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STEAM CONDENSATION:

Putting Surface Tension to Work

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Introduction

Since 1765, when James Watt conceived the idea of using a separate surface condenser in a steam engine,[1] the condenser has become an important component in steam power systems. Heat rejection in the condenser is vital to a steam power cycle, and condensers are designed to reject heat at the lowest possible vapor temperature (and therefore pressure) so that a high thermo-dynamic efficiency is achieved. In the last century, the surface condenser has evolved considerably as designers have understood more about the complex heat transfer processes which occur when steam flows into a bundle of water-cooled tubes.[2]

Today, considerable interest exists in the Navy to make propulsion systems smaller, lighter and, where feasible, more efficient.[3,4] These higher-power-density systems will require compact surface condensers where enhanced heat transfer occurs on both the inside (i.e., the cooling water side) and on the outside (i.e., the steam side) of the tubes. The benefits of using heat transfer enhancement in naval condensers have been explored recently and reductions in condenser size of as much as 30 percent were shown to be possible.[5]

Since the early 1970s, a great deal of attention has been focused on heat transfer enhancement techniques for use in a variety of heat exchanger applications.[6,7] Most of the work, however, deals with single-phase heat transfer such as turbulent flow of water in a tube, and not as much information is available when change-of-phase occurs, such as in a steam condenser. In this more complex situation, additional research needs to be performed before fruitful solutions will be possible.

When a vapor condenses on a cold surface, the condensate which is formed creates a thermal barrier which reduces heat transfer. For several decades, numerous techniques have been proposed to reduce the thickness of the condensate layer, but as yet, none of these techniques has been successfully put into practice in steam condensers. Because of the very high surface tension of water, however, this property may be utilized effectively to thin the condensate layer on horizontal tubes which can lead to dramatic increases in heat transfer for steam condensers. Since 1980, a research program at the Naval Postgraduate School has been studying how the high surface tension of water can be put to advantage in thinning the condensate film on horizontal tubes. This research has been focused on two entirely separate techniques. In one case, the use of very thin coatings of polymer materials (such as Teflon, which is used in "no stick" frying pans) to alter the *properties* of the tube surface has been investigated, whereas, in the second case, the use of fins or fine wires to alter the *geometry* of the tube surface has been explored.

In Search of Permanent Dropwise Condensation

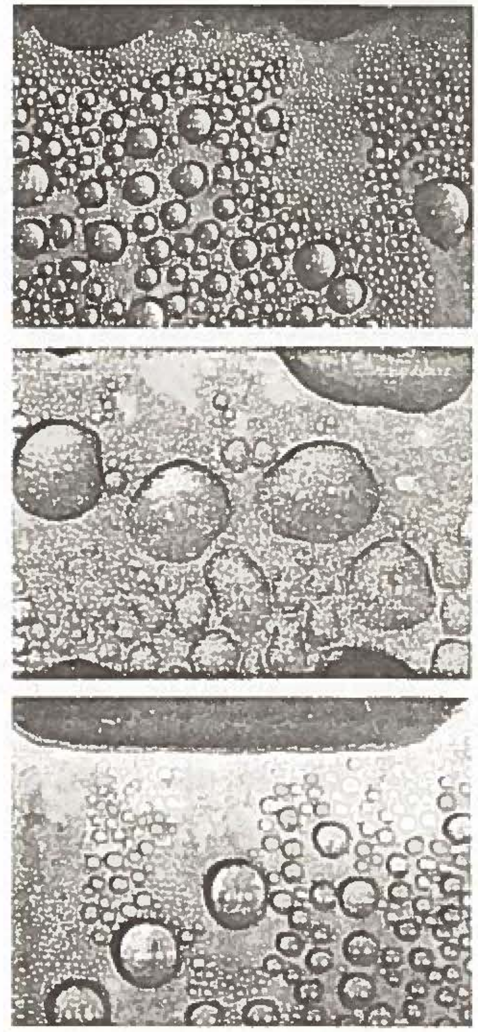
Although dropwise condensation of steam has been studied for over 50 years, permanent hydrophobic coatings have not as yet been developed to the satisfaction of condenser designers. Recently, both noble metals and organic polymers have been used as permanent hydrophobic coatings,[8] and progress has been made toward understanding the variables which affect the long-term endurance of these coatings when exposed to steam.[9-11]

