Chapter 9
Vapor Space Condensation

Prof. Min Zeng

Outline

1. Introduction
2. Dropwise Condensation
3. Survey of Enhancement Methods
4. Conclusions
1. Introduction

This chapter is concerned with enhancement of vapor space condensation. Geometries include plates and tubes (horizontal and vertical). If the vapor flows in the direction of the draining condensate film, the interfacial shear stress will enhance condensation. Condensation with significant vapor velocity is called convective condensation.

The majority of enhancement techniques of practical interest are limited to the passive types. These include special surface geometries for enhancement of film condensation and nonwetting coatings or additives for promotion of dropwise condensation. Electric field enhancement of film condensation appears to be very promising.

Condensation will occur on a surface whose temperature is below the vapor saturation temperature.
Techniques of Heat Transfer Enhancement and their Application

The condensed liquid formed on the surface will exist either as a wetted film or in droplets. Droplets are formed if the condensate does not wet the surface. Although dropwise condensation yields a very high heat transfer coefficient, it cannot be permanently sustained. Dropwise condensation may be promoted by liquid additives or surface coatings that inhibit surface wetting. As the surface slowly oxidizes, the surface will eventually become wetted, and the process will revert to filmwise condensation. Hence, filmwise condensation is currently the more important process.

Study of the literature shows that surface tension effects are an important phenomenon in enhancement of film condensation. The importance of surface tension forces in enhancement of film condensation was first described by Gregorig [1954]. However, its importance in affecting condensation on extended surfaces (e.g., integral-fin tubes) was not recognized until the late 1970s (e.g., Karkhu and Borovkov [1971]). Consequently, the separate classifications of extended surfaces and surface tension devices applied to film condensation is somewhat ambiguous.
Since 1981, significant advances have been made in understanding the importance of surface tension in enhancement of film condensation on finned surfaces—for plates and horizontal tubes. The key advances involve understanding the role that surface tension force plays in draining the condensate from the fins, and in retaining condensate within the interim region of finned tubes. This understanding has culminated in the development of analytical models for predicting the condensation rate on horizontal integral-fin tubes and on banks of integral-fin tubes.

1.1 Condensation Fundamentals

The Nusselt [1916] analysis provided the foundation for the present understanding of laminar film condensation. By neglecting the convection terms in the energy equation, the thermal resistance across the condensate film, of thickness $\delta$, is given by the Fourier heat conduction equation. Defining the condensation coefficient in terms of $(T_{\text{sat}} - T_w)$, one obtains

$$q = h(T_{\text{sat}} - T_w) = \frac{\lambda_I(T_{\text{sat}} - T_w)}{\delta} \quad (9.1)$$
1.2 Basic Approaches to Enhanced Film Condensation

As shown by Equation 9.1, the thermal resistance in film condensation is that of conduction across the condensate film. The local film thickness is determined by the force that drains the condensate. The Nusselt’s results assume that gravity force drains the condensate film. Other possible drainage forces are surface tension, suction, and centrifugal force. Any technique that yields a reduced film thickness will enhance the film condensation coefficient.

Therefore, a surface geometry that promotes reduced film thickness will provide enhancement. Short, vertical fins on horizontal tubes will have a smaller film thickness than on the base tube, thus providing enhancement.

An alternative to gravity-drained films is the use of surface tension forces for condensate removal. An example is the vertical fluted tube proposed by Gregorig [1954].
In vapor shear-controlled condensation, high vapor velocity will provide positive effects due to interfacial shear or condensate entrainment.

In shear-controlled flow, enhancement may be provided by reducing the cross-sectional vapor flow area as condensation proceeds to lower vapor qualities. This is possible for tube-side condensation in a multipass design by reducing the number of tubes in parallel in each succeeding pass.

When noncondensibles are present, an additional thermal resistance is introduced in the vapor at the vapor-liquid interface. Mixing of the gas film will substantially reduce this thermal resistance. The maintenance of high vapor velocities, or special surface geometries, which promote a higher heat transfer coefficient in this gas film will substantially alleviate the performance deterioration due to noncondensibles.

