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A ROTATING SHALLOW CONE EVAPORATOR

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ABSTRACT

A prototype rotating cone evaporator with a cone half-angle of 80^o to the vertical has been built and tested. At optimum liquid flows across the surface the overall heat transfer coefficient, using water as the evaporating liquid, was of the order 14 kW/(m^{2}K), more than double that of normal rotating cone evaporators, and many times that of short tube evaporators.

At low flow rates the heat transfer coefficient is low, but increases rapidly with increasing flow rate to a peak. With further increase in flow rate the overall heat transfer coefficient declines slowly.

At low temperature differences the overall heat transfer coefficient generally increases with increasing temperature difference, but at high temperature differences the reverse is true.

At low speed of rotation of the cone, there is a rapid increase of heat transfer coefficient with increasing speed, but at higher speeds there is little change.

As the resistance across the metal interface can be a significant proportion of the total thermal resistance, the material of which the cone is made, and the thickness of that material can be important

There appears to be a good application of this type of evaporator in the oil industry as reboilers for distillation columns.

INTRODUCTION

Reboilers for distillation columns in the oil industry have traditionally been short tube evaporators. In other industries, particularly the dairy industry, there has been a steady evolution of different types of evaporator, as is shown in table 1.

Table 1. Typical Overall Heat Transfer Coefficients for Different Types of Evaporator.

Evaporator Type	**Overall Heat Transfer Coefficient kW/(m^2 K)**
Short Tube	0.8
Long Tube	1.0
Plate	1.5
Rising Film	1.5
Falling Film	3.0
Centritherm	7.0
Rotating Shallow Cone	14.0

The shallow rotating cone is a development of the Centritherm, which is a rotating cone evaporator having a cone half-angle to the vertical of 30^o, the same as the Alfa-Laval separators. Jebson and Parker, 2003, found that in rotating cone evaporators, flatter cones with a larger angle to the vertical had higher heat transfer coefficients, but there was a minimum temperature difference, between the heating surface temperature and the evaporation temperature, below which no evaporation took place. The increased coefficient was thought to be a result of the greater gravitational effect at large cone angles, giving higher liquid film velocities and a thinner film. The minimum temperature difference effect is thought to be a result of droplets from bursting vapour bubbles subject to centrifugal force, traveling radially and dragging vapour with them, thus increasing the vapour pressure in a radial direction, and decreasing the temperature difference. Figure 1 illustrates this idea.

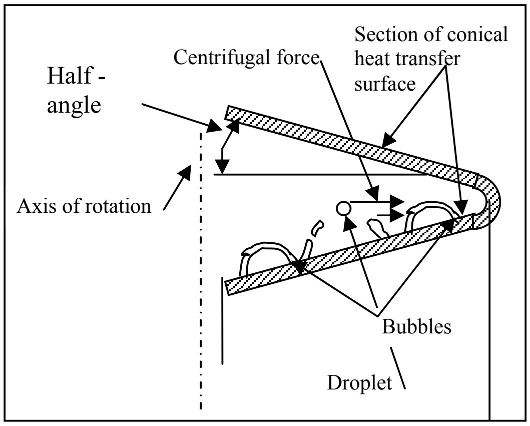

Figure 1. The effect of centrifugal force on droplets from collapsed bubbles

Particularly in cones with a small angle to the vertical, when bubbles form, the portion of the bubble film on the inside of the bubble will again be subjected to a centrifugal force, which will be trying to flatten the bubble (figure 2).

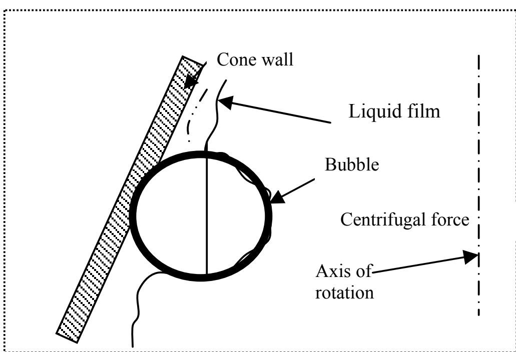

Figure 2. The effect of centrifugal force on a bubble.

For the bubble to be stable the pressure inside it must increase. A rise in this pressure will cause the evaporation temperature to increase, lowering the temperature difference, and lowering the heat transfer coefficient calculated from the apparent temperature difference.