At the Naval Postgraduate School, a wide variety of polymer materials has been studied for use as coatings on condenser tubes. Fluorinated polymers are known to have surface free energies less than the surface tension of water. The high surface tension of water causes it to roll up into droplets on a polymer-coated surface rather than to form a continuous liquid film, and it is well known that this dropwise mode of condensation can generate heat transfer coefficients more than 10 times those of filmwise condensation. However, the problem in the past has been to find a durable polymer coating which can be applied in an ultra-thin layer to avoid insulating the condenser tube appreciably. (The organic coatings are poor thermal conductors, so the coatings must be applied to a thickness of approximately 1 micron or less.) Therefore, an important part of the research has been to test the long-term steam endurance of various ultra-thin polymer coatings using a specially built endurance apparatus.

More than one dozen polymer coatings were tested and those which showed sustained endurance after thousands of hours of exposure to steam were selected for heat transfer performance evaluation. Figure 1 is a photograph showing the endurance of a fluoroacrylic coating, developed at the Naval Research Laboratory.[12] The substrate material was titanium which is a lightweight, corrosion-resistant metal being proposed for naval condenser tubes. It was roughened with a glass bead spray prior to being coated, in order to improve adherence. In Figure 1(a), after exposure to steam for 700 hours, the appearance of the dropwise condensation is very good (many small, spherically-shaped droplets is a sign of good dropwise conditions). However, when examined after 17,000 hours of operation (Figure 1(b)), the coating shows signs of deterioration with large, flattened drops being evident. Apparently, the very thin (2-3 microns thick) coating absorbs sufficient water with time to reduce its effectiveness as a hydrophobic material. This is not evident with a gold coating which continued to show excellent dropwise behavior after 17,000 hours (Figure 1(c)). Figure 2 gives comparison data for the measured steam-side condensation heat transfer coefficient on a horizontal tube for several of the polymer coatings; comparisons are with an electroplated silver coating and with filmwise condensation data on an uncoated tube. Some of the coatings (Emralon-333[a] and No-Stik[b]) showed no improvement over the filmwise case because these coatings were too thick (10-50 microns). However, the Parylene-D[c] and Fluoroacrylic coatings showed enhancements of 3 to 5 times the filmwise data, depending upon coating thickness. The best heat transfer enhancement was with the electroplated silver coating which exhibited an increase of approximately 7 times the uncoated, filmwise tube.

Figure 1

Photographs showing the quality of dropwise condensation on coated specimens.



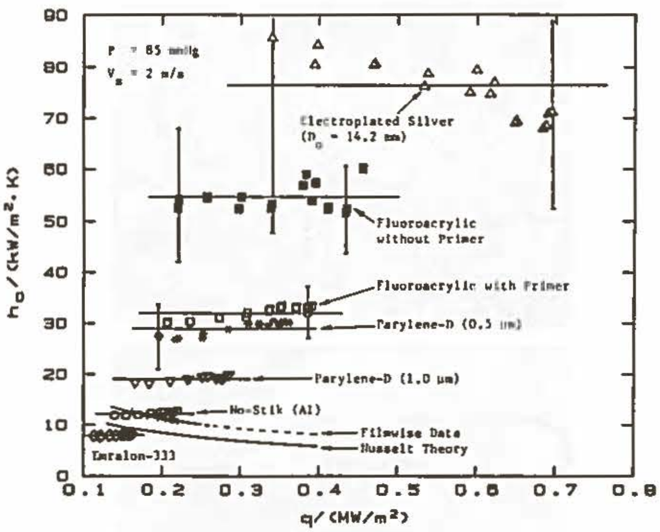
(a) Trade name of a fluorocarbon lubricant developed by Acheson Colloids Company.

(b) Trade name of a thermally conducting plastic coating developed by Plasma Coatings, Inc.

(c) Generic name for members of a thermoplastic polymer series developed by Union Carbide Corporation.

