JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 19, No. 1, January–March 2005

Cost-Effective Techniques for Enhancing Heat Transfer Rate in Steam Condensation

S. Vemuri* and K. J. Kim†
University of Nevada, Reno, Nevada 89557
A. Razani‡
University of New Mexico, Albuquerque, New Mexico 87131
T. W. Bell§
University of Nevada, Reno, Nevada 89557
and
B. D. Wood¶
Utah State University, Logan, Utah 84322

Two different cost-effective techniques were used to enhance the condensation heat transfer rate of steam over a horizontal copper (99.9% Cu, 0.1% P) tube surface period. The first technique was using self-assembled monolayers (SAMs), and the second technique was using small amounts of heat transfer additives. Results of the experimental investigations done using these two techniques are presented. The use of SAMs of *n*-octadecyl mercaptan promotes dropwise condensation, which facilitates the deposition of desirable films that are only as thick as the length of composite molecules. When compared to complete filmwise condensation, the SAM coating increased the condensation heat transfer rate by a factor of 3 for copper surfaces in a horizontal tube configuration. Using effective additives, the condensation heat transfer coefficient can be enhanced as much as 1.4 times as compared to operating without additives. The steam condensation, which occurred in our experiments using effective additives, was mostly dropwise. When heat transfer additives function effectively, the condensate droplets become more dispersed than those produced without additives. We attempt to explain this flow behavior based upon the Marangoni effect (in terms of thermodynamic equilibrium) in connection with obtained dynamic surface-tension data.

Nomenclature

A_i	=	inside area of the test tube, m^2
A_o	=	outside area of the test tube, m^2
c_p	=	specific heat, $J/kg \cdot K$
d_i	=	inside diameter of tube, m
d_o	=	outside diameter of tube, m
h_c	=	condensation heat transfer coefficient, $W/m^2 \cdot K$
h_w	=	inside heat transfer coefficient, $W/m^2 \cdot K$
K	=	thermal conductivity, $W/m \cdot K$
l	=	length of the tube, m
m_w	=	coolant mass flow rate, kg/s
Nu	=	Nusselt number, $h_w l/K$
Pr	=	Prandtl number, $c_p \mu/K$
Q_w	=	heat transfer rate, W
q	=	heat flux, W/m^2
Re	=	Reynolds number, Vl/γ
T_i	=	inlet water temperature, K
T_o	=	outlet water temperature, K
T_s	=	vapor temperature, K
t	=	drop frequency, Hz
ΔT	=	surface subcooling temperature, K
ΔT_{LMTD}	=	log mean temperature difference, K
U	=	overall heat transfer coefficient, $W/m^2 \cdot K$
V	=	coolant velocity, m/s
γ	=	kinematic viscosity, m^2/s
μ	=	viscosity, $N \cdot s/m^2$
σ	=	surface tension of the liquid, dyne/cm

I. Introduction

VIRTUALLY every heat exchanger is a potential candidate for enhanced heat transfer. Benefits of enhancement include the possibilities of size reduction for the particular heat exchanger, reduced driving potential or required temperature difference for desired output, or reduced required pumping power for desired output. Dropwise condensation (DWC) exhibits a significantly higher heat transfer coefficient[1,2] than filmwise condensation (FWC) when properly promoted. However, long-term DWC conditions are usually difficult to maintain. Over the years many researchers have used different techniques to enhance heat transfer in steam condensation; some of them are discussed below.

Erb and Thelen[3] used coatings of inorganic compounds such as metal sulfides and found out that a sample of sulfided silver on mild steel showed excellent DWC. Extensive studies on condensation were made by researchers[4,5] using noble metal–plated surfaces and showed that noble metal–plated surfaces have consistently shown excellent dropwise characteristics. However, the hydrophobic characteristics of these noble metals as DWC promoters have been controversial in the literature[6,7] and also the cost incurred in manufacturing such surfaces has limited their applications. Organic materials[8,9] such as hydrocarbons and polyvinylidene chloride coatings have also received considerable attention for their hydrophobic capability to promote DWC. Many researchers[10–12] have used different types of technologies to employ polymer coatings for promoting DWC and reported that heat transfer enhancements were up to 30 times higher than those from film condensation. Das et al.[13] used an organic monolayer coating and they concluded that self-assembled

Received 20 September 2003; revision received 17 July 2004; accepted for publication 3 August 2004.

