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ENHANCED STEAM CONDENSATION AS A RESULT OF HEAT TRANSFER ADDITIVES

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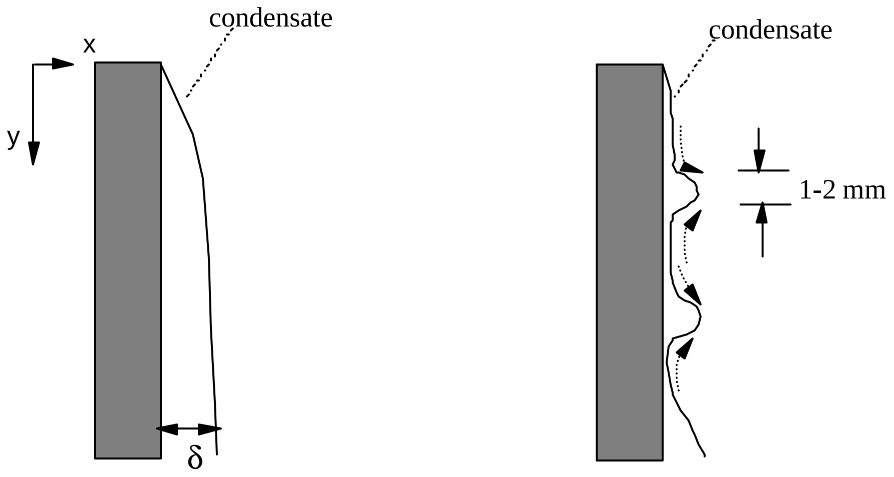
In this paper, the importance of heat transfer additives as they pertain to steam condensation in a single, internally cooled, vertical tube is discussed. The authors report that the condensation heat transfer rate can be significantly enhanced by using effective additives as compared to the heat transfer rate without additives. When heat transfer additives function effectively the condensate becomes more active and exhibit *dropwise-like* behavior. Beginning at the top of the tube small droplets, as opposed to the typical falling film condensation, form along the entire length of the tube. This behavior can be explained by the Maraongoni effect, which relates the importance of dynamic surface tension. Normal octanol, a non-ionic surfactant, is noted as an effective one in this study.

INTRODUCTION

It is well known that the dropwise condensation is an effective means of heat transfer for condenser design for many industrial applications including steam condensation in power industries. In dropwise condensation most of the heat transfer to the cooling surface is conducted through small drops and results in heat and mass transfer rates significantly larger than those associated with filmwise condensation. However, long-term dropwise condensation conditions are truly difficult to maintain. As a result, most surface condensers, therefore, are designed to operate in the filmwise mode. Effectively and simply, *dropwise-like* condensation can be achieved by introducing small amounts of heat transfer additives (i.e. surfactants) into the condenser. When they are condensed together with condensates, the effective additives can trigger *interfacial turbulence* that leads to the loss of hydrodynamic stability at the vapor/liquid interface and produce a spontaneous surface convection. As a result, condensation heat transfer can be significantly increased. Interfacial turbulence (often called the surface convection or *Marangoni* effect) is an important mechanism in various heat and transport processes such as condensation, extraction, crystal growth, distillation and absorption, and many other interfacial transport processes (as first noted by Sterling and Scriven, 1959). It is now widely accepted that interfacial turbulence is caused by local variations in the surface tension, meaning that it is principally related to the additive concentration dependence of surface tension. Usually, a surface tension gradient causes the convective flows and leads to a substantial increase in the heat (and/or mass) transfer rate in certain conditions such as one in this case. For a striking example, intensifying heat transfer in absorption cooling systems, interfacial turbulence created by heat transfer additives, was proven to be an effective way of overcoming the limitation that diffusion has without applying externally-driven, forced convection (Kim et al., 1996a, Kim et al., 1996b).

It appears that in the presence of effective additives, the steam condensation process observed in our experiment was mostly a *dropwise-like* condensation process (Kim et al., 2001). When effective heat transfer additives were present, the condensate began to form small droplets along the length of the vertical tube. The observed size of the droplets with heat transfer additives was approximately 1-2 mm in diameter in the additive concentration range of 100-500 ppm. Note that the additive concentration is defined by the mass of the added heat transfer additive divided by the total mass of the water in the boiler. Along with these small droplets of heat transfer additives present, there was also more condensation activity at the condenser surface. As soon as condensate appeared on the surface of the condenser tube, the film contracted into small droplets. Effective additives displayed considerably vigorous disturbances. The *dropwise-like* condensation covers the entire length of the tube (see Figure 1). We also observed that film substrates appear to become thinner compared to those without additives. Overall, we believe that added surfactants play a pivotal role in improving *dropwise-like* condensate activity that leads to a significant benefit for condensation heat transfer.



