ENHANCED HEAT TRANSFER

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Contents

Summary

The heat transfer enhancement techniques have been discussed. Both active methods requiring external energy input and passive methods requiring no additional external energy input have been discussed. Single-phase flow of liquids and gases has been dealt with and their enhancement techniques have been discussed at length. Also, boiling and condensation enhancement techniques are included in the discussion. Previously, the heat transfer enhancement techniques were using only simple geometries. Relatively complex geometries were limited by manufacturing processes. However, in the present days, advances in manufacturing methods have enabled using complex surface geometries. Higher and higher generation enhanced heat transfer surfaces are now being used in air-conditioning, automotive, electronic cooling, process and power industries. The present article deals with these advanced enhanced heat transfer surfaces.

1. Introduction

Energy must be saved by all means for the sustainable development of the planet earth. Heat transfer takes place in every walk of day-to-day life. Heat transfer must be enhanced to reduce consumption of energy. The heat transfer Q in heat exchangers is given by $Q=hA\Delta T$ where h is the convective heat transfer coefficient, A is the surface area through which the heat is being transferred and ΔT is the temperature difference under which the heat is being transferred. The heat transfer may be enhanced by increasing either h, or A, or both. Of course, the increase in pressure drop in pumping the fluid should be kept to a minimum. Heat exchangers, without enhanced surfaces, are initially developed to use plain (or smooth) heat transfer surfaces. An enhanced heat transfer surface with a special surface geometry provides a higher hA value per unit base surface area than a plain surface. The enhancement ratio, E_{h} is given by

$$E_{\mathrm{h}} = \frac{hA}{(hA)_{\mathrm{p}}} \quad (1)$$

where the subscript p refers to the plain surface. The heat transfer rate for a two fluid counterflow heat exchanger is given by

$$Q = UA\Delta T_{\mathrm{m}} = \frac{UA}{L} L\Delta T_{\mathrm{m}} \quad (2)$$

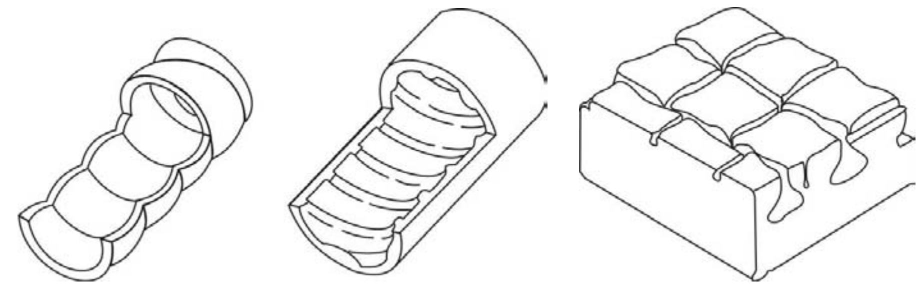
The term L/UA is the overall thermal resistance per unit tube length. The performance of the heat exchanger will be enhanced if the term UA/L is increased. If the heat exchange rate Q is held constant, the heat exchanger length may be reduced. This will necessitate a smaller heat exchanger. For increased UA, with reduced ΔT_{m}, if Q and L are held constant, the ΔT_{m} may be reduced giving increased thermodynamic process efficiency and this yields reduced operating costs. For increased heat exchange, with constant L, the increased UA/L results in increased heat exchange rate for fixed fluid inlet temperatures. The enhanced heat exchanger needs reduced pumping power for fixed heat duty.

1.1. The Heat Transfer Enhancement Techniques

There are several heat transfer enhancement techniques. The techniques are classified into two major groupings: passive and active techniques. Passive techniques do not require external power; they have special surface geometries or fluid additives which cause enhancement. The active techniques require external power such as electric or acoustic fields and surface vibration.

