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Concentration of liquid foods in a pilot-scale falling film evaporator

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INTRODUCTION

Evaporation is one of the most important unit operations in food processing. Large quantities of fruit and vegetable juices, sugar, and syrups are concentrated in several types of commercial evaporators.

In the concentration of many fruit juices and other heat sensitive materials, single pass evaporators are preferred, because the product quality is not damaged appreciably by the short time exposure to heat. Single pass evaporators include the tubular rising film, falling film, combination of these (8,9,16), and the plate and centrifugal types (2).

Experimental work on new products or new processing techniques is difficult in commercial units, because of the large volume of liquids required, and the inflexibility of the equipment to experimental manipulation. For this purpose, experimental work in small, pilot-scale evaporators is more economical and useful. Modern food and chemical research laboratories have installed various pilot evaporators, and some experimental results have been published in the literature (5,8,9,10).

After a preliminary survey of the pilot-scale evaporators, it was decided to install a falling film unit in the pilot plant of the Geneva Food Research Laboratory. Falling film evaporators are used extensively in the food industry, but there is only limited published information on their performance under various operating conditions. The proposed falling film evaporator was relatively easy

to construct and operate, and experimental data obtained with it could be scaled up to larger units. The main body of the evaporator would be a vertical tube, similar to those used in the commercial units. The use of stainless steel equipment would provide more reliable data than using a glass evaporator, operated under laboratory conditions (20).

This report contains the experimental work and results obtained in the evaporation of water, apple and grape juices, and soymilk. The emphasis is on the physical and engineering aspects of evaporation; i.e., evaporation rates, fluid flow, heat transfer, and scale formation. The chemical and quality changes are not covered in this report, and it is recognized that further work on specific products is needed in this direction. The pilot-scale evaporator can be considered as an experimental chemical reactor, in which time and temperature may influence the rates of various chemical reactions (7).

—PILOT SCALE FALLING FILM EVAPORATOR—

The principle of falling film evaporation is illustrated in Figure 1; The liquid feed is pumped through a preheater to the top of the evaporator tube, and it is distributed as a liquid film on the tube walls. The main body of the evaporator consists of a vertical tube, surrounded by a steam jacket. Evaporation takes place as the liquid film flows down the tube, and the generated vapors flow concurrently with the liquid into a vapor-liquid separator, located at the bottom of the tube.

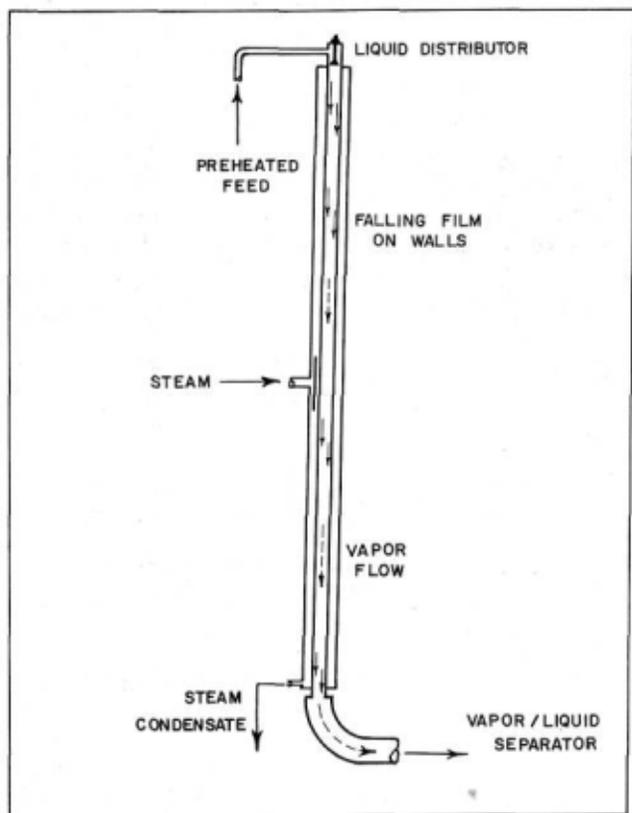


Fig. 1.—Principle of falling film evaporation.

Figure 2 is a diagram of the pilot-scale evaporator installed in the Food Research Laboratory of the New York State Agricultural Experiment Station, Geneva, N. Y. The whole unit was designed and constructed at the Geneva Laboratory. Preliminary design calculations were made for sizing the critical parts of the unit; i.e., the preheater, evaporator, separator, and the condenser, using accepted fluid flow and heat transfer equations (3,6). As a basis of the design, the evaporator tube was selected to be of 2 in. O.D., 10 ft. long, operated at a liquid feed rate of 1.0 to 1.5 gpm.

The main parts of the installation are shown in Table 1. All equipment coming into contact with the liquid food and condensate was made of 304 stainless steel.

The feed pump is adjusted to the desirable speed with a Reeves manually adjustable mechanism. The discharge pump has an electronic variable speed drive (Ratiotrol, Boston Gear Co.). The feed flow rate was measured with a calibrated rotameter of maximum capacity 1.94 gpm.

The preheater is essentially a double pipe heat exchanger with a stainless steel plug inserted in the inner tube to improve heat transfer. The plug was satisfactory with water and dilute juices, but viscous products were pumped with some difficulty, as evidenced by the sharp increase in

pressure drop (up to 100 psig), measured with a pressure gauge at the entrance of the preheater.

In early experiments the liquid feed was distributed at the top of the evaporator tube with a spray nozzle (Spray Systems Co., Deflector nozzle 8686, 1/8, 0.75, 150). The nozzle performed well with water and dilute juices. However, because of the high pressure drops and the possibility of plugging with viscous products, it was replaced with the bell-type distributor, which was similar to the Blaw-Knox ferrule (4).

For visual inspection of the vapor-liquid separator and the flow of concentrate into the discharge pump, two Pyrex glass sections were installed, a cylindrical part in the separator (12-1/2 in. diameter x 36 in.), and a tube section (2-1/2 in. diameter x 12 in.) between the separator and the pump.