A difficulty with cones with a large angle to the vertical is that the surface area increases very rapidly with increasing radius. Combined with the increasing film velocity with increasing centrifugal force, and the effect of evaporation, all of which will decrease film thickness, the film at large radii may become too thin and break up, drastically decreasing the amount of evaporation. To reduce the chance of film breakup, a method of collecting the concentrate from two sets of cones and feeding it to a third set for further evaporation was devised. A diagram of the evaporator with this system is shown in fig. 3. Milk flowed from the delivery pipe through nozzles onto the four upper conical surfaces in parallel. Concentrate from the upper pair of surfaces drops through vertical pipes to the lower pair, from which all the concentrate passes though a transfer pipe to the lowest pair of surfaces. After further concentration on these surfaces the milk passes out of the evaporator.

EXPERIMENTAL

Equipment

The liquid to be evaporated was pumped by a variable speed pump through a Spiraflo heat exchanger, where the liquid was heated to the evaporating temperature, and then into the feed tube. After passing through the feed tube, the liquid was fed onto the inner surface of the cone, close to the axis, and flowed down on the surface as an extremely thin, fast-moving, evaporating liquid film under the centrifugal force caused by the speed of rotation. For experiments with different cone angles, the Centritherm was replaced by a specially built evaporator of generally similar design to the Centritherm. For the rotating tube (0^o cone) the tube of a single tube evaporator was fitted with bearings and seals, and the tube rotated with a drive from an electric motor. Details of this evaporator are given by Jebson et al., 1997.

RESULTS AND DISCUSSION

The Angle of the Cone

As the cone angle increases the effect of centrifugal force is greater, and the film thickness smaller (figure 4, Chen et al., 1997). Hence the heat transfer coefficient should increase with cone angle. The experimental results illustrated in figure 4 indicate that generally this is true, but there are some anomalies. At low cone angles, when a bubble forms, extra pressure is required to move the bubble film inwards against the action of the centrifugal force. This extra pressure will increase the pressure of the vapours, increasing the evaporation temperature and reducing the temperature difference. At high cone angles droplets formed when the bubbles burst fly radially, dragging vapour with them, and increasing its pressure. The theory of the pressure increase is given by Jebson & Parker, 2003. Shinn, 1971, stated that a cone half - angle of 30^o to the vertical is desirable, as with greater angles the area increases rapidly with radius, and it is difficult to maintain adequate coverage. However as is shown in section 2 the heat transfer coefficient does not change rapidly with flow rate, and as there is less area at small radii, when the flow rate is increased to ensure coverage, the overall heat transfer coefficient in the inner portion of the cone, where the film would be thicker, is not seriously affected.