Figure 2

Heat transfer results for dropwise condensation on coated horizontal tubes.



Even with these promising findings, some very important questions remain to be answered. For example, what combination of molecular structure and thickness of an organic coating, and what substrate surface roughness will yield long-term adherence and excellent hydrophobic conditions? Can metal powder dispersions be used within organic coatings to enhance the effective thermal conductivity of the coating? How uniformly can these coatings be applied to long condenser tubes? Can these coatings be applied to installed tubes in an existing condenser? What heat transfer enhancement can be achieved reliably? These questions, as well as questions pertaining to relative cost, must be addressed in order to conclude this seemingly endless search for the "perfect" coating.

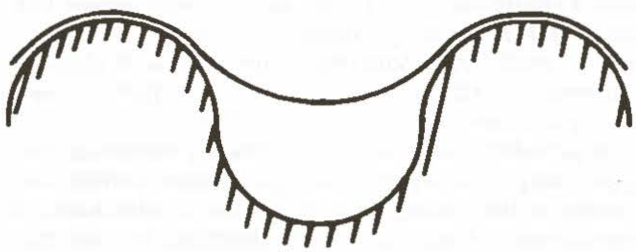
Film Condensation on Extended Surfaces

Finned Tubes

The use of extended surfaces to increase the surface area of a heat exchanger is well known,[13] and one of the most common types of extended surfaces in use today is the integral-fin tube. During condensation on this type of tube, the fins not only increase the surface area, but they can also create large surface-tension forces near the fin tips due to the small radius of curvature of the film in this region. These forces thin the condensate film near the tip of the fins,[14] as shown schematically in Figure 3, which leads to higher heat transfer rates. This effect should be more pronounced for sharply profiled fins and for high-surface-tension liquids, such as water. Historically, however, finned tubes have been used only for low-surface-tension liquids like the refrigerants (e.g., Freon 11). They have not been used in steam condensers because it was thought that the high surface tension of water would cause the condensate to bridge over between fins, causing flooding to occur between fins, and adversely affecting heat transfer performance.

Figure 3

Condensate film profile on a finned surface.



The main thrust of the research at the Naval Postgraduate School has, therefore, been to obtain steam condensation data for a wide variety of horizontal finned tubes under carefully controlled conditions, with the objective of examining the effects of fin spacing, thickness, height and shape on heat transfer performance.[15] Test data have been obtained for over 60 different tube samples under both vacuum and atmospheric conditions. Figure 4 shows the variation of the steam condensation heat transfer coefficient with heat flux for a smooth tube and for one family of finned tubes under vacuum conditions. These tubes were made of copper, and had a 19 mm fin root diameter. Rectangular-shaped fins were machined into the walls of these tubes, with both fin height and fin thickness held constant at 1.0 mm. However, each tube had a different fin spacing (i.e., distance between fins) of 0.5, 1.0, 1.5, 2.0, 4 and 9 mm. It is clear from these results that an optimum fin spacing exists near 1.5 mm (i.e., about 10 fins per inch) and at this optimum spacing, an enhancement over the smooth tube of approximately 3.5 is possible. When these data are plotted as the enhancement ratio (the ratio of the finned-tube steam condensation coefficient to the smooth-tube value at a specified heat flux and based upon the smooth-tube surface area) versus the fin spacing, the optimum is more evident, as shown in Figure 5,

Figure 4

Variation of steam condensation heat transfer coefficient with different fin spacings.