Flow of a laminar condensate film
over a vertical surface (w/o additives)

Flow of a condensate film
over a vertical surface (w additives)

Figure 1. Flow characteristics of condensate film with (left) and without (right) additives.

Steam, whether or not it contains non-condensable gas, always condenses in a film on clean surfaces. A simple approach to formulate laminar film condensation heat transfer on a vertical surface is the Nusselt's approach (Incropera and Dewitt, 1996). In this approach, the mass transfer rate, *G,* is obtained as,

$$\Gamma(x) = \frac{g \boldsymbol{r}_l (\boldsymbol{r}_l - \boldsymbol{r}_v) \boldsymbol{d}^3}{3 \boldsymbol{m}_l} \qquad (1)$$

Applying an energy balance around the condensate film we obtain an expression for the heat transfer to the condensing surface by finding an appropriate heat transfer coefficient, $\overline{h}_L$. Now equating the heat transfer at the vapor-liquid interface to the liquid-surface interface, an expression for the film thickness becomes

$$d(x) = \left[\frac{4 k_l m_l (T_{sat} - T_s)}{g r_l (r_l - r_v) h_{fg}} \right]^{1/4} \tag{2}$$

As well known, the overall heat transfer coefficient for the entire length of pipe is

$$\overline{h_L} = 0.943 \left[\frac{g r_l (r_l - r_v) k_l^3 h'_{fg}}{m_l (T_{sat} - T_s) L} \right]^{1/4} \tag{3}$$

And finally, the heat transfer rate is

$$q = \overline{h_l} A (T_{sat} - T_s) \tag{4}$$

The Marangoni instability in a two-phase flow leads to the loss of hydrodynamic stability at the interface and a spontaneous periodic convection pattern or chaotic behavior develops at the interface (Ravinovich, 1992). A recent work by Morrison and Deans (1997) was on ammonia/water condensation. Overall, the general conclusion of the Marangoni convection in condensation is that, if a local surface tension tends to increase with an increase in film thickness, then the film will be unstable (Kim et al., 1996a; 1996b; Morrison and Deans, 1997). In other words, if there is a local region of thick film with higher interfacial tension, it tends to draw liquid from adjacent thin film regions with lower surface tension. If it is true, a general criteria for the Marangoni effect considering concentration is the sole variable, would be,

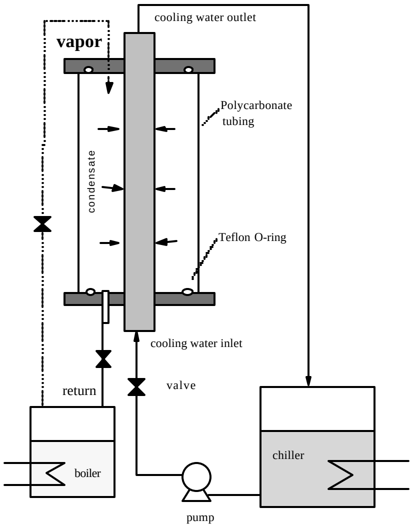
$$\frac{\partial s}{\partial d} > 0 \text{ , where } \frac{\partial s}{\partial d} = \left(\frac{\partial s}{\partial C} \right) \left(\frac{\partial C}{\partial d} \right) \tag{5}$$

Note that d and C are the film thickness and solute concentration, respectively. The fulfillment of the equation can make the condensate unstable so as to enhance the condensation process significantly. It should be also noted that the Marangoni effect has often been observed at the liquid interface in contact with vapors. It appears that this phenomenon is always associated with simultaneous mass transfer (in our experiment-condensation), and the effects are more pronounced when mass transfer is rapid (meaning that it is more effective as the driving potential increases). It is most common in multi-component systems but also some binary system such as this one. The Marangoni effect, which has been described, is by no means well understood yet. Obviously, it stems from the localized variations of surface tension dynamically. The significant feature of the Marangoni effect in condensation is the hydrodynamic instability of the surface motion, which continues as long as steam condensation takes place with the presence of additives.

EXPERIMENTAL

Figure 2 shows a schematic drawing of the constructed test steam condensation apparatus, which is connected with the cold reservoir, condenser, and water chiller. The condenser design was a closed system, made of Lexan™ plastic for ease of viewing the condensate. Steam is being generated at the boiler by an immersion heater with a total heating capacity of 7,200 W with a controller. The water evaporates and moves up an insulated tube where it empties into the condenser. Figure 3 shows a photograph of a single, vertical tube that run through the condenser. Cooling water flows through the copper tube. The copper tube is filled with turbulators in order to insure high heat transfer rate through the condensing tube. When the steam hits the cold copper tube, it condenses and eventually falls back to the boiler. The entire condenser was evacuated to a vacuum pressure of approximately 15 in Hg. A number of shake-up tests were performed to meet a favorable leak rate less than 10^{-3} Torr/hour so as to minimize the detrimental effect of non-condensable gases to the condensation process. The condenser tubes were 16 mm outside diameter with wall thickness of 2 mm. The entire system was properly insulated.