The discharged product was cooled to room temperature by pumping through a double-pipe coil (Parker 3101, 6-12-10x, 3/8 in. O.D. inner tube, 20 ft. long). Very viscous products were pumped with difficulty, and a different heat exchanger should be used for such materials.

In both preheater and evaporator, steam was introduced at the middle of the jacket, and special baffles were installed at the steam entrance for better distribution of the steam. Vents from the top and bottom of the steam jackets were connect-

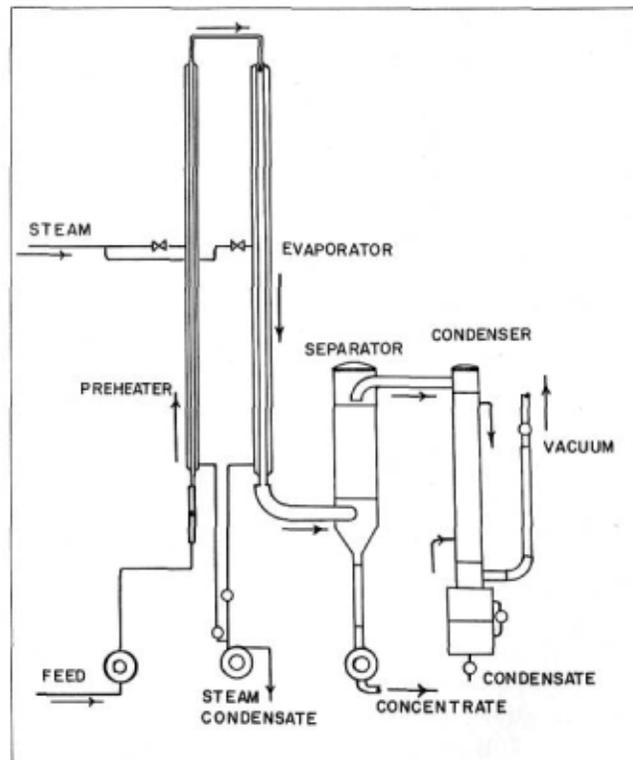


Fig. 2.—Pilot scale falling film evaporator, New York State Agricultural Experiment Station.

Table 1. Main Parts of Pilot-Scale Falling Film Evaporator

Feed Pump	Waukesha 2R, sanitary type
Preheater	Inner tube, 1 in. O.D. (16 ga.), 9 ft. long, inside surface area, 2.05 sq.ft. Center plug, 13/16 in. O.D., 1.91 sq.ft. Jacket tube, 3.5 in. O.D. (Sch. 5)
Evaporator	Distributor, Bell-type, 1.57 in. diameter, 90 Inner tube, 2 in. O.D. (16 ga.), 10 ft. long, inside surface area, 4.9 sq.ft. Jacket tube, 4.5 in. O.D. (Sch. 5)
Separator	Separator body, 11.5 in. I.D., inlet to outlet distance, 38 in. Inlet diameter, 3.834 in. I.D. Outlet diameter, 3.334 in. I.D.
Discharge Pump	Waukesha 10 DO, sanitary type
Condenser	Vertical, condensing in tube side. 36 tubes, 5/8 in. O.D., 0.527 in. I.D., 4 ft. long, surface area, 23.5 sq.ft. Shell diameter, 6 in. I.D.
Condensate Receiver	Capacity, 2.04 gal. (upper), 2.72 gal. (lower)
Steam Condensate Pump	Weinman, vortex liquid ring

ed to the vacuum line for the removal of non-condensable gases. The steam pressures were maintained at set values by two Taylor 440R controllers, having an operating range of 30 in. Hg vacuum to 30 psig. The steam condensate was removed through two Sarco B66 traps. In vacuum operation of the steam jackets, the condensate was removed with the Weinman pump, which could maintain a vacuum of 28 in. Hg. When heating under vacuum, the superheated steam was cooled to near saturation by sprays of cold water.

The evaporator was evacuated by connecting the bottom of the condenser to the vacuum line through a 2-1/2 in. pipe. Vacuum was measured by two dial gauges and was controlled manually with a valve. A Pyrex glass tube, 3-1/2 in. diameter x 24 in., packed with ceramic sandles, was installed between the condenser and the vacuum valve, for washing the inert gases of any volatiles escaping into the vacuum line.

The condenser operates with cooling water (50° to 70° F) in the shell side and the vapor condenses in the vertical tubes. The flow rate of water was

measured with a rotameter, and it was found that 20 gpm was satisfactory in most experiments. By material balance, it was found that normally all evaporated water was collected as condensate. Some losses of water vapor into the vacuum line were found when operating at boiling temperatures lower than 90° F. These losses increased at high evaporation rates, ranging from 5 to 14 per cent of the condensate. An appropriate correction was made in the calculation of the condensate rate under such conditions.

Evaporative Capacity

The evaporative capacity of the pilot-scale evaporator was calculated from the weight of condensate collected for a fixed period of time. Corrections, when applicable, were made for radiation losses in the separator, and for vapor losses in high vacuum operations. Thus, the evaporation rate;(*w*) of water in the evaporator tube was estimated in lb./hr., for any set of experimental conditions. The feed rate of the liquid was measured either with the calibrated rotameter, or by weighing the feed tank periodically.

The over-all heat transfer coefficient (*U*) in the evaporator was calculated from the equation $w\lambda = UA\Delta T$, where *w* is the evaporation rate, *X* is the heat of vaporization of water, *A* is the heat transfer area, 4.9 square feet, and *AT* is the temperature difference. The heat of vaporization of water was taken at the boiling temperature, measured with a dial thermometer at the entrance of the separator. The steam temperature was taken from steam tables, assuming that the steam, in the heating jacket, was saturated at the indicated pressure.