*Graduate Research Assistant, Department of Mechanical Engineering.
†Associate Professor, Department of Mechanical Engineering; kwangkim@unr.edu.
‡Halliburton Professor, Mechanical Engineering Department.
§Professor, Department of Chemistry.
¶Professor and Head, Mechanical and Aerospace Engineering Department.

monolayer (SAM) coatings increased the condensation heat transfer coefficient by a factor of 4. However, the durability of the coated surfaces has not been determined. In general, organic coatings are difficult to maintain and require strong long-term adhesion forces between the coating and the metal substrate. Some researchers[14–17] have used heat transfer additives to enhance the condensation heat transfer rate based on the concept of surface tension and Marangoni flow.

The main objective of the current research is to evaluate different cost-effective techniques for enhancing the heat transfer rate in steam condensation, which would eventually reduce the manufacturing cost of condensers. Self-assembled monolayers (SAM) were formed on condenser tubes to study their condensation characteristics. In general, a SAM system with a long-chain hydrophobic group is nano resistant, meaning that such a system forms a protective hydrophobic layer with negligible heat transfer resistance. The substrate surface was oxidized initially before the SAM coating was applied. The oxidized substrate surface enables stronger bonding between the SAM and the substrate surface. These monolayers appear to offer a strong potential for long-term DWC promotion along with their low manufacturing costs. Though the concept of promoting DWC using SAMs looks promising, the durability of these surfaces needs to be determined for any industrial applications. It also helped us to evaluate different kinds of heat transfer additives for enhancing the heat transfer rate, as the additives act to decrease the surface tension of the working fluid, thus decreasing the liquid film thickness on the condensing surface and also enhancing condensate mixing and ultimately increasing the heat transfer rate.

II. Experimental Apparatus

To promote and study dropwise condensation, an apparatus was built that allowed a cool surface to be put into a saturated steam environment. The experimental apparatus system[18] as shown in Fig. 1 is made of a boiler, a chiller, a vacuum pump, a moisture trapper, and the condensing chamber. The condenser design was a closed system made of carbon steel with dimensions of 40.64 cm (length) × 25.4 cm (width) × 25.4 cm (height). The condensing chamber is designed to be flexible in order to accommodate testing of various tube geometries. The test section also contains a viewing port made of Plexiglas (15.24 cm × 10.16 cm) on both sides, which has magnetic wipers as well, to wipe off any water that condenses on the viewing port in order to view clearly the condensation process and to take images of the process. The condensing chamber is tested for any leaks in order to minimize the detrimental effect of noncondensables on the condensation process.[19,20] The condensing chamber is properly insulated in order to avoid any energy losses to the surroundings. A vacuum pump is used to create a vacuum inside the condenser chamber. Steam is generated from a boiler that has a total heating capacity of 2.36 kW using a proportional integral derivative (PID) controller (OMEGA CN 350). The steam generated from the boiler flows vertically downward across the horizontal condenser tube through which the cold water flows, which allows condensate to form on the outside of the condensing surface. The outside diameter of the condenser tube is 19.05 mm with a wall thickness of 2.057 mm and a length of 406.4 mm. Resistance temperature detectors (RTDs) are used to measure the temperature at the entrance of the cool water into the test section as well as at the exit. There are also thermocouples and a pressure gauge placed at various places in the test section. The thermocouples and the RTDs are connected to a data acquisition system (FLUKE Hydra Series II), where the temperatures are monitored and stored. The tests are repeated for each tube under the same vacuum pressure conditions (33.86 kPa) in order to determine repeatability.

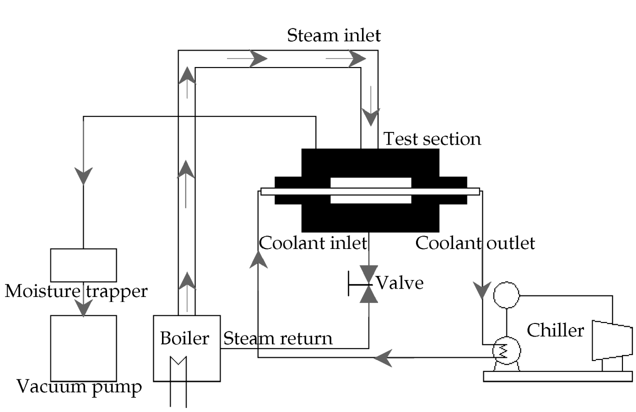


Fig. 1 Apparatus schematic.