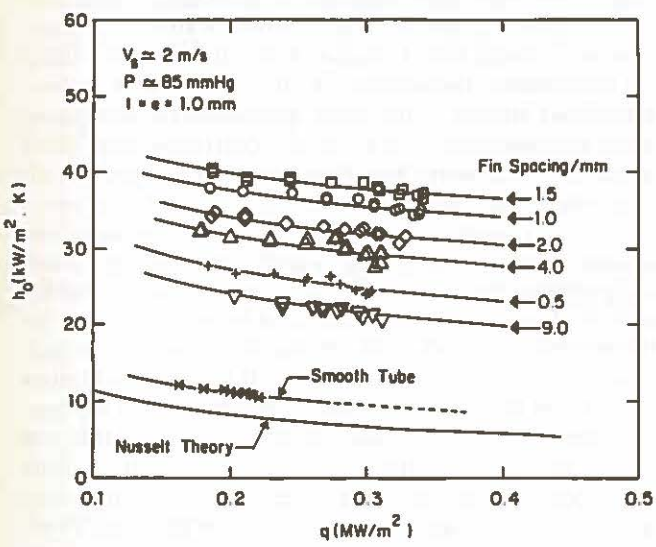
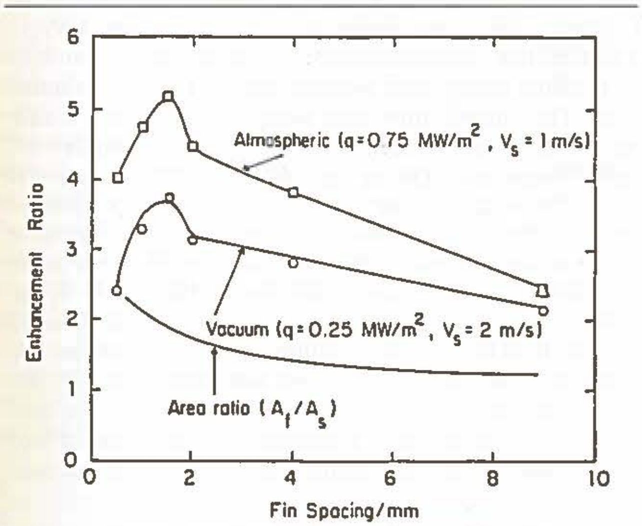


Figure 5

Dependence of steam-side enhancement ratio on fin spacing.



and the enhancement ratio increases with operating pressure. Also, it is clear that the enhancement ratio is always larger than the area ratio, indicating the beneficial effect of surface tension in thinning the condensate film on the fins. This effect of fin spacing is much more important than the size and shape of the fins,[16,17] although fin material can also alter the results considerably.[18] Poor conductivity metals such as stainless steel and titanium yield poor results as extended surfaces.

Wire-Wrapped Tubes

As an alternative to the use of integral fins, a fine wire may be coiled around a smooth tube to thin the condensate film *between the wires.*[19] As shown in Figure 6, when wires are fixed to the tube surface (they don't have to be bonded to the surface), a low pressure region is developed in the film near the base of the wires due to the concave shape of the condensate film. As a result, the condensate along the tube wall is pulled toward the wires and is therefore thinned *between the wires.* This thinner condensate reduces the thermal resistance across the film, leading to enhanced heat transfer between wires. Beneath the wires, the combination of a thick condensate film, and possibly a thermal contact resistance between the wires and the tube wall, reduces the heat transfer rate in this region to a small value. Thus, the addition of wires to a smooth tube enhances the heat transfer process between wires and reduces the heat transfer process beneath the wires. This is unlike the finned tube, where the major heat transfer occurs at the fin tips, which depends upon fin metal conductivity. With wire-wrapped tubes, the wire thermal conductivity plays a very minor role in the heat transfer process. However, it is very important to know what wire diameter and wire pitch will give the best thermal performance. For this purpose, a series of measurements were completed at the Naval Postgraduate School for nine wire-wrapped tubes. Fine titanium wires were coiled around 19 mm diameter smooth copper tubes and were anchored in place at their ends. Three different wire diameters of 0.5, 1.0 and 1.6 mm were used, and for each wire size, three different nominal spacings of 1, 2 and 3 mm were fabricated. The vacuum runs for these tubes yielded the steam condensation heat transfer coefficient data shown in Figure 7. The best configuration appears to be for a wire pitch (i.e., center to center distance between wires) of 2.5 mm (thus about 10 wires per inch). In this case, an enhancement over the plain tube of about 1.8 is possible.

Figure 6

Condensate film profile on a wire-wrapped surface.