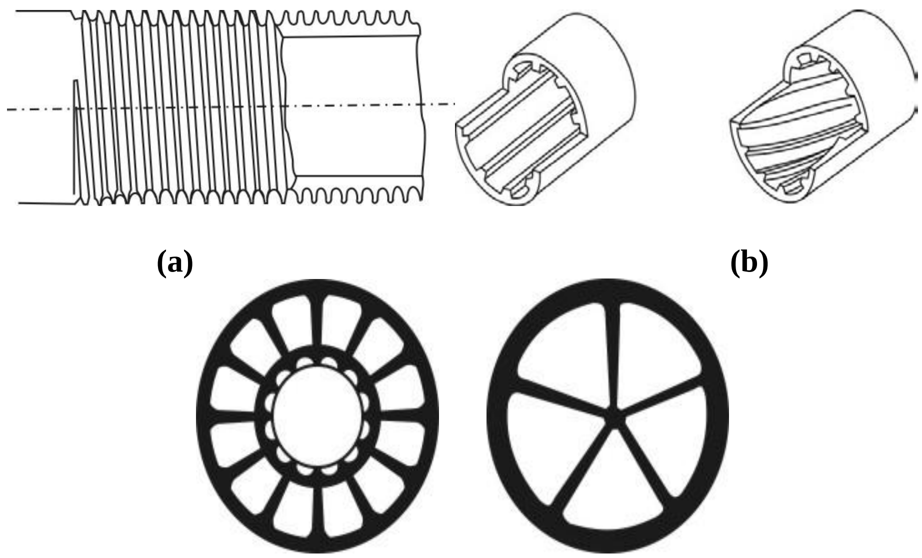
1.1.1. Passive Techniques

Passive techniques are coated surfaces involving metallic or nonmetallic, nonwetting or hydrophilic coating on the surface. Rough surfaces may be either integral to the base surface formed by machining or restructuring the surface or made by placing a roughness adjacent to the surface. Figure 1(a) shows two examples of integral roughness. Figure 1 (b) shows an enhanced rough surface for nucleate boiling. Artificial nucleation sites are formed by structuring the surface. The performance is much better than that in a plain surface. Also, there are extended surfaces. Figure 2 shows extended surfaces for liquids. Figure 2(a) shows an externally finned tube and Figure 2(b) shows an internally finned tube. Figure 2(c) shows internally finned tubes made by multiple concentric internally finned tubes. Figure 2(d) shows tubes containing a five-element extruded aluminum insert. The surrounding tube compressed onto the insert provides good thermal contact. Figure 2 geometries have also been used for forced convection vaporization and condensation. Displaced insert devices are used with single- and two-phase flows. These are devices inserted into the flow channel to improve heated surface energy transport indirectly. Figures 3 (a) and 3 (b) cause mixing in the main flow and mixing in the wall region flow. Figure 3 (c) shows wire-coil insert placed at the edge of the boundary layer. In this case, the mixing is only within the boundary layer and the main flow is affected minimum. Swirl flow devices include a number of geometrical arrangements or tube inserts for forced flow that create rotating or secondary flow. Such devices are full-length twisted-tape inserts, inlet vortex generators and axial core inserts with a screw-type winding. A flow inverter or static mixer is used for laminar flow and alternating clockwise and anti-clockwise swirls are generated in this device. Coiled tubes have secondary flow which produces higher heat transfer coefficient. Surface tension devices drain or transport liquid films during condensation and boiling. Additives for liquids are solid particles or gas bubbles and additives for gases are liquid droplets or solid particles.



(a) **(b)**

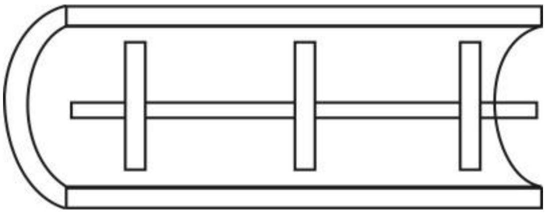
Figure 1. (a) Tube side roughness for single-phase or two phase flow (b) rough surface for nucleate boiling [From Webb, R. L. and Kim, N. H., 2005, Principles of Enhanced Heat Transfer, Taylor & Francis, NY, USA, 2nd Edition.]