The apparatus was fitted with five type-T thermocouples in order to take temperature measurements. A thermal couple was placed at the inlet and outlet of both the hot (steam) side, and the cold side. A final thermal couple was placed on the boiler. A pressure gage was positioned inside the condenser to monitor the pressure condition. The thermocouples were connected to a computerized data acquisition system (LabView™) where the temperatures were monitored and stored. Initial experiments were conducted with deionized water to allow ones to familiarize themselves with the apparatus, and to gain a reference frame in which to measure the additives against. A twenty-gallon thermal reservoir was connected to the condenser for the cooling water. Using the chiller, water was cooled to reach a temperature of approximately 7° C. The steam would enter the condenser chamber at approximately 55° C. Inside the chamber, steam condensed onto the copper tube. The condensed liquid would flow back into the boiler where it was reheated. This cycle was allowed to proceed until the system reached a steady state. At steady state the values of all five thermal couples were recorded. Experiments were completed in a time frame of about two hours. Several data points were taken with each increase in additive. These data points were averaged and plotted to display any trends in the data. The film starts at the top of the tube and flows downward under gravity. Both the film thickness and condensate mass flow rate increase as the film flows down. The heat transfer occurs from the vapor/liquid interface through the film to the surface.



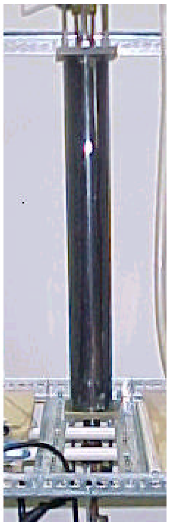


Figure 2. A schematic drawing of the single tube condensation apparatus (left)
Figure 3. A photograph of the single tube condenser (right)

RESULTS, DISCUSSION, AND CLOSURE

In order to evaluate the effectiveness of the additives, the heat input to the boiler, and the pressure inside the condenser chamber were controlled. This approach is convenient to evaluate the performance of the additives. Effective additives should exhibit larger values of the heat transfer rate, and thus a higher coefficient of heat transfer. In general we conceive that an effective heat transfer additive, n-octanol, enhances the heat transfer rate by as much as 50 percent, which is believed to be a significant benefit for condenser design. Although minute but significant changes in surface tension of water/additives starts at approximately 10 ppm, a noticeable increase in condensation heat transfer truly starts at about 100 ppm. So, there exits an onset in the range from 10-100 ppm for n-octanol.

The heat transfer rate across the cold side of the condenser was calculated in order to make relative comparisons among data collected. By calculating the heat transfer rate, the additive performance was easily evaluated. The heat transfer rate for the cold side of the condenser was found using the equation,

$$q = \dot{m}\, c_p \Delta T_{cold} \tag{6}$$

where *m* is the mass flow rate of cooling water, c_p is the heat capacity for water, and ΔT_{cold} is the increase in temperature from the inlet to the outlet of cooling water. The graph in Figure 4 shows how the heat transfer rate increases with an increase in amount of additive. Values for the heat transfer coefficient were also found by equating the mass transfer equation to the convection equation, and solving for *h*. The convection equation per unit area can be written as:

$$q = h\Delta T_{hot} \tag{7}$$

Where *h* is the heat transfer coefficient and $\Delta T_{hot} = T_{sat} - T_{surface}$. Setting these two equations equal to one another assumes no heat transfer to the environment has occurred. This assumption is valid for making comparisons between the heat transfer coefficients with and without additives. By increasing the heat transfer coefficient, the corresponding saturation temperature for the condenser can be lowered, there by reducing the power input required to the boiler.

It is convenient to look at the data in terms of heat transfer enhancement factors, F_e. that is defined as the ratio of heat transfer rates with and without additive.

$$F_e = \frac{q}{q_o} \tag{8}$$

The enhancement factor is a dimensionless group by which we can easily monitor the effects of heat transfer additives. The heat transfer rate and the heat transfer coefficient are as much as 2 times greater with 500 ppm of n-octanol added to the working fluid of the condenser. Another advantage of using additives could attribute to the increased contact time of drops during the condensation. However, no measurement was performed to quantify it. Figure 4 shows the relationship between an enhancement factor, F_e, and the amount of additive. The heat transfer coefficient is found only from experimental methods but it can be compared with reasonable accuracy.