Surface roughness may also provide mixing within the condensate film. However, this will not be effective if the film is laminar.
2. Dropwise Condensation

If surface wetting can be prevented, high-performance dropwise condensation will occur.

Griffith [1985] reviews recent advances and presents an excellent discussion of the expected performance and practical aspects of applying dropwise condensation to steam condensers. Two basic techniques for promoting dropwise condensation exist, namely, nonwetting surface coatings and chemical additives. Because low-surface-tension fluids more easily wet a surface than do high-surface tension fluids, steam is a much more viable candidate for promotion of dropwise condensation than are the refrigerants or many organics.
3. Survey of Enhancement Methods

This section discusses film condensation on vertical plates and tubes and on horizontal tubes. Each enhancement technique is separately discussed.

3.1 Coated Surfaces

![Figure 9.1 Cross section of a vertical condensing surface on which nonwetting strips are attached.](image)

Figure 9.1 shows the cross section of a vertical condensing surface on which nonwetting strips are attached. Brown and Matin show that the enhancement is dependent on the liquid contact angle and the thermal conductivity of the base surface.

A U.S. patent by Notaro [1979] describes a coated surface geometry for enhanced film condensation. It consists of an array of small-diameter metal particles bonded to the tube surface. The particles are 0.25 to 1.0 mm high covering 20 to 60% of the tube surface.
A porous coating on the base surface can be a very effective enhancement method for film condensation. Condensate drainage is assisted by capillary flow within the porous coating, resulting in a thinning of the condensate film thickness. Because the temperature drop across a laminar condensate film is the condensation thermal resistance, such capillary-assisted film thinning is effective in reducing the condensate thermal resistance.
3.2 Roughness
Medwell and Nicol [1965] and Nicol and Medwell [1966] investigated enhancement due to a closely knurled roughness for a condensate film flowing down a vertical surface. The knurled roughness provides mixing in the condensate film, and hence increases the condensing coefficient. Their theory shows that, the benefits of roughness are characterized by the roughness Reynolds number, \( e^+ = eu^*/\nu \). For constant film thickness (\( \delta \)), increasing roughness height increases \( e^+ \), which reduces the thermal resistance of the viscous influenced region.

3.3 Horizontal Integral-Fin Tubes
Horizontal integral-fin tubing illustrated in Figure 9.3 has found wide commercial acceptance for condensation on horizontal tubes. These tubes are commercially available with 433 to 1575 fins/m (11 to 40 fins/in.).

![Figure 9.3](image)

**Figure 9.3** Horizontal, integral-fin tube.
Integral-fin tubes provide substantial performance improvement over plain tubes, particularly for low-surface-tension fluids, which use 748 to 1575 fins/m. This occurs because of the area increase provided by the fins and because of the thin condensate films formed on the short fins. The thin condensate films are primarily due to surface tension effects.

**Table 9.1** Enhancement Ratio for R-11 Condensing on Integral-Fin Tubes ($d_f=19$ mm, $T_s=35^\circ$ C, $\Delta T_{vs}=9.5$ K)

<table>
<thead>
<tr>
<th>Fins/m (m$^{-1}$)</th>
<th>$e_o$ (mm)</th>
<th>$h$ (mm)</th>
<th>$h/h_p$ (W/m$^2$-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>748</td>
<td>1.5</td>
<td>8,070</td>
<td>2.64</td>
</tr>
<tr>
<td>1024</td>
<td>1.5</td>
<td>11,970</td>
<td>3.91</td>
</tr>
<tr>
<td>1378</td>
<td>0.9</td>
<td>16,140</td>
<td>5.28</td>
</tr>
</tbody>
</table>

**Condensate Retention.** The integral-fin tubes listed in Table 9.1 are routinely used for condensation of low-surface-tension fluids. However, they will not be effective for high-surface-tension fluids, such as water (steam). This is because capillary (surface tension) force retains condensate between the fins on the lower side of the tube, where the condensate thickness is $\delta=e_o$ (fin height). Since $h=k/\delta$, the condensation coefficient in this condensate-flooded zone is very small.
Figure 9.4 Condensate flooding angle (β) on horizontal integral-fin tubes.