Radiation losses from the separator, at boiling temperatures up to 130° F, were negligible. At higher temperatures, especially at 212° F, these heat losses may be significant. When the evaporator was operated at atmospheric pressure, a film of condensate could be seen falling down the glass walls of the separator. The following calculation gives an idea of the possible radiation losses at 212° F: Assume room temperature, 82° F. Temperature difference between separator and room, 130° F. Surface of the separator, 9.2 square feet. Combined radiation and convection heat transfer coefficient (6), 2.4 Btu/hr.sq.ft.°F. Heat losses are equal to 2.4 x 9.2 x 130 = 2,850 Btu/hr. For a mean evaporation rate of water of 100 lb./hr., the radiation losses at 212° F are 2.85 per cent. Therefore, a correction of 3 per cent was made in calculating the evaporation rate at 212° F from the weight of condensate.

Various liquids were evaporated in the experimental evaporator in order to obtain a picture of its capacity and operating problems. Water was used extensively in the early tests, which provided useful data needed in the subsequent work with food products.

Three types of apple juice were prepared in the Geneva pilot plant from New York State apples. McIntosh apples were ground in a hammer mill, the pulp was mixed with a press aid (wood pulp) and then extracted in a continuous screw press. Unfiltered apple juice was prepared by passing the extracted juice through a vibrating screen (Sweco, 94 mesh bolting cloth). Cloudy apple juice was obtained from the screened juice by filtration through a rotary vacuum filter, using a Celite 503 precoat. Depectinized apple juice was prepared by treating the screened juice with a depectinizing enzyme preparation and filtering through the rotary precoat filter.

Filtered Concord and Delaware grape juices were prepared from stemmed and crushed grapes, by extraction in the continuous screw press, using the appropriate amount of press aid. The extracted juice was passed through the Sweco screen and filtered through the rotary precoat filter. Clarified Concord grape juice was prepared by treating the crushed grapes with a commercial depectinizing enzyme at 140° F for 45 minutes, and passing the juice through the Sweco screen and the rotary precoat filter. Part of the depectinized grape juice was stored at 25° F for about 9 months for precipitation of the tartrates.

Soy milk, containing 7 per cent total solids, was prepared by presoaking soybeans in distilled water at 50°C for 2 hours, and then grinding in a Bauer attrition mill at a setting of 0.001 in., using #6945 grinding plates. Feed rate to the mill was 780g of soaked beans and 10 liters of water per minute, with live steam injection. The resulting slurry was filtered through a pilot-scale filter press. 1

EVAPORATION OF VARIOUS LIQUIDS

Evaporation of Water

The pilot-scale evaporator was tested thoroughly by evaporating tap water, before any liquid food was concentrated. The purpose of these tests was to establish the principal parameters that influence the evaporative capacity of the unit. Over-all heat transfer coefficients (U) were calculated from the experimental data, and they were used for comparison of the evaporative capacity. Variables investi-

gated were the boiling temperature, the liquid flow rate, and the temperature difference. Boiling temperature had the greatest effect on the ' U ' value and temperature difference was the least important variable.

Figure 3 shows that the heat transfer coefficient ' U ' increased from 260 to 420 as the boiling temperature of water was increased from 90° to 212° F. The rise in heat transfer rate was more rapid from 90° to 120° F. At boiling temperatures higher than 130° F, the coefficient ' U ' increased linearly with temperature, but at a much slower rate.

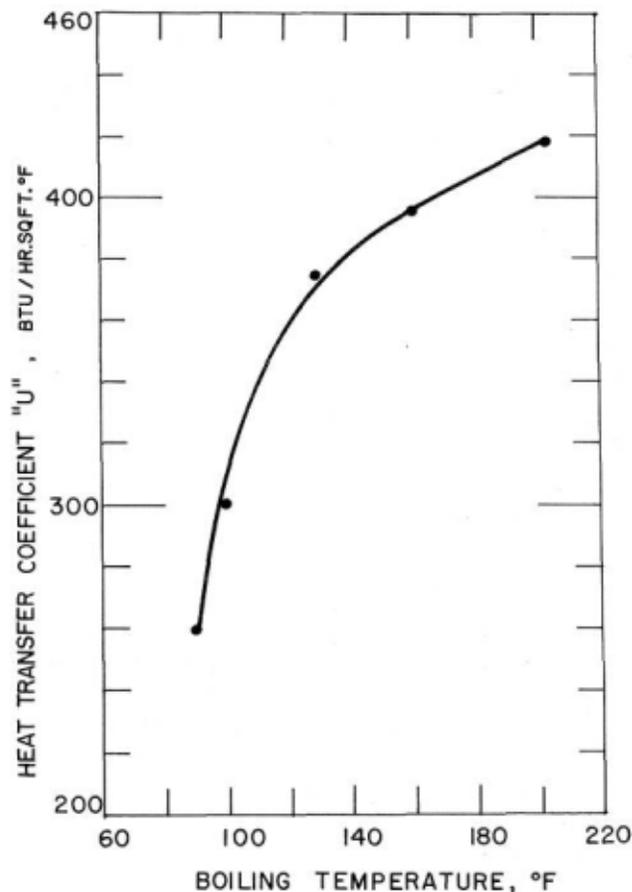


Fig. 3.—Evaporation of water.

The direct relationship between boiling temperature and evaporation rate has been found in several types of evaporators (17). It is attributed to the progressive decrease of liquid viscosity (water or other liquid) at higher temperatures. As discussed later, viscosity has a strong effect on the heat transfer coefficient of the falling liquid film.

The liquid flow rate of the feed had no effect on the evaporation capacity at rates 1.5 gpm or higher. There was a continuous decrease in evaporation

rate as the liquid flow was reduced below 1.5 gpm (Fig. 4).