The uncertainties in the reduced data and calculated quantities were also determined. The temperatures of the inlet and outlet cooling water and the steam were measured with carefully calibrated four-wire high-precision RTDs having an accuracy of ±0.1°C. Calibrated copper–constantan T-type thermocouples were used to measure the temperature of the steam inside the condensing chamber. The flow rate of the coolant was measured using a flow sensor (SIGNET 515/2356 rotor-X flow sensor) which is connected to a SIGNET battery-operated flow meter to read the data. The accuracy of the flow rate measured was ±2% of the full range (6 m/s). The uncertainties in the independent variables were measured, estimated, and calculated using Coleman and Steele's procedure.[21] An uncertainty of 2% was found in the values of overall heat transfer coefficient, 2% for heat transfer rate and 4% in the condensation heat transfer coefficient.

III. Experimental Procedure, Results, and Discussion

Heat Transfer Analysis

The coolant velocity in the tube was varied from 1.4 to 3.2 m/s, corresponding to Reynolds numbers ranging from 19.5×10^3 to 45.1×10^3. The rate of heat transfer the condensation tube Q_w was determined from the following equation:

$$Q_w = m_w c_p (T_o - T_i) \tag{1}$$

Energy balances obtained from Eq. (1) for Q_w and the total heating capacity of the boiler agreed to within 15%, with some of the energy generated from the boiler being lost to the surrounding environment. Q_w is used to calculate the overall heat transfer coefficient,

$$U = \frac{Q_w}{A_o \Delta T_{\mathrm{LMTD}}} \tag{2}$$

$$\Delta T_{\mathrm{LMTD}} = \frac{T_o - T_i}{\ln[(T_s - T_i)/(T_s - T_o)]} \tag{3}$$

The convective heat transfer coefficient (h_w) for cooling water inside the tube was determined by the following correlation, reported earlier for relatively short tubes:[12]

$$Nu = 0.062 Re^{0.75} Pr^{0.353} \tag{4}$$

The mean condensation heat transfer coefficient, h_c, on the outside of the tube was determined by subtracting the inside and wall thermal resistances from the overall thermal resistance, or

$$h_c = 1 \Bigg/ \left\{ \frac{1}{U} - \frac{A_o}{A_i h_w} - A_o \left[\frac{\ln(d_o/d_i)}{2\pi . l . K} \right] \right\} \tag{5}$$

The surface subcooling temperature ΔT, with an uncertainty of about 4% in the calculated value, was hence obtained by dividing the mean heat transfer rate, q, by the average condensation heat transfer coefficient,

$$q = Q_w / A_o, \qquad \Delta T = q / h_c \tag{6}$$

Self Assembled Monolayer Coating

The ability to tailor the surface properties of the metal substrate using SAMs provides a new capability for controlling the behavior of working fluids on a heat transfer surface and can lead to significantly improved heat transfer rates. We used a finely polished copper alloy (99.9% Cu, 0.1% P) tube with an outside diameter of 19.05 mm, a