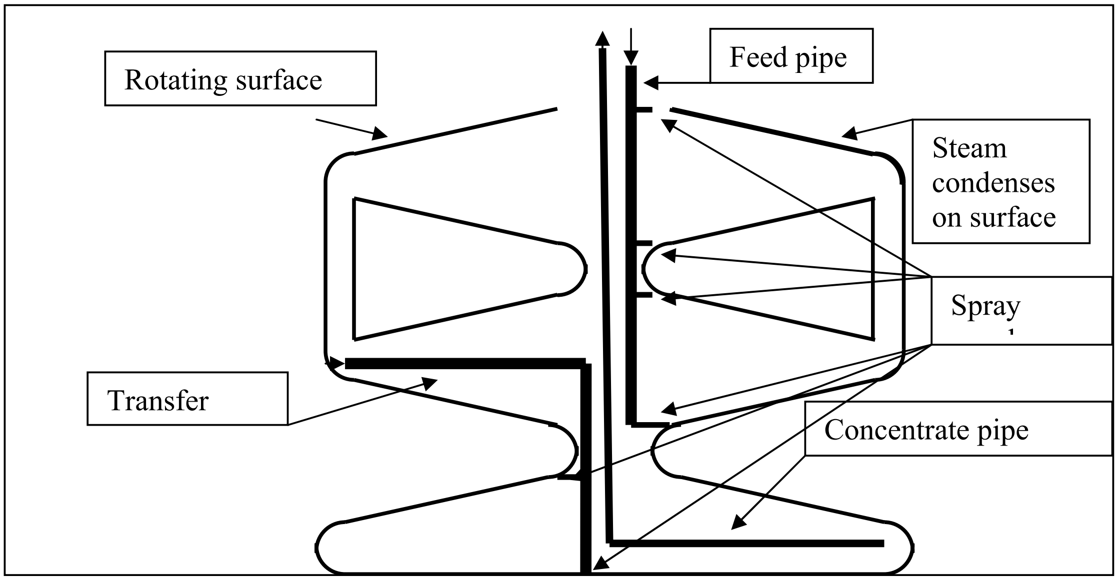

Figure 3. Diagram of an 80^o half-angle cone

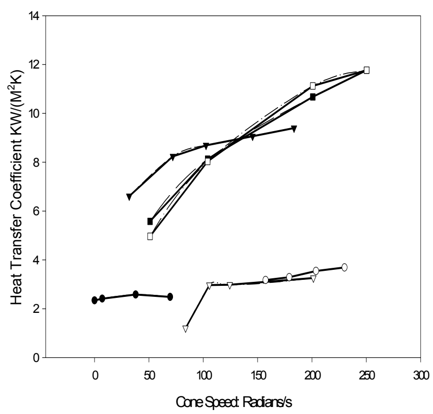

Figure 4. Effect of cone angle on heat transfer coefficient at different cone rotating speeds. The angle is the half-angle from the vertical. Legend: ● 0^o Cone o 87^o cone experimental ▼ 30^o cone □ 80^o cone ▽10^o cone ■ 87 ^{o} cone etheoretical using equation 2 of Jebson et al, 2003; } * 87^o half-angle modified curve, calculated from the experimental results but with the temperature difference adjusted adjusted using equation 9 of Jebson et al, 2003.

|Feed Flow Rate

Jebson and Parker, 2003, showed that there is a minimum flow below which the overall heat transfer coefficients were very low as a result of dry patches forming on the surface.

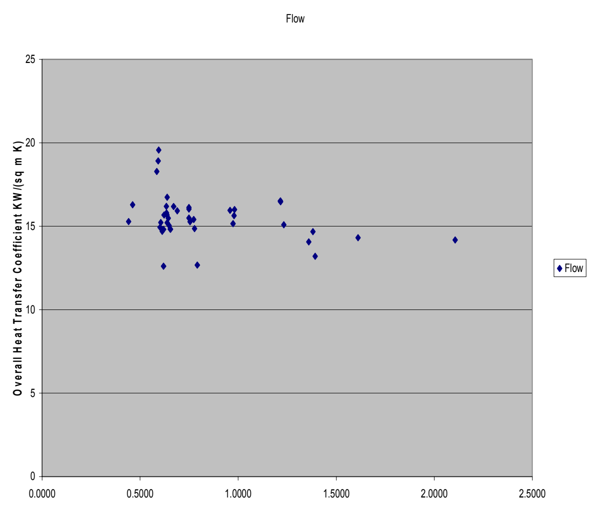

Figure 5. The effect of flow rate on the overall heat transfer coefficient.

For these experiments the flow was kept above this minimum. The results are shown in figure 5, and show a certain amount of scatter, partly a result of experimental error, but particularly in the region where the proportion of dry patches is low, close to the optimum flow, dry patches can be unstable (sometimes there and sometimes not, Paramalingam et al., 2001), and this will result in variation of the proportion of wetted surface, and the consequent variation in the measured heat transfer coefficient.

Generally there is a decline in the overall heat transfer coefficient with increasing flow. This will be caused by thicker films with increased flow rate.

Steam - Evaporating Liquid Temperature Difference

Figure 6 shows typical curves of overall heat transfer coefficient versus temperature difference, for water, 20% sugar solution and skim milk, when a 30^{o} half-angle cone was used. To avoid solids deposition on the cone surface at high temperature differences, the sugar solution and the skim milk temperature differences were kept below 30^{o}C. The results reported here suggest that the surface evaporation occurs only at low temperature difference, in which the heat transfer coefficient increases as the temperature difference increases. Bubble formation may have commenced at about 10^{o}C when the increase of heat transfer coefficient with temperature increase starts to decrease. The presence of bubbles would increase the film thickness, decreasing the rate of heat transfer to the liquid-vapour interface. Hence the rate of increase of heat transfer coefficient, with increasing temperature difference, is decreasing as the contribution of direct liquid-vapour interface evaporation (which is the more effective at low film thicknesses) would diminish until bubble formation was the main effect.

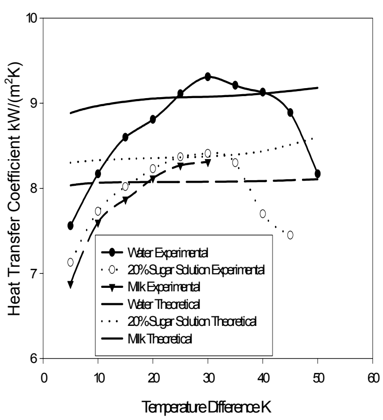

Figure 6. The effect of difference between steam temperature and evaporating temperature on the overall heat transfer coefficient

For temperature differences over 30^{o}C, there appears to be a possibility of the bubbles causing an isolating vapour film between the heat transfer surface and the product. At this stage the heat transfer coefficients would decrease rapidly with further increase of temperature difference, as can be observed in figure 6.