In order to better quantify the effectiveness of the additive in steam condensation, its effect on the surface tension of water (condensate) was measured and compared to the surface tension of water alone. The experiment focused on measuring the surface tension of water in the presence of additive vapor. The drop volume method is applied in making the surface tension measurements. An apparatus was constructed for this experiment. Experimental apparatus consists of a test chamber, drop creator, collection flask, scale, additive flask, heat mantle, reservoir, cold trap, and pump. Details can be found in elsewhere (Stone et al., 2002). In order to run the surface tension apparatus approximately 15 ml of additive were brought to a boiler. Using a stopwatch the desired drop frequency was achieved before the vapor was connected to the test chamber. The additive vapor was then connected to the test chamber, and the pump was started. The vapor ran through a cold trap in order to condense it back to liquid. Next, the number of drops were counted and weighed over a specified period. Five runs for each additive at each frequency were tabulated. The surface tension for each run was calculated and averaged over the number of runs. Figure 5 shows the dependence of surface tension on frequency of the drops. As can be seen, surface tension shows a dynamic phenomenon. This fact can be translated into the fact that the additive vapor goes through a condensation process and takes a finite amount of time to diffuse into the water droplet or adsorb on the interface.

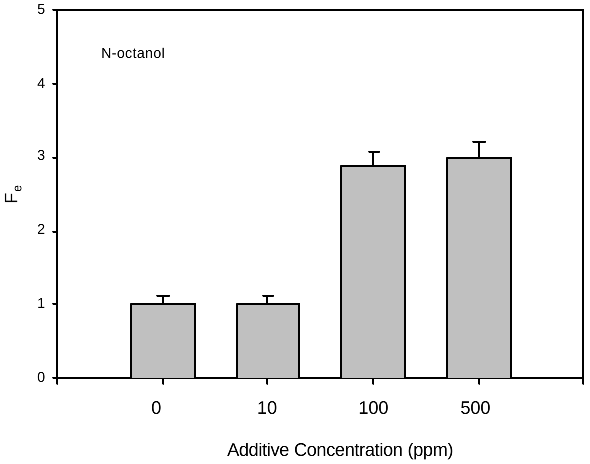


Figure 4. The effect on the heat transfer rate by adding heat transfer additives in terms of enhancement factor, Fe, defined in Eq. (8). The uncertainty was shown in terms of error bars.

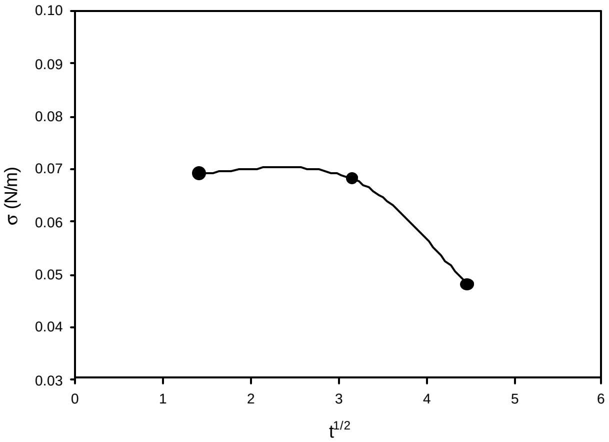


Figure 5. Surface tension as a function of exposure time, $t^{1/2}$

When the exposure time is large and the surface tension reaches a dynamically equilibrated value once the vapor has been truly saturated (Burdon, 1949). Therefore, once a liquid contains more than one molecular species, equilibrium could be reached only when the surface layers comprise those molecules that make the free energy of the surface a minimum. It takes an appreciable amount of time for the surface tension of a liquid of more than one molecular species to reach its equilibrium value. During the case when no additive was present the droplet would form on the tip of the drop creator and hesitate. The droplet would begin to neck and would not drop until a relatively large amount of necking had taken place. During the case when additive was present in the test chamber, relatively very little necking was seen. Significantly smaller drops would appear at the tip of the drop creator and would quickly fall drop into the collector flask.

By means of effective use of surfactants, the steam condensation heat transfer enhancement mechanism can be manipulated by local variation in the surface tension. In this work experimental study of steam condensation on a single vertical tube has shown that adding small amounts of additives is an effective method of increasing the local variation in surface tension, thus, often increasing the heat transfer rate along the condenser tube. In the presence of n-octanol a *dropwise-like* condensate was observed along the vertical tube, and a dramatic increase in the heat transfer rate was found. Succeeding research will provide a function of the heat transfer coefficient, h, in terms of thermophysical properties and the amount of additive mixed into the working fluid.

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Nomenclature

g = gravity
μ_l = viscosity
ρ_l = liquid density
ρ_v = vapor density
δ = film thickness
$\dot{m}$ = mass flow rate
$T(x)$ = mass flow rate in the x direction
T_{sat} = saturation temperature
T_s = surface temperature
h_{fg} = latent heat
h'_{fg} = $h_{fg}(1 + 0.68Ja)$
A = area
r = radius
c_p = heat capacity
C = conentration
σ = surface tension

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