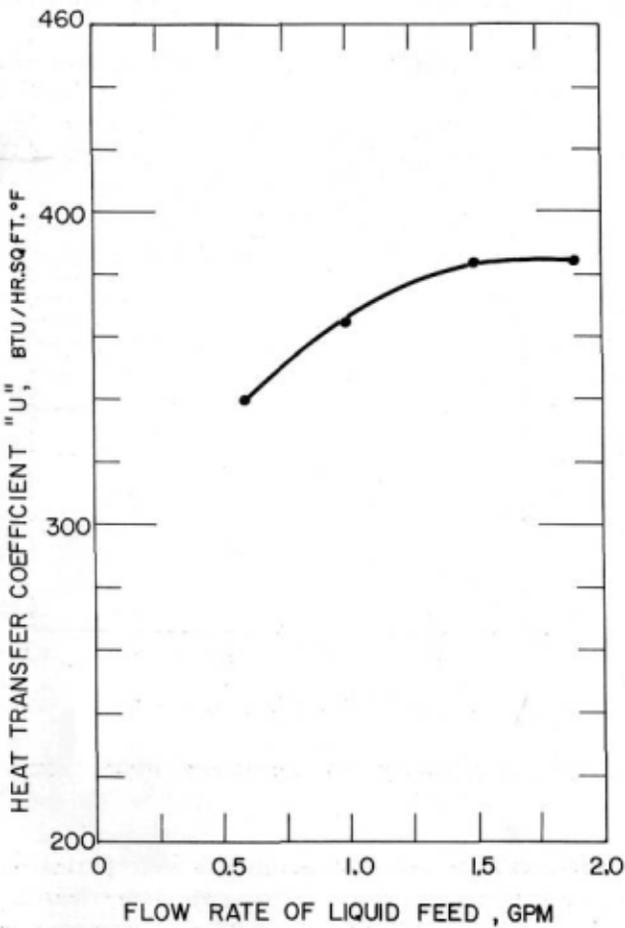


Fig. 4.—Evaporation of water at 130° F.

It seems that, at lower liquid rates, the tube walls are not covered thoroughly with the liquid film, resulting in a decreased evaporative capacity. Higher water evaporation rates were obtained, at low liquid flow rates, when the spray nozzle was used instead of the normal bell distributor. The spray nozzle appeared to give a better liquid distribution at low liquid rates. However, its use is limited to water and other low-viscosity liquids. Highly viscous liquids were handled with difficulty in the spray nozzle, causing excessive pressures in the feed line.

In almost all subsequent experiments, a constant liquid flow rate of 1.5 gpm (corresponding to a feed of 750 lb/hr of water) was used.

Temperature difference, between the steam jacket and the boiling liquid, had only a small effect on the heat transfer coefficient (Fig. 5). The relatively small effect of temperature difference

and liquid flow is characteristic of the falling film evaporators, as reported in the literature (17,19). In other types of evaporators, notably rising film and forced circulation, temperature difference and liquid flow rate have a much higher effect on the heat transfer coefficient because the resulting higher turbulence increases the film heat transfer coefficient in the evaporator tube. In the falling film evaporator, water evaporates mainly from the surface of the liquid film, and liquid turbulence is expected to have a small effect on evaporation. Available temperature differences may be limited in falling film evaporators operating in a multiple effect system. High temperature differences may cause excessive vapor velocities, creating erosion problems at the exit of the tubes. Most of the evaporation data, presented in this report, were obtained at temperature differences of 60 to 100° F.

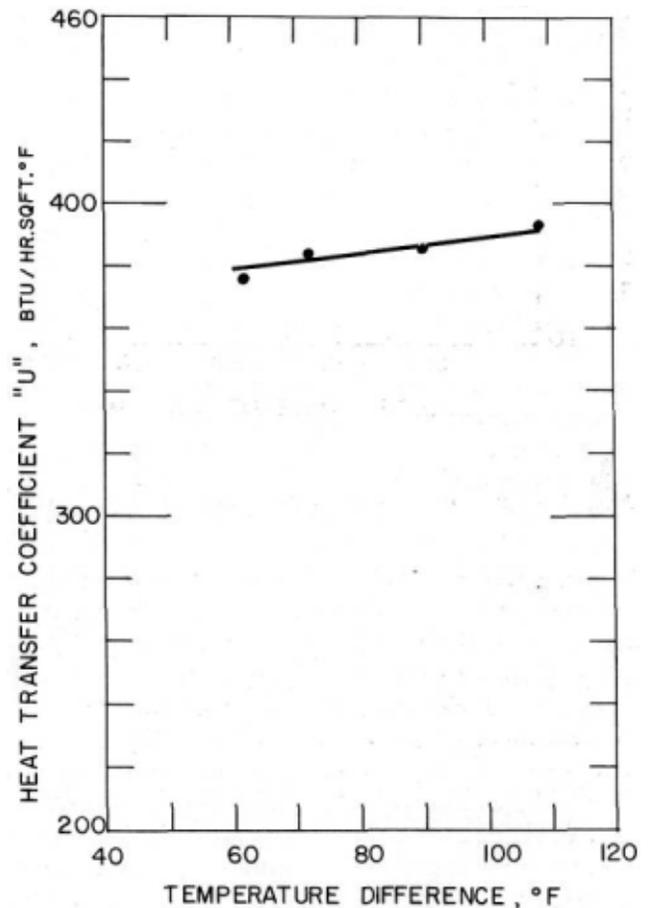


Fig. 5.—Evaporation of water at 130° F.

Concentration of Apple Juice

Various types of apple juice were evaporated in order to establish the main parameters affecting

evaporation. The most important variable was the degree of clarification of the apple juice. Depectinized apple juice, free of any suspended solids, was evaporated very effectively, obtaining the over-all heat transfer coefficients shown in Figure 6.