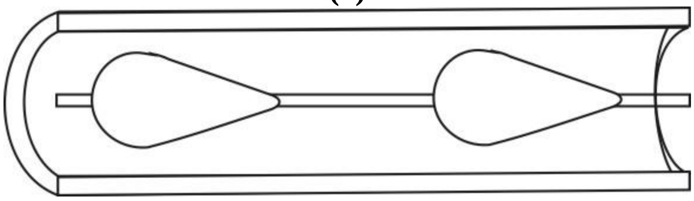
(a) **(b)**

(c) **(d)**

Figure 2. (a) Integral fins on outer tube surface (b) Internally finned tubes (axial and helical fins) (c) Cross sections of multiply internally finned tubes (d) tube with aluminum star insert [From Webb, R. L. and Kim, N. H., 2005, Principles of Enhanced Heat Transfer, Taylor & Francis, NY, USA, 2nd Edition.]



(a)



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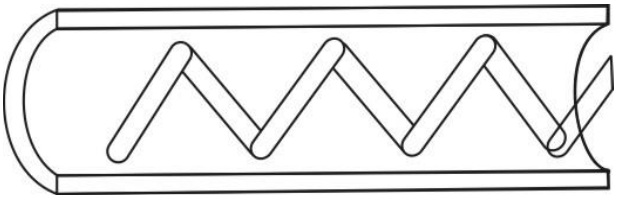

(c)

Figure 3. (a) Spaced disk devices (b) Spaced streamline-shaped insert devices (c) Displaced wire-coil insert [From Webb, R. L., 1987, Enhancement of Single-Phase Heat Transfer, Handbook of Single Phase Heat Transfer, S. Kakac, R. K. Shah and W. Aung, Eds., John Wiley and Sons, NY, USA.]

1.1.2. Active Techniques

Mechanical aids are surface scrapers. Surface vibration at low and high frequency improves primarily single-phase heat transfer. A piezoelectric device vibrates surface and impinges small droplets onto a heated surface promoting spray cooling. Fluid vibration in the range of 1 Hz to ultrasound is primarily used for single-phase heat transfer enhancement. Electrostatic fields, both a.c and d.c., in dielectric fluids cause greater bulk fluid mixing in the vicinity of the heat transfer surface. Injection of fluid causes single-phase heat transfer enhancement. Suction causes vapor removal in nucleate or film boiling. Jet impingement forces fluid normally or obliquely toward the surface.

1.1.3. Usefulness of Enhancement

Heat transfer enhancement may be in the form of increased h with A constant, increased A with h constant or both increased h and A. Figure 4 shows basic approaches to have doubly enhanced tubes by selecting independently the shell-side and tube-side enhancement geometries. Figure 4 (a) gives good tube-side enhancement for liquid flow and good shell-side condensation performance. Material aspect is of serious concern to choose a particular enhancement technique. One enhancement technique may be in competition with the other. The favored method is the one with the highest performance at minimum cost for the material of interest.