Figure 9.4 shows that the fins are condensate flooded over an angle β.

\[
\beta = \pi c_h = \cos^{-1}(1 - \frac{4\sigma}{d_o \rho g s}) \quad (9.2)
\]

Advanced Surface Geometries. Integral-fin tubes having a sawtoothed fin shape have been developed, which have higher condensing coefficients than the standard integral-fin tubes. Figure 9.5a, c, and d shows three such sawtooth fin geometries, which are commercially used in refrigerant condensers.

Figure 9.5 Enhanced condensing tubes, (a) Hitachi Thermoexcel-C, (b) Wieland GEWA-SC, (c) Wolverine Turbo-C, (d) Sumitomo Tred-26
Table 9.2 Dimensions of the Figure 9.3 and 9.5 Tubes (All Dimension in mm)

<table>
<thead>
<tr>
<th>Tube Type</th>
<th>Figure</th>
<th>$d_o$ (mm)</th>
<th>$e_o$ (mm)</th>
<th>Fins/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integral-fin</td>
<td>9.3</td>
<td>18.9</td>
<td>1.3</td>
<td>1024</td>
</tr>
<tr>
<td>Thermoexcel-C</td>
<td>9.5a</td>
<td>18.9</td>
<td>1.2</td>
<td>1378</td>
</tr>
<tr>
<td>GEWA-SC</td>
<td>9.5b</td>
<td>18.9</td>
<td>1.3</td>
<td>1024</td>
</tr>
<tr>
<td>Turbo-C</td>
<td>9.5c</td>
<td>18.9</td>
<td>1.1</td>
<td>1575</td>
</tr>
<tr>
<td>Tred-26D</td>
<td>9.5d</td>
<td>18.9</td>
<td>1.3</td>
<td>1024</td>
</tr>
</tbody>
</table>

Figure 9.6 R-11 condensation coefficient on copper enhanced horizontal tubes. (From Webb and Murawski [1990].)
Steam Condensation. Figure 9.7 shows six tube geometries consciously developed for steam condensation.

![Figure 9.7](image)

Figure 9.7 Horizontal integral-fin tubes developed for steam condensation by Jaber and Webb [1993]. (a) Wolverine Korodense, (b) copper Wieland 11-NW, (c) copper-nickel Wieland 11-NW, (d) stainless steel Wieland NW-16, (e) UOP attached particle tube, (f) Yorkshire MERT (multiply enhanced roped tube).

The Figure 9.7 tube dimensions are listed in Table 9.3. Note that they typically have a larger fin pitch than the tubes listed in Table 9.2. Only one of the Table 9.3 tubes is made of copper.

### Table 9.3 Dimensions of the Figure 9.7 Tubes

<table>
<thead>
<tr>
<th>Tube Type</th>
<th>Figure</th>
<th>Fins/m</th>
<th>Material</th>
<th>$d_o$ (mm)</th>
<th>$e_o$ (mm)</th>
<th>$t_b$ (mm)</th>
<th>$t_t$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wolverine Korodense</td>
<td>9.7a</td>
<td>None</td>
<td>Cu/Ni</td>
<td>22.2</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Wieland NW-11C</td>
<td>9.7b</td>
<td>433</td>
<td>Cu</td>
<td>19.0</td>
<td>1.1</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Wieland NW-11C/N</td>
<td>9.7c</td>
<td>433</td>
<td>Cu/Ni</td>
<td>22.2</td>
<td>1.1</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Wieland NW-16SS</td>
<td>9.7d</td>
<td>630</td>
<td>S Stl.</td>
<td>18.9</td>
<td>0.3</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>UOP A/P-50</td>
<td>9.7f</td>
<td>—</td>
<td>Cu/Ni</td>
<td>22.2</td>
<td>0.5</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Yorkshire MERT</td>
<td>9.7f</td>
<td>1000</td>
<td>Cu/Ni</td>
<td>25.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Figure 9.8 Steam condensation on 13.7-mm-diameter tubes having 1.0-mm-high, triangular-shaped fins at 472 fins/m. (From Mitrou [1986].)