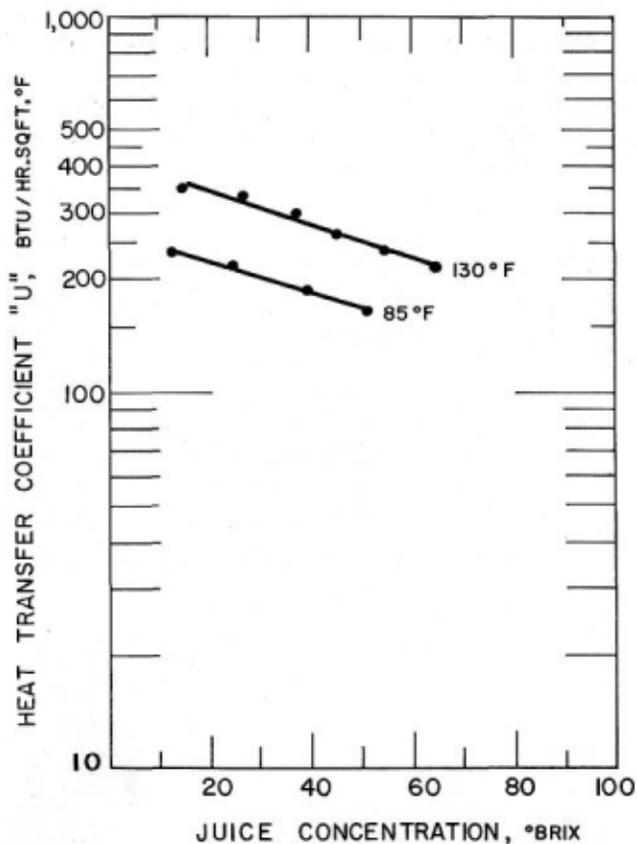


Fig. 6.—Evaporation of depectinized apple juice.

Depectinized apple juice was evaporated more effectively at higher boiling temperatures, following a curve similar to that of water (Fig. 3) and grape juice (Fig. 8). The gradual decrease of heat transfer at higher concentrations, shown on Figure 6, is expected on account of the higher liquid viscosities. At high juice concentrations, evaporation is facilitated if higher boiling temperatures are used (14).

Unfiltered apple juice, containing large amounts of suspended and colloid solids, was concentrated at considerably lower rates than the depectinized juice (Fig. 7). Boiling temperature had a smaller effect on the heat transfer coefficients of the unfiltered juice and the evaporation rate decreased rapidly at higher juice concentrations. The viscosity increased rapidly with concentration and the 60° Brix concentrate formed a solid gel upon cooling to room temperature.

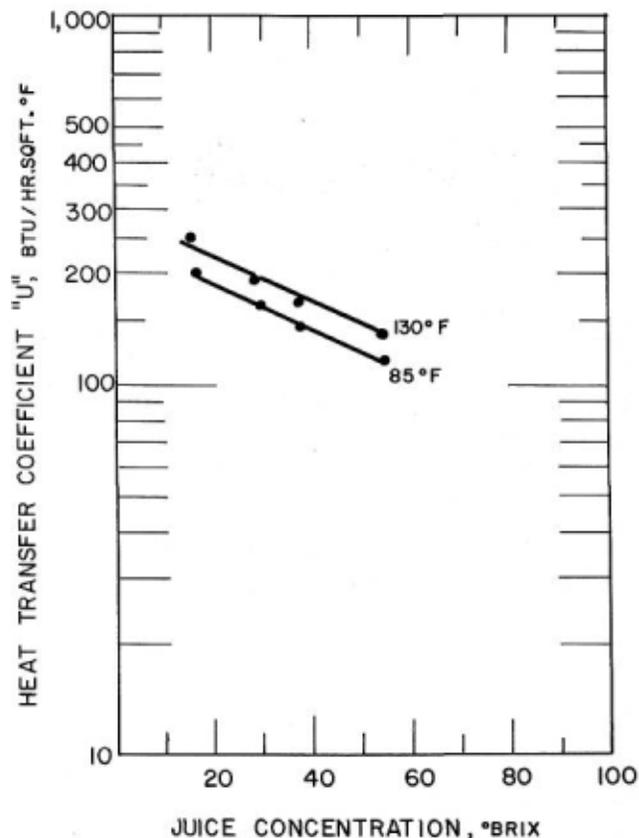


Fig. 7.—Evaporation of unfiltered apple juice.

Some concentration experiments were performed with precoat filtered, but not depectinized, apple juice. This cloudy juice was evaporated effectively at boiling temperatures up to 150°F, obtaining heat transfer coefficients similar to those of depectinized apple juice. At boiling temperatures higher than 150° F the evaporative capacity of the experimental evaporator decreased substantially, even when dilute (fresh) juice was used. The significant decrease in the heat transfer coefficients was attributed to the marked increase of fouling in the evaporator tube at the high boiling temperatures. The suspended solids in the cloudy (and the unfiltered) juice had a tendency to precipitate on the evaporator tube, particularly at high temperatures, and the deposited film cut down the rate of heat transfer. The fouling effect was very high when evaporation was attempted at atmospheric pressure (212° F). The cloudy apple juice could be concentrated up to 65° Brix, resulting in a very viscous thixotropic product. On the other hand, liquid concentrates of 75° Brix of depectinized apple juice were prepared easily in the experimental evaporator.

Cloudy and unfiltered apple juices are pseudo-plastic (non Newtonian) fluids, particularly at concentrations higher than 30° Brix, while

depectinized juice is a Newtonian fluid at all concentrations. The apparent viscosity of the pseudoplastic juices decreases only slightly at higher temperatures, in contrast to the Newtonian juices, where temperature has a profound effect on viscosity, especially at high concentrations (14).

Other fruit juices, containing suspended solids, are expected to behave in a manner similar to cloudy apple juice in a falling film evaporator. For example, orange juice has rheological properties similar to cloudy apple juice (14). Actual experimental tests are, however, necessary with the particular juice before a large commercial evaporator is installed.