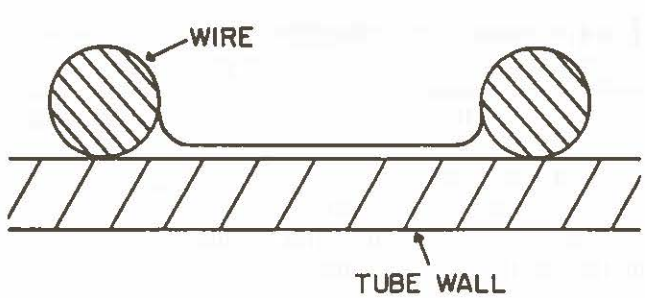


Figure 7

Effect of wire pitch on steam condensation heat transfer coefficient for wire-wrapped tubes (Wire Diameter = 0.5 mm).

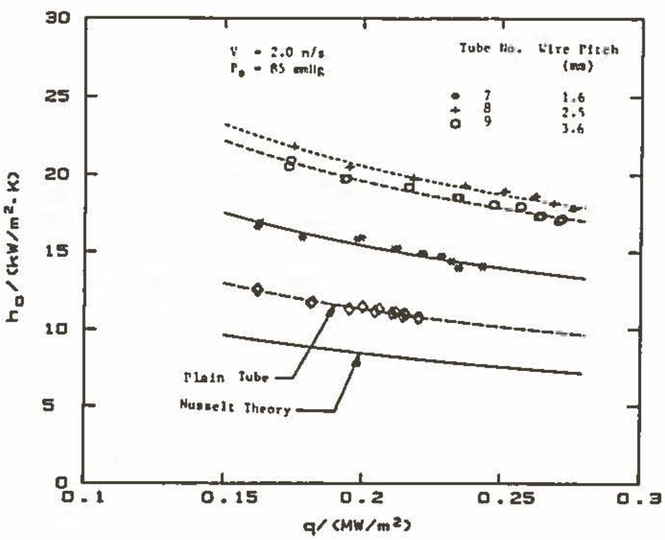
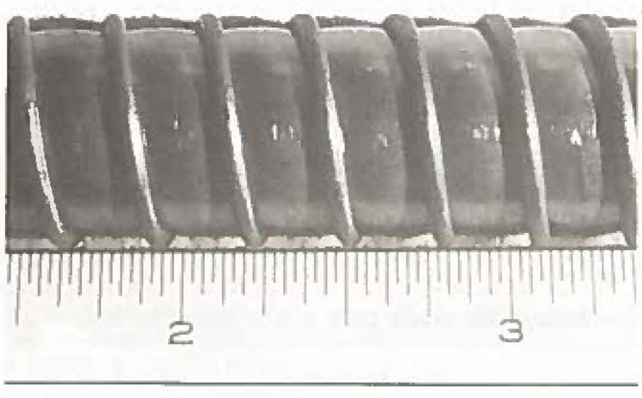


Figure 8

Photograph of wire-wrapped "roped" tube.



When the results of the three different wire diameters were compared, the smallest wire diameter proved to be the best performer, presumably because with the smaller wire diameter a smaller fraction of the tube surface is being blocked off for heat transfer. These wires can be easily wrapped around "roped" tubes, as shown in Figure 8, which will provide heat transfer enhancement on both the steam-side (due to the wires) and on the cooling-water-side (due to the internal ridges causing additional turbulence).