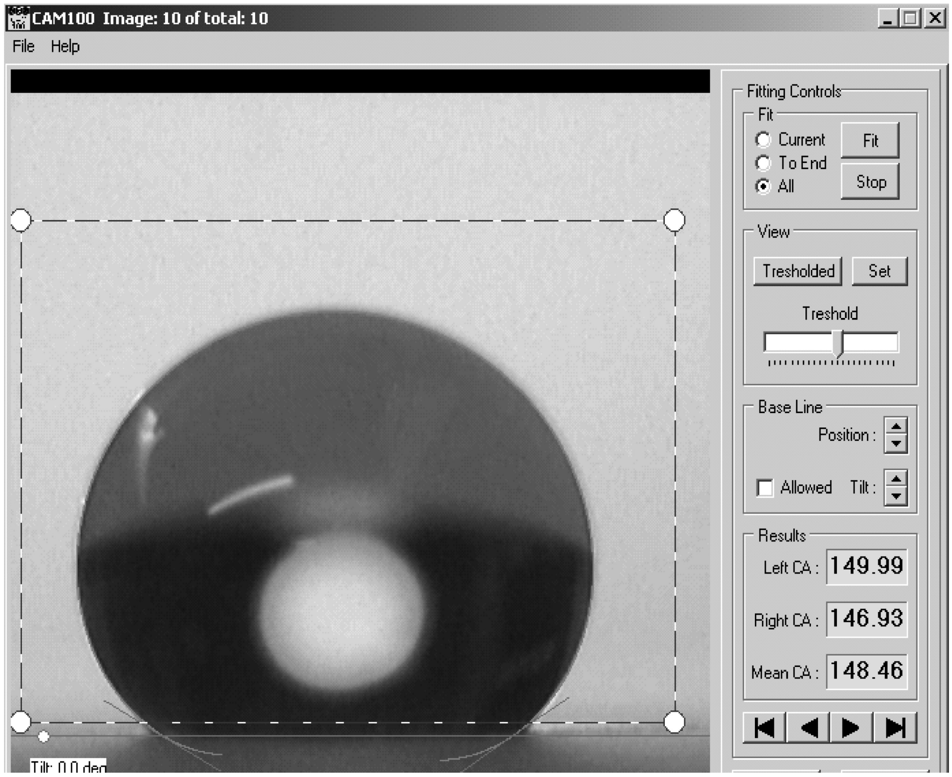


Fig. 2 Contact-angle measurement of water droplet on copper alloy surface with *n*-octadecyl mercaptan coating.

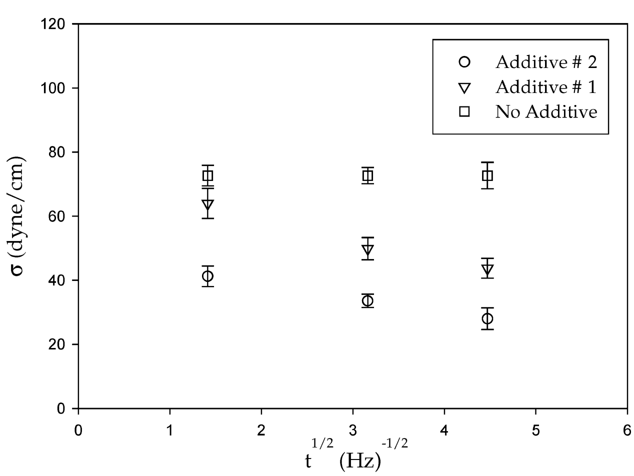


Fig. 3 Surface tension (σ) as a function of frequency of drops ($t^{1/2}$). Note that additive # 1 and additive # 2 are hexyl alcohol and 2-methyl-1-pentanol, respectively.

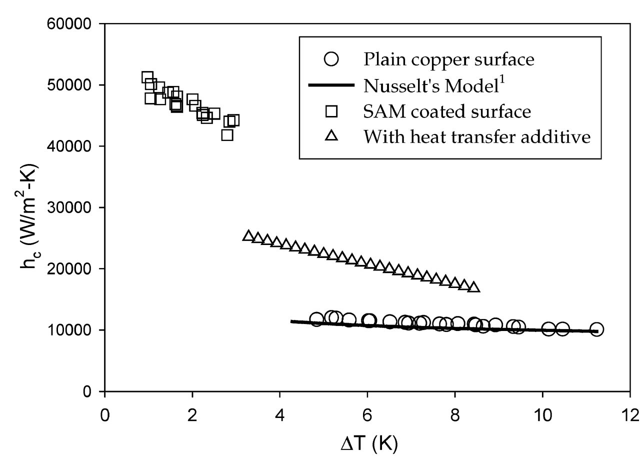
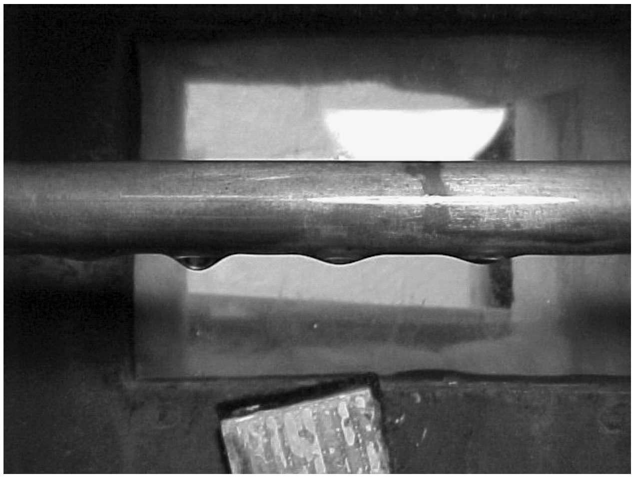


Fig. 4 Condensation heat transfer coefficient versus vapor-to-tube wall temperature difference operated at vacuum pressure. SAM-coated tube is based on *n*-octadecyl mercaptan–coated surface; heat transfer additive was 2-ethyl-1-hexanol.