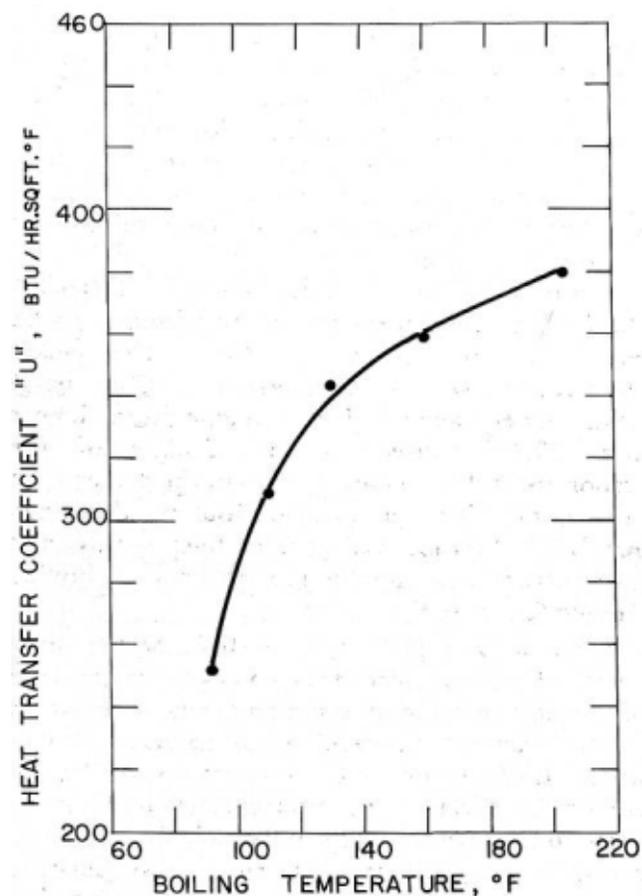


Fig. 8.—Evaporation of clarified Concord grape Juice.

Concentration of Grape Juice

As in the case of apple juice, clarification was the most important variable in the evaporation of grape juice. Concord grape juice, clarified by treatment with pectic enzymes followed by pre-coat filtration, was concentrated effectively, obtaining heat transfer coefficients similar to those of depectinized apple juice. Figure 8 shows that

the evaporative capacity of fresh clarified grape juice increases as the boiling temperature is increased, in a manner similar to the evaporation of water.

Concord grape juice contains significant amounts of tartrates, which tend to precipitate as the juice is concentrated, with an apparent decrease in evaporative capacity of the evaporator. Part of the tartrates can be removed before evaporation by cold storage of the juice for a period of several days. The evaporation of clarified and cold-stored Concord grape juice is shown in Figure 9.

At grape juice concentrations higher than 50° Brix, the evaporative capacity decreased more sharply than in depectinized apple juice of the same concentration (Fig. 6). This difference may be attributed to the higher viscosity of Concord grape juice at concentrations higher than 50° Brix, as compared to apple juice (13). Concord grape juice is a Newtonian fluid up to 50° Brix, which changes into a pseudoplastic fluid at higher concentrations. This change may be due to the precipitation of tartrates and other suspended solids. Concentrates of 70° Brix clarified grape

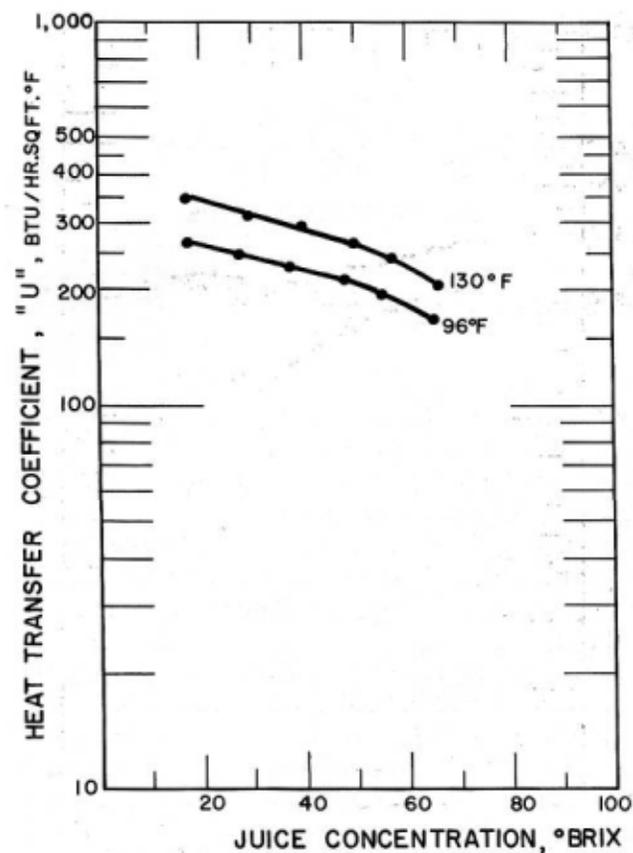


Fig. 9.—Evaporation of clarified, cold-stored Concord grape juice at 96° and 130° F.

juice were produced experimentally by employing higher boiling temperatures at the last stages of evaporation.

Figure 10 shows the evaporation rates of filtered Concord and Delaware grape juices at 130° F.

Both juices were cold-pressed and precoat filtered but they were not clarified by enzyme treatment. The juices were evaporated immediately after preparation. Delaware juice was evaporated at a relatively high rate, similar to that of clarified Concord grape juice (Fig. 9). The unclarified Concord juice was evaporated at a substantially lower rate, particularly as the juice concentration was increased. The significant difference in evaporative capacity is evidently due to differences in composition between the two juices. The Concord juice was generally more viscous and it deposited a film on the evaporator tube, which reduced the heat transfer rate. Because of the high viscosity and the presence of large amounts of suspended solids, Concord juice could not be concentrated higher than 52° Brix, and the concentrate formed a gel upon cooling. The Delaware juice contained less suspended solids and it remained fluid at concentrations up to 65° Brix. These experiments demon-