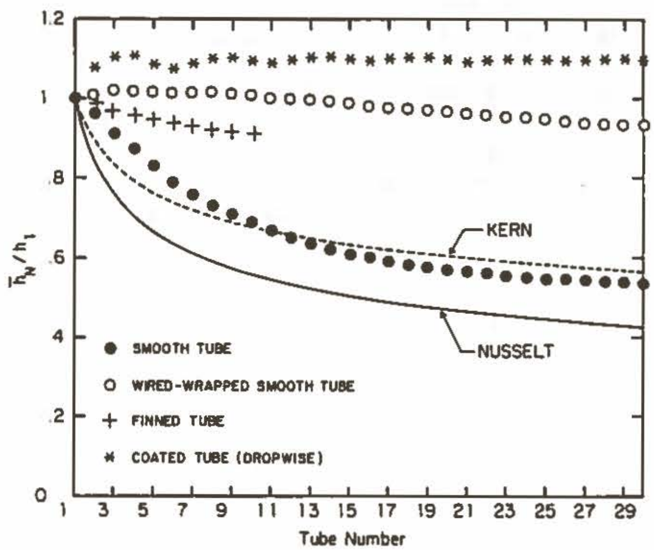
Tube Bundle Performance

All of the information described above pertains to a single tube. Shell-side condensation in an actual naval condenser, however, may be widely different from condensation on a single tube because of the deteriorating effect of condensate inundation from neighboring tubes. Numerous studies of the effect of condensate inundation upon the condensing heat transfer coefficient have been made, but these works have been primarily concerned with plain tubes. The Nusselt analysis[20] for plain tubes assumes that all the condensate from a given tube drains as a continuous laminar sheet directly onto the top of the tube below it. It predicts that the average heat transfer coefficient for a vertical row of N tubes compared to the coefficient for the top tube falls off as $N^{-1/4}$ The Kern model,[21] which assumes that the condensate drops off by discrete droplets or columns of liquid which cause disturbances in the condensate film, predicts a less conservative relationship of $N^{-1/6}$. Recently, improvements to the Nusselt analysis have been made by noting that when condensate drops onto a lower tube, it does not spread much in the axial direction. Evidence indicates that the degree of spreading may be influenced by the amount of condensate and the tube spacing.

The effect of inundation for enhanced tubes is not clearly established at present. However, some preliminary data taken at the Naval Postgraduate School are shown in Figure 9. These data were taken for five active tubes in a vertical row. Additional tubes in a bundle were simulated by flooding the top tube with condensate from a perforated tube. The smooth tube data were correlated reasonably well by the Kern model, and show a considerable fall-off with tube number. On the other hand, the finned tube and the wire-wrapped tube experience little deterioration because, with these tubes, the condensate dropping from above is not allowed to spread axially on the lower tubes because of the presence of the fins or the wires. In the case of dropwise condensation, the effect of inundation is actually to *increase* the bundle performance because the drops from above help to sweep away the large stagnant drops on the lower tubes in the bundle. From this preliminary information, it appears that an enhanced tube bundle may perform substantially better than a smooth tube bundle.

Figure 9

The effect of condensate inundation on the thermal performance of enhanced tubes.



Conclusions

Significant insight has been gained in the use of surface tension to enhance steam condensation heat transfer on horizontal tubes. This enhancement may be obtained either by altering the free energy of the surface (with dropwise condensation) or by altering the geometry of the surface (with filmwise condensation). Each of these techniques has merit depending upon design constraints, and should be studied further under realistic naval condenser conditions in tube bundles where vapor velocity effects, condensate inundation effects and non-condensable gas effects are present. The potential for considerable steam-side enhancements has been demonstrated, and when this is coupled with water-side enhancements, the payoff in naval condenser volume and weight could be of significant benefit to tomorrow's naval steam propulsion systems.

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Biography

Dr. Paul J. Marto is a Distinguished Professor of Mechanical Engineering, Naval Postgraduate School. He teaches in the areas of heat transfer, thermodynamics and nuclear power systems. In addition to his research interests in condensation, he has published a variety of papers involved with nucleate boiling phenomena. He is a Fellow of the American Society of Mechanical Engineers and a Technical Editor for the *Journal of Heat Transfer.*

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Growth and motion of vortices generated by a plate at an angle of attack of 60 degrees. The picture is taken in a recirculating water table and the vortices are visualized by means of aluminum dust. The alternate shedding of vortices takes place practically about all bluff bodies (cylinders, cables, missiles, etc.) and gives rise to large drag, oscillating lift force, and hydro- or aero-elastic oscillations. The flow field may be simulated numerically through the use of the fundamental equations of motion. The visualization of flow helps to our physical understanding of the phenomenon and provides data for comparison with those obtained in numerical experiments. (See article beginning on page 3.)

Photograph is the courtesy of Professor Turgut Sarpkaya (NPS).

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