<table>
<thead>
<tr>
<th>Tube code</th>
<th>$h_e = a_1(\beta)^2 + a_2(\beta) + a_3$, W/m²K at $\Delta T_v = 20$ K, $\beta = 1 \sim 5^\circ$</th>
<th>$h_e = a(\beta)^{n_1}$, W/m²K $\Delta T_v = 20$ K, $\beta = 1 \sim 5^\circ$</th>
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<tbody>
<tr>
<td>A</td>
<td>-485</td>
<td>4760</td>
</tr>
<tr>
<td>B</td>
<td>-470</td>
<td>4620</td>
</tr>
<tr>
<td>C</td>
<td>-600</td>
<td>5610</td>
</tr>
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</table>

5.5.3 Effect of tube inclination on heat transfer enhancement and heat transfer augmentation

The effect of tube inclination on the heat transfer enhancement ratio ($\varepsilon_{AT}$) at $\Delta T_v = 20$ K is shown in Fig.5.11. The heat transfer enhancement ratios are calculated when compared to the plain tube (of 22.0 mm outer diameter) data obtained using the Nusselt equation at $\Delta T_v = 20$ K. The heat transfer enhancement ratio obtained with the tube-D is about 3.5 and remains constant for all the tube inclinations. In case of tube A, B, and C, as the slots drains the condensate better, heat transfer enhancement
Fig. 5.11. Variation of $\varepsilon_{\Delta T}$ with tube inclination at $\Delta T = 20^\circ$ K.

Fig. 5.12. Variation of heat transfer augmentation ratio with tube inclination at $\Delta T = 20$ K when compared to tube-D.
ratio increases with increase in tube inclination. As the trends of variation of the curves are exactly inline with the curves shown in Fig.5.10, the same explanation is applicable here again. The tube-A gives the highest heat transfer enhancement ratio of 4.75 when the tube inclination is 5°.

The heat transfer augmentation (i.e., the heat transfer performance of tubes A, B, and C when compared to tube-D) as a function of tube inclination is shown in Fig.5.12. The tubes A, B, and C provide significant heat transfer augmentation when they are kept inclined. It is possible to augment the condensation heat transfer rate by about 30% by making an axial slot at the finned tube bottom and keeping the tube inclined by 5° with respect to horizontal. A comparison has been made in the Table.5.3 with the heat transfer performance of other drainage mechanisms. It can be noticed that the present technique is superior to solid drainage strips and are at par with the performance of porous strips.

**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 (* Strip material)</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>R-113</td>
<td>0.39</td>
<td>36%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Methanol</td>
<td></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>Steam</td>
<td>1.5</td>
<td>25%</td>
</tr>
<tr>
<td>3</td>
<td>Yan zhong and Qinjin (1986)</td>
<td>Solid drainage strip, Copper*, 5 - 8 mm height, 1.0 mm thick</td>
<td>R-11</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>R-11</td>
<td>0.30</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R-11</td>
<td>0.30</td>
<td>10%</td>
</tr>
<tr>
<td>5</td>
<td>Trela and Butrymowicz (1999)</td>
<td>Brass tube, Solid Copper* drainage strip, 1.0 mm thick and 4.0 mm height.</td>
<td>R-11</td>
<td>0.5</td>
<td>19%</td>
</tr>
<tr>
<td>6</td>
<td>Present study</td>
<td>Machining an axial slot of 1.0 ~ 3.0 mm width at the bottom of the finned tube and keeping the tube inclined by 5° with the horizontal.</td>
<td>Steam</td>
<td>1.3</td>
<td>30%</td>
</tr>
</tbody>
</table>
5.6 CLOSING REMARKS

Though the surface tension provides significant heat transfer enhancement during condensation over HIF tubes in the unflooded 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 much significant with high surface tension fluids like water. Thus, it is not possible to use fin spacing below 0.75 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 strips at the tube bottom and reported heat transfer augmentation of 10 ~ 25 % (during condensation of steam) over the tubes without such strips. However, such strips are not used in practical condensers because of three major reasons, viz., (i) use of such strips makes the fabrication much complicated, (ii) the use of drainage strips increases the vertical distance between the tubes which makes shell size larger and is not desirable, and (iii) the 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 slot at the finned tube bottom and keeping the tube inclined by 5° with respect to horizontal, it is possible to reduce condensate flooding by 40 %. Heat transfer measurements has shown that 30 % augmentation when compared to a HIF tube of same dimensions without such slot and tube inclination. The major advantage of the present technique is that it does not add any extra element (like drainage strips). Hence, neither the shell-side tube spacing nor the shell-side flow is disturbed. In addition, by properly placing the circumferential discs at strategic locations, it is possible to control the condensate drainage pattern, by which the condensate inundation effects could be minimized significantly in practical condensers.