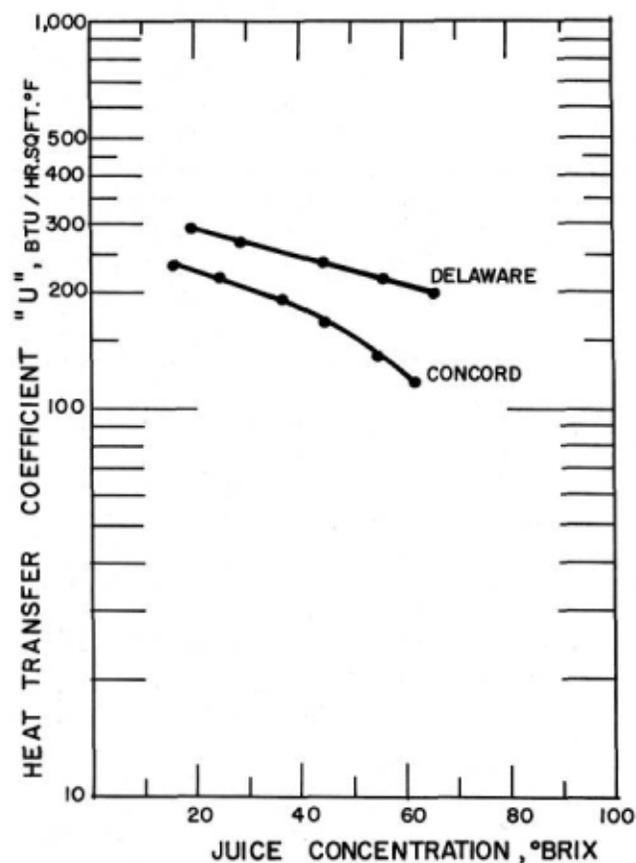


Fig. 10.—Evaporation of cold pressed, filtered Concord and Delaware grape juices at 130° F.

strate the need for thorough clarification of the juices before evaporation.

The selection of a boiling temperature, for optimum operation of the falling film evaporator, depends primarily on the composition and the heat sensitivity of the liquid food. For fruit juices, our experience with the pilot scale evaporator suggests an optimum temperature of about 130° F. Higher temperatures may cause progressive fouling of the evaporator tube and heat damage to the product (10), while lower temperatures result in lower heat transfer coefficients and very high viscosities of the concentrated liquid.

Concentration of Soymilk

Soymilk, an aqueous extract of soybeans containing about 7 per cent total solids, may be evaporated to produce a fluid concentrate, which may be further spray-dried. Soymilk is very sensitive to heat, and concentration at high temperatures has been found to cause gelation. It was found necessary to operate the evaporator at low boiling temperatures.

Figure 11 shows the heat transfer coefficients obtained in concentrating soymilk from 7 to 22 per cent total solids at 85° F. The jacket temperature was maintained at 150°F, using steam under vacuum. Jacket temperatures higher than 150°F caused a rapid fouling of the evaporator tube, resulting in a sharp decrease of the evaporation rate. This fouling depended mainly on the tube wall (jacket) temperature, and it occurred even at the lowest possible boiling temperature (80° F).

Soymilk is a pseudoplastic fluid which upon concentration becomes very viscous and thixotropic. Its proteins must be very sensitive to heat, because they tend to precipitate rapidly when they come into contact with heated evaporator surfaces. Soymilk appears to be more heat-sensitive than cow's milk, which can stand higher temperatures without appreciable precipitation of proteins. The need for low jacket temperatures suggests the use of circulating hot water as the heating medium. However, hot water is expected to result in lower over-all heat transfer coefficients.

Stripping of Volatile Aromas

The falling film evaporator is basically a one-pass flash evaporator with a very short residence time of the treated liquid. It is, therefore, a useful piece of equipment for the stripping of volatile aroma compounds from fruit juices and other liquid foods.

Most of the volatile aroma compounds,

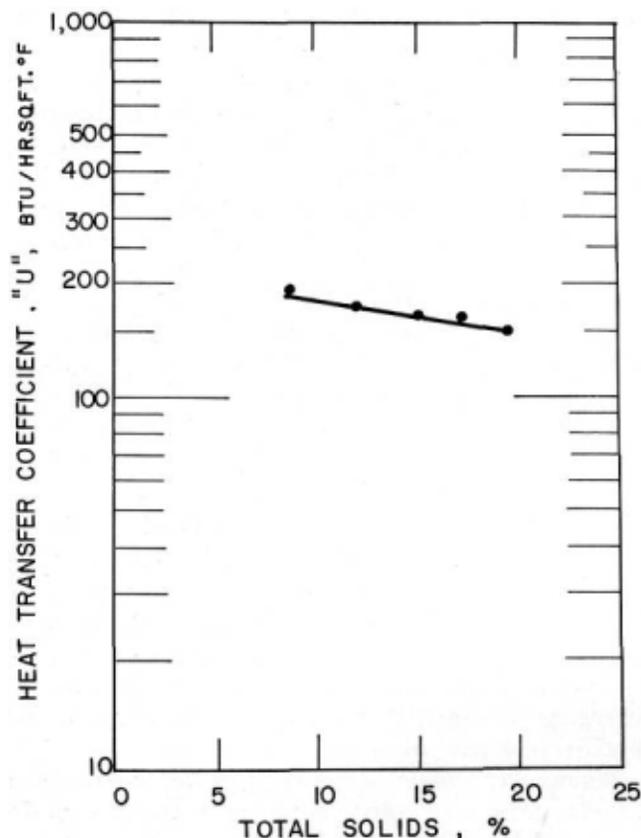


Fig. 11.—Evaporation of soymilk at 85° F.

consisting of esters, alcohols, and aldehydes, can be stripped effectively by flash evaporation of a certain portion of the fruit juice, normally 10-30 per cent. Some high-boiling aroma compounds, like methyl anthranilate in Concord grape juice, are less volatile and they require stripping in multiple-plate columns, operating at high boil-up rates (11,15).

The pilot-scale evaporator was used in a number of experiments for the stripping of volatile esters from synthetic solutions and fruit juices (21). It was found that very volatile esters, like ethyl acetate and ethyl butyrate, were recovered thoroughly (about 90%) by stripping 10-15 per cent of the aqueous solutions at atmospheric pressure. Similar recoveries of volatile esters were obtained in stripping apple and grape juices.

Recovery of the volatile esters under vacuum was less efficient, because of the loss of a significant portion into the vacuum line. It is possible that the losses in vacuum can be prevented by using lower condenser temperatures, and by trapping or scrubbing the volatiles with cold water. However, these experiments indicate that operation at atmospheric pressure is very

efficient, provided that the juice is not damaged by the elevated temperature.