Angeletti and Burton, 1983, suggested that there are two mechanisms of vapour evaporation from causing an isolating vapour film between the heat transfer surface and the product. (1) direct evaporation at the liquid-vapour interface; (2) bubble formation at the heating tube wall. They also pointed out that the mechanism of direct liquid-vapour interface evaporation prevails when the total temperature difference is less 10^{o}C. Mälkki et al., 1967, suggested that the heating in the Centritherm occurs mainly by conduction, and the mechanism of the evaporation is from the surface. In these experiments the overall heat transfer coefficient was found to increase slightly with increasing the temperature difference (10-50^{o}C), but Pajumen et al., 1974, found the opposite (range 40-70^{o}C). Dengler and Addoms, 1956, pointed out that in all cases an increase in liquid velocity past a surface was shown to raise the temperature difference required to initiate nucleate boiling at that surface. Hence the effect of temperature difference is likely to depend on the factors that change the velocity of the liquid film, notably cone speed, flow rate, and viscosity. The experiments described above were carried out in a Centritherm, rotating at constant speed, with a 30^{o} cone half - angle. As indicated by equation 14, (Jebson et al. 2003) there will be an increase in pressure with an increase in the rotational speed. This will cause a constant reduction in the effective temperature difference which will be proportionally greater at small temperature differences. Part of the increase in heat transfer coefficient with temperature difference observed in the experimental curves in figure 6 may be ascribed to this cause. However the liquid film in the Centritherm under the experimental conditions is fairly thin 0.02-0.03mm (figure 6, Chen et al., 1997) and the increase in temperature as a result of the increased pressure in the bubbles is not large. Bubbles form at imperfections in the surface, and are likely to remain fixed, impeding the liquid flow at least at the earlier stages of their growth. As the temperature difference increases the number of bubbles will increase and their impedance to the liquid flow will cause the film thickness to increase, increasing the pressure in the bubbles and further decreasing the available temperature difference.

The effect of changes in the temperature difference using water in an 87^{o} half-angle cone is shown in fig. 7. In this case the effect of droplets on the effective pressure difference, described in the theory, is important. Near the inner radius of the cone there are few droplets and the local pressure is close to the evaporating pressure. At greater radii the effect of the droplets travelling radially is to increase the local pressure. At low temperature differences a point is reached at which the local pressure is equal to the steam temperature, and beyond this point the evaporated vapour will condense back into the film, and there will be no vapours leaving the evaporator.

Speed of Rotation

Figure 4 shows the effect of the speed of rotation of the cone at different cone angles, and figure 7 shows the effect with different fluids. An increase of heat transfer coefficient with increasing rotating speed can be seen in these figures, indicating that the component of centrifugal force along the rotating surface plays a very important role in the heat transfer. As the rotating speed of the cone increases, then the speed of the liquid moving on the surface of the cone will increase, and the film thickness will reduce. Other effects shown in this figure are discussed in detail by Jebson and Parker, 2003.

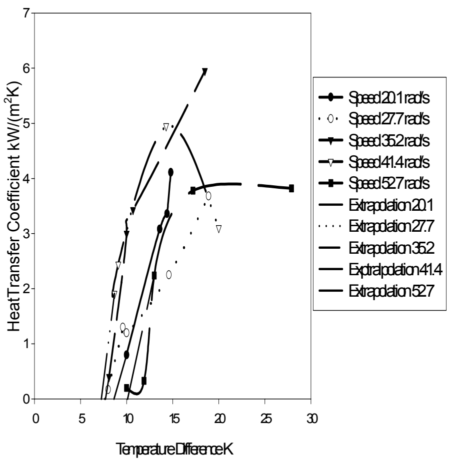

Figure 7. The effect of the rotational speed of the cone on the heat transfer coefficient for a Centritherm evaporator. Flow rate 0.025 kg sec. Temperature difference 10 ^{o}C.

Effect of Liquid Properties

Jebson and Parker, 2003, showed that of the liquid properties viscosity was the most important. However fig. 8 shows only a small drop in overall heat transfer coefficient with increasing viscosity when milk is evaporated.

Effect of Evaporating Temperature

Jebson and Parker, 2003, showed that an increase in the evaporating temperature increased the overall heat transfer coefficients slightly. The effect appeared to be associated with a decrease in viscosity.

Effect of Metal Properties

When overall heat transfer coefficients are of the order 1-3 kW/(m^2K) the thickness and thermal conductivity has little influence on the coefficient. When coefficients are of the order of those reported here, the resistance through the metal becomes important. In the dairy industry the necessity to use stainless steel limits ability to change the resistance but in the oil industry if high conductivity metals such as aluminum alloys are used, even higher overall heat transfer coefficients may be possible.

CONCLUSION

Rotating shallow cone evaporators are an effective means of evaporating liquids, and their use for distillation column reboilers would appear to be a distinct possibility.

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