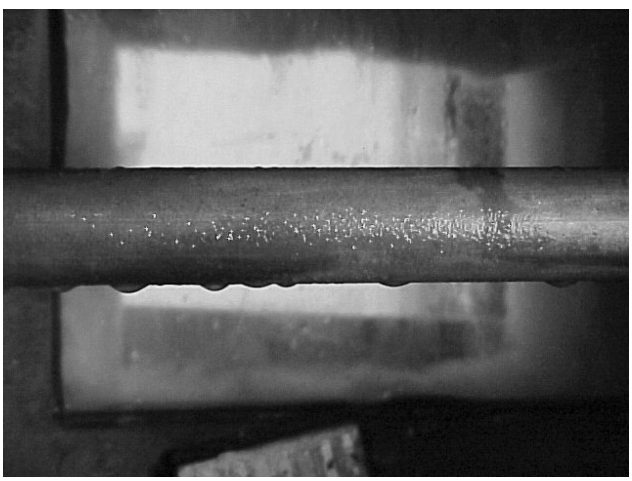
wall thickness of 2.057 mm, and a length of 406.4 mm. An oxide layer was formed on the surface of the copper for stronger bonding of the SAM coating to the condensing surface by immersing the copper tube in a 30% hydrogen peroxide solution for 8 h, while stirring using a stir bar. The tube was then removed from the hydrogen peroxide solution and immersed in a 2.5 mM solution of *n*-octadecyl mercaptan in ethanol for 15 h. A thin film of the organic compound formed on the surface of the copper, which was then washed with ethanol (99.9%) and dried. The organic film was produced by self-assembly of molecules attached to the metal oxide surface by covalent bonds and had better bonding to the substrate surface due to its higher electrostatic attraction in the covalent bonding. To determine the hydrophobic nature of the SAM-coated surface, contact angles were measured using a CAM-100 type contact-angle measurement apparatus with an accuracy of ± 0.5 deg. Figure 2 shows the contact-angle data of a water droplet on a copper alloy surface having an *n*-octadecyl mercaptan coating measured at room temperature. From Fig. 2 it can been seen that the mean contact angle measured for the water droplet is 148.46 deg, as shown on the right-hand side of the Fig. 2. The mean contact angle is calculated by taking the average of the left and right contact angles measured, which are also shown in the Fig. 2.

Surface Tension Analysis

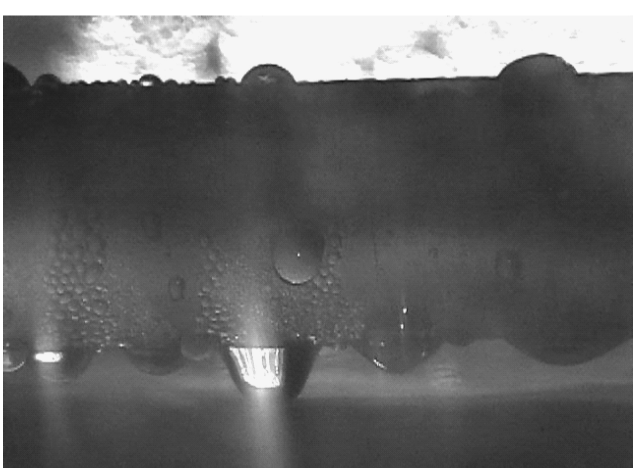
To better quantify the effectiveness of each additive, its effect on the surface tension of water was measured and compared to the surface tension of water alone. The drop volume method[22–24] was applied in making the surface tension measurements and was based upon a force balance on drops. Figure 3 shows the dependence of surface tension on the frequency of the drops. For the case when no additive was present the droplet would begin to neck and would not separate until a relatively large amount of necking



a)



b)



c)

Fig. 5 Photographs of condensation on a) a plain copper tube (filmwise), b) a tube with heat transfer additives, and c) a SAM-coated tube.

had taken place. For the case when additives are present, a relatively little necking was seen at the tip of the drop creator. Significantly smaller drops would appear at the tip of the drop creator and would quickly fall into the collector flask. Out of the two additives tested, 2-methyl-1-pentanol had the lower surface tension, meaning that the value of (σ_{water}-σ_{additive}) for additive 2 is greater than that of additive 1, creating a larger driving potential for Marangoni flow.