Figure 9.9 Enhancement level vs. fins/m, $e=1.0$ mm, $t_b=0.9$ mm, $t_t=0.2$ mm, $D_o=22.23$ mm. (From Jaber and Webb [1996].)
3.4 Corrugated Tubes

Figure 9.10 Doubly enhanced tube geometries for condensation on horizontal tubes tested by Marto et al. [1979]. (a) Helically corrugated tube, (b) Turbotec tube, (c) corrugated tube formed by rolling a corrugated sheet and steam welding.

Figure 9.10 shows three basic types of commercially available corrugated tubes. These tubes also provide tube-side enhancement.

Figure 9.11 Steam condensation data on corrugated tubes (Fig. 9.10a) reported by Mehta and Rao [1979]. Figure 9.11 shows their results for \( p=6.35 \text{ mm} \) with \( e_i \) increasing from 0.13 to 1.0 mm. The enhancement \( (h/h_p) \) initially increases with increasing groove depth and attains a maximum of 1.38 at \( e_i=0.35 \) mm, after which \( h/h \) decreases with increasing groove depth. The \( h/h_p \) decreases for increasing groove pitch \( (e_i=\text{constant}) \), as one would expect.
3.5 Surface Tension Drainage

The use of surface tension forces to affect condensate drainage is a very important and effective enhancement technique. We have previously noted enhancement by surface tension forces. In this section, the discussion briefly describes data for various geometries. The detailed discussion of the mechanism and theory of surface tension enhancement can be found in some Refs. The geometries described in this section are limited to those that do not provide significant increased surface area.

Vertical Fluted Tubes. Gregorig [1954] was the first to propose use of surface tension forces to enhance laminar film condensation on a vertical surface.

Figure 9.12 Vertical fluted tubes, (a) Cross section of fluted tube, (b) photo of doubly fluted tube, (c) detail of fin cross section.
Due to the **surface curvature**, the liquid pressure in the convex film is greater than that of the vapor. The **combination of convex and concave surfaces** establishes a surface tension force that draws the condensate from the convex surface into the concave region. A high condensation rate occurs on the convex portions of the fluted surface due to nearly horizontal drainage by the surface tension force. The concave portions serve as vertical, gravity drainage channels.

The resulting heat transfer coefficients averaged over the total surface area are substantially higher than for a uniform film thickness on a smooth tube. The size of the flutes should be selected such that the drainage channel will be filled to capacity at the bottom of the vertical surface. **Therefore**, longer tubes would require larger drainage channels.
Mori et al. [1979] also investigated the effect of placing circular disks (Figure 9.13a) at spaced intervals to remove the condensate flowing down the tube, thereby exposing new condensing surfaces below the disk.

![Figure 9.13](a) Vertical fluted tube fitted with drainage skirt; (b) predicted and experimental results on tube having drainage skirt

Axial Wires on Vertical Smooth Tubes. Loosely attached, spaced vertical wires on a vertical surface (Figure 9.14) can also provide surface tension condensation enhancement.

![Figure 9.14](a) Vertical tube fitted with loosely attached wires for enhancement of condensation (b) detail showing condensate drainage
If the wire diameter \((e)\) is appreciably larger than the condensate film thickness \((\delta)\) and the wires are wetted by the condensate, surface tension force draws the condensate into a rivulet at the wire (region A). This produces film thinning in the space between the wires (region B). The enhancement occurs due to the thinned film in region B, and the condensate drains down along the wires.

4 CONCLUSIONS

Surface tension forces are dominant in draining the condensate from the fins on plates and tubes having typical commercial fin geometries. With the geometry of the condensate-vapor interface defined, models exist to predict the condensation coefficient. Finned horizontal tubes experience condensate retention, which fills the interfin region around a fraction of the tube circumference. Future research is needed to characterize and predict the condensation coefficient for the more complex surface geometries (e.g., those having a sawtooth fin shape).
Thank you for your attention!

Prof. Min Zeng

Key Laboratory of Thermo-Fluid Science and Engineering, Ministry of Education, Xi’an Jiaotong University
Xi’an, Shaanxi, 710049, P.R. China
Email: zengmin@mail.xjtu.edu.cn
http://gr.xjtu.edu.cn/web/zengmin
Tel: +86-29-82665581