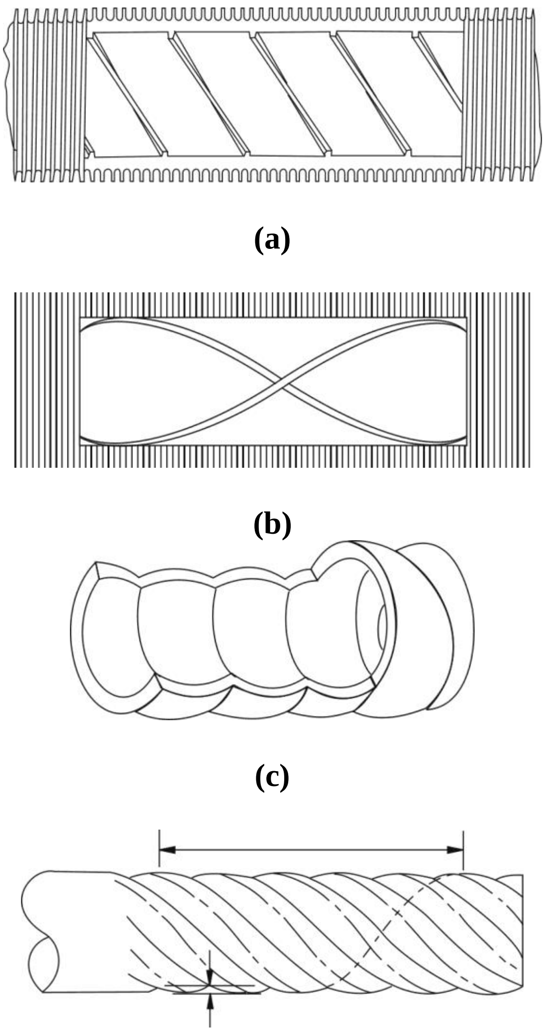

Figure 4. Methods used to make doubly enhanced tubes. (a) Helical rib roughness on inner surface and integral fins on outer surface, (b) Insert device (twisted tape) with integral fins on outer surface, (c) Corrugated inner and outer surfaces, (d) Corrugated strip rolled in tabular form and seam welded. [From Webb, R. L., 1987, Enhancement of Single-Phase Heat Transfer, Handbook of Single Phase Heat Transfer, S. Kakac, R. K. Shah and W. Aung, Eds., John Wiley and Sons, NY, USA.]

2. Performance Evaluation Criteria (PEC)

An enhancement technique is accepted only when its performance is better than the performance of the plain smooth surface. The three considerations in surface performance are the performance objective, the operating conditions and the constraints. The basic performance characteristic of an enhanced surface for single-phase heat transfer is defined by the Colburn j-factor and f vs. Reynolds number curves. The pressure drop constraint is a very important consideration for calculating the performance benefits of an enhanced surface in single-phase flow. The PEC analysis for two-phase heat transfer is differently evaluated since the pressure drop of a two-phase fluid also reduces the local saturation temperature of the fluid. Thus the driving potential for heat transfer is also affected. The PEC for single-phase flow is modified to account for the effect of pressure drop and the PEC for two-phase flow (boiling and condensation) is obtained.

FG criteria: The cross-sectional flow area and tube length are held constant. FN criteria: The cross-sectional flow area remains fixed whereas the length of the heat exchanger varies. VG criteria: The heat exchanger is sized for a required heat duty with a specified flow rate. Table 1 and Table 2 show the PEC for single-phase heat exchange system and two-phase heat exchange system with constant tube inside diameter, respectively.

		Fixed				
Case	**Geometry**	W	P	Q	ΔT_i	**Objective**
FG-1a	N, L^a	x			x	$\uparrow Q$
FG-1b	N, L^a	x		x		$\downarrow \Delta T_i$
FG-2a	N, L^a		x		x	$\uparrow Q$
FG-2b	N, L^a		x	x		$\downarrow \Delta T_i$
FG-3	N, L^a			x	x	$\downarrow P$
FN-1	N	x	x	x	x	$\downarrow L$
FN-2	N	x		x	x	$\downarrow L$
FN-3	N	x		x	x	$\downarrow P$
VG-1		x	x	x	x	$\downarrow NL$
VG-2a	N, L^b	x	x		x	$\uparrow Q$
VG-2b	N, L^b	x	x	x		$\downarrow \Delta T_i$
VG-3	N, L^b	x	x	x	x	$\downarrow P$

Table 1. Performance Evaluation Criteria for Single-Phase Heat Exchange System with d_i =constant [From Webb, R. L. and Kim, N. H., 2005, Principles of Enhanced Heat Transfer, Taylor & Francis, NY, USA, 2nd Edition.]

		Fixed				
Case	**Geometry**	W	P_w	Q	ΔT_i	**Objective**
FG-1a	N, L			x		$\uparrow Q$
FG-1b	N,L		x	x	x	$\downarrow \Delta T_i$
FG-3	N, L	x		x	x	$\uparrow P_w$
FN-1	N	x		x	x	$\downarrow L$
FN-2	N	x		x	x	$\downarrow L$
FN-3	N	x		x		$\downarrow P_w$
VG-1		x	x	x		$\downarrow NL$
VG-2a	N, L		x		x	$\uparrow Q$
VG-2b	N, L		x		x	$\downarrow \Delta T_i$
VG-3	N, L	x		x		$\downarrow P_w$

Table 2. Performance Evaluation Criteria for Two-Phase Heat Exchange System [From Webb, R. L. and Kim, N. H., 2005, Principles of Enhanced Heat Transfer, Taylor & Francis, NY, USA, 2nd Edition.]

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