Condensation Heat Transfer Coefficient

Every experimental run was operated at a constant pressure (33.86 kPa) for more than 2 h after reaching steady state. All tests were repeated at least once on a different day. As a check, the experimentally determined heat flux and condensation heat transfer coefficient, measured with this apparatus for pure FWC on a bare tube, compared well with the well-known Nusselt correlation.[1] Figure 4 shows the variation of the condensation heat transfer coefficient as a function of surface subcooling operated at vacuum pressure (33.86 kPa). From Fig. 4 it can be seen that the condensation heat transfer rate was enhanced by a factor of 1.4 with the heat-transfer additives added and a factor of 3 when the condensing surface was coated with SAM, as compared to the values for film condensation on a bare copper–brass tube. It can be seen that the driving potential (or required temperature difference) for both experiments, using additives or SAM coatings, was significantly reduced as compared to that for FWC for the applied input power. The improvement during DWC results primarily from the presence of numerous microscopic droplets on the hydrophobic surfaces that do not exist during FWC. Active sweeping of larger droplets from above helps to continue the nucleation of small droplets on the surface, after a larger droplet sweeps off the surface. The DWC cycle then repeats itself. This sweeping effect controls the sizes of droplets on the lower part of the tube, as they are prevented from growing too large by their coalescence into the sweeping drop. Figure 5 shows a still frame from the video recordings of tests for a plain copper tube, a tube with heat transfer additives, and a SAM-coated tube.

IV. Summary

The techniques used showed a remarkable enhancement of the condensation heat transfer rate and are very cost-effective as compared to other techniques used. Self-assembled monolayer coated tubes showed a drastic enhancement in condensation heat transfer of up to three times over FWC. Excellent DWC was obtained on the SAM-coated surface. SAMs have negligible heat transfer resistance. The durability of the SAM coating is strongly dependent upon the bonding between the coating and the condensing surface. As of now, after 600 h of operation, the SAM-coated surfaces still exhibite good dropwise characteristics, and further durability tests are being carried out. An enhancement in condensation heat transfer of up to 1.4 times was achieved by adding only 1% of 2-methyl-1-pentanol. Because of the Marangoni effect, the true condensation heat transfer enhancement was caused by local variation in the surface tension. This means that it is primarily related to the dependence of the additive concentrations upon surface tension. In the presence of effective additives, the steam condensation process observed in our experiment produced mostly dropwise condensation.

Acknowledgments

The authors are grateful for the financial support provided by the U.S. DOE/National Energy Technology Laboratory (NETL, UCR Program DE-FG26-02NT41543 and 98FT40148) and the Nevada Ventures Nanoscience Program. We also thank S. Govindaraju and J. Paquette of the University of Nevada, Reno, and A. Stone of the University of New Mexico, Albuquerque, for their contributions toward this research.

References

[1]Collier, J. G., *Convective Boiling and Condensation*, 2nd ed., McGraw–Hill, New York, 1981, pp. 430–487.

[2]Kakac, S., and Liu, H., *Heat Exchangers*, CRC Press, New York, 1998, pp. 201–246.

[3]Erb, R. A., and Thelen, E., "Dropwise Condensation Characteristics of Permanent Hydrophobic Systems," U.S. Office of Saline Water R&D, Report No. 184, Washington, DC, 1966, pp. 54–57.

[4]Woodruff, D. W., and Westwater, J. W., "Steam Condensation on Electroplated Gold: Effect of Plating Thickness," *International Journal of Heat and Mass Transfer*, Vol. 22, April 1979, pp. 629–632.

[5]Woodruff, D. W., and Westwater, J. W., "Steam Condensation on Various Gold Surfaces," *Journal of Heat Transfer*, Vol. 103, Nov. 1981, pp. 685–692.

[6]O'Neill, G. A., and Westwater, J. W., "Dropwise Condensation of Steam on Electroplated Silver Surfaces," *International Journal of Heat and Mass Transfer*, Vol. 27, No. 9, 1984, pp. 1539–1549.

[7]Marto, P. J., Looney, D. J., Rose, J. W., and Wanniarachchi, A., "Evaluation of Organic Coatings for the Promotion of Dropwise Condensation of Steam," *International Journal of Heat and Mass Transfer*, Vol. 29, No. 8, 1986, pp. 1109–1117.

[8]Holden, K. M., Wanniarachchi, A., Marto, P. J., Boone, D. H., and Rose, J. W., "The Use of Organic Coatings to Promote Dropwise Condensation of Steam," *Journal of Heat Transfer*, Vol. 109, Aug. 1987, pp. 768–774.

[9]Haraguchi, T., Shimada, R., Kumagai, S., and Takeyama, T., "The Effect of Polyvinylidene Chloride Coating Thickness on Promotion of Dropwise Steam Condensation," *International Journal of Heat and Mass Transfer*, Vol. 34, No. 12, 1991, pp. 3047–3054.

[10]Ma, X., Xu, D., and Lin, J., "Dropwise Condensation on Super Thin Polymer Surface," *Journal of Chemical Industrial Engineering (China),* Vol. 44, No. 2, 1993, pp. 165–170.

[11]Zhao, Q., Zhang, D., and Lin, J., "Surface Material with Dropwise Condensation Made by Ion Implantation Technology," *International Journal of Heat and Mass Transfer*, Vol. 34, No. 11, 1991, pp. 2833–2835.

[12]Ma, X., Chen, J., Xu, D., Lin, J., Ren, C., and Long, Z., "Influence of Processing Conditions of Polymer Film on Dropwise Condensation Heat Transfer," *International Journal of Heat and Mass Transfer*, Vol. 45, July 2002, pp. 3405–3411.

[13]Das, A. K., Kilty, H. P., Marto, P. J., Andeen, B. G., and Kumar, A., "The Use of an Organic Self-Assembled Monolayer Coating to Promote Dropwise Condensation of Steam on Horizontal Tubes," *Journal of Heat Transfer*, Vol. 122, May 2000, pp. 278–286.

[14]Ford, J. D., and Missen, R. W., "On the Conditions for Stability of Falling Films Subject to Surface Tension Effect Disturbances: The Condensation of Binary Vapor," *Canadian Journal of Chemical Engineering*, Vol. 46, Oct. 1968, pp. 309–316.

[15]Morrison, J. N. A., and Deans, J., "Augmentation of Steam Condensation Heat Transfer by Addition of Ammonia," *International Journal of Heat and Mass Transfer*, Vol. 40, No. 4, 1997, pp. 765–772.

[16]Morrison, J. N. A., Philpott, C., and Deans, J., "Augmentation of Steam Condensation Heat Transfer by Addition of Methylamine," *International Journal of Heat and Mass Transfer*, Vol. 41, Nov. 1998, pp. 3679–3683.

[17]Kim, K. J., Lefsaker, A. M., Razani, A., and Stone, A., "The Effective Use of Heat Transfer Additives for Steam Condensation," *Applied Thermal Engineering*, Vol. 21, Dec. 2001, pp. 1863–1874.

[18]Vemuri, S., Kim, K. J., Wood, B. D., Govindaraju, S., and Bell, T. W., "The Effect of Nano-tailored Surfaces on Steam Condensation," *Proceedings of IMECE-2003*, ASME International Mechanical Engineering Congress, New York, 2003, IMECE2003-43083.

[19]Ameel, T. A., Kim, K. J., and Wood, B. D., "Non-Absorbable Gas Effects on the Heat and Mass Transfer in Wavy Laminar Film Absorption," *Solar Energy*, Vol. 60, No. 6, 1997, pp. 301–311.

[20]Minkowycz, W., and Sparrow, E., "Condensation Heat Transfer in the Presence of Non-Condensable, Interfacial Resistance, Superheating, Variable Properties, and Diffusion," *International Journal of Heat and Mass Transfer*, Vol. 9, Oct. 1966, pp. 1125–1144.

[21]Coleman, H. W., and Steele, W. G., *Experimentation and Uncertainty Analysis for Engineers*, Wiley, New York, 1989, Chap. 3.

[22]Burdon, R. S., *Surface Tension and the Spreading of Liquids*, 2nd ed., Cambridge Univ. Press, Cambridge, UK, 1949.

[23]Adamson, A. W., *Physical Chemistry of Surface*, Wiley, New York, 1983.

[24]Kulankara, S., and Herold, K. E., "Theory of Heat/Mass Transfer Additives in Absorption Chillers," *International Journal of Heating, Ventilating, Air-Conditioning, and Refrigerating Research*, Vol. 6, No. 4, 2000, pp. 369–380.