FLUID FLOW AND HEAT TRANSFER

Residence Time

In falling film evaporators, very short residence times are achieved, because the liquid flows through the evaporator tube in one pass, and there is no recirculation or significant liquid hold-up. Considerably longer residence times are characteristic of other types of evaporators, such as rising film and forced circulation (7). Since changes in quality of liquid foods during evaporation are a function of temperature and time, high temperatures can be tolerated when the residence time is short.

The residence time in an evaporator can be determined experimentally by injecting a trace compound (dye or electrolyte) in the feed and measuring the time required for its disappearance in the discharged concentrate. Experimental residence times reported in the literature range from 1.5 minutes for falling film to 4.0 minutes for rising-falling film evaporation of sugar solutions (7,8,9). The residence time can be calculated as the ratio Q/W , where Q is the hold-up volume of the liquid in the evaporator, and W is the mean liquid flow rate. The difficulty, in this case, lies in determining the hold-up volume of the liquid, which, in a falling film unit, is relatively small. Calculated residence times range from 9 seconds for falling film to 20 seconds for rising-falling film evaporation of sugar solutions (7,9). It should be noted that the shortest residence time (7 sec.) may be obtained in a centrifugal evaporator (2). Residence time in the agitated film evaporators is about 25 seconds (12).

The relatively longer residence times obtained in trace experiments may be due, in part, to the fact that the measurement of trace concentration is made after the product is pumped out of the evaporator. There may be a significant time lag between the moment the liquid appears at the exit of the evaporator tube and the moment the measurement is made on the discharged liquid. This difference is very important when the residence time is very short, as in the case of a falling film evaporator.

Some measurements of residence time were made during the evaporation of water in our pilot-scale evaporator. Tap water was used, which was made alkaline by adding 50 g of sodium hydroxide in 100 kg of water. After the evaporator reached a steady state operation, a solution of phenolphthalein in ethanol was

injected at the top of the evaporator tube. The resulting red color was observed visually in the glass tube located between the vapor-liquid separator and the extraction pump. The residence time was taken as the time interval, measured with a stopwatch, from the moment of dye injection until all color disappeared from the liquid discharged from the bottom of the evaporator tube. All measurements were made with a liquid feed rate of 1.5 gpm. The residence time varied from 10 to 15 seconds, and a maximum color intensity was observed about midway. Boiling temperature (85°, 130°, and 212°F) had little effect on the measured residence time. Although the visual method lacks the accuracy of instrumental readings, reproducible results were obtained, which were useful as a preliminary information.

A theoretical calculation of the residence time is possible, employing fluid flow equations for falling liquid films. The flow rate of a liquid film (Γ) in a vertical tube of diameter D is given by the equation

$$\Gamma = \frac{W}{\pi D}$$

where W is the gravimetric flow rate. The thickness $[m]$ of the liquid film is given by the equation

$$m = \left(\frac{3\Gamma\mu}{g\rho^2} \right)^{1/3},$$

where μ is the viscosity and ρ is the density of the liquid at the mean film temperature (3). The gravity constant g is taken in appropriate units. The average film velocity (V) is then calculated as

$$V = \frac{\Gamma}{m\rho}$$

Finally, the residence time is equal to L/V , where L is the length of the tube. For water at 130°F and at a mean liquid flow rate of 1.2 gpm, the film thickness becomes 0.017 inch, the average liquid velocity is 3.6 ft/sec, and the residence time becomes 2.7 seconds. At 212°F the calculated residence time was 2.2 seconds.

It was concluded that the equations for film flow can be used only as an approximation, giving residence times shorter than the experimental values. In liquids other than water, the film thickness and the residence time are expected to vary approximately with the cube root of the film viscosity (when the liquid flow rate is kept constant). For example, 60° Brix depectinized apple juice has a viscosity of 13 cp at 130°F, while water at the same temperature is only 0.51 cp. If the residence time for water is 2.7 seconds, then the residence time for the apple juice concentrate will be

$$2.7 \times \left(\frac{13}{0.51} \right)^{1/3} = 8 \text{ sec.}$$

In comparing residence times in various evaporators, the tube length should be taken into consideration. Many industrial units have tubes 15 feet or longer, which result in residence times longer than the 10 foot tubes.

Vapor Velocities

The vapor velocity in the falling film is expected to increase gradually from near zero at the top to the maximum exit velocity at the bottom of the tube. The exit vapor velocity is a function of the evaporation rate and the absolute pressure in the evaporator. Assuming that all evaporation takes place in the evaporator tube; i.e., that there is no flashing in the vapor-liquid separator, the exit vapor velocity is equal to

$$V = \frac{144wv}{900\pi D^2}$$

where, w is the evaporation rate (lb/hr), v is the specific volume of water vapor and D is the internal tube diameter (1.87 in.). The following three typical exit vapor velocities were calculated, at the indicated boiling temperatures: 63 ft/sec (212°F), 560 ft/sec (130°F), and 900 ft/sec (85°F).

The exit vapor velocity, at a given boiling temperature, can be increased by increasing the temperature difference (i.e., the steam pressure in the jacket). High vapor velocities are, in general, desirable, because they promote heat transfer in the evaporator tube. Exit vapor velocities higher than 1,000 ft/sec were obtained at low boiling temperatures by applying high temperature differences. These high vapor velocities increased the liquid entrainment in the separator, and they caused some erosion at the exit of the evaporator. In selecting the operating conditions for an evaporator, the vapor velocities should be chosen carefully.

Pressure drop, due to vapor flow, along the evaporator tube is expected to be relatively low. Calculation of pressure drops at various boiling temperatures, using mean vapor velocities, gave values of 1 to 4 mm Hg, which would have a negligible effect on the boiling point along the evaporator tube. In an attempt to confirm these calculations, the vapor temperature near the top of the evaporator was measured with a thermocouple, and it was found to be about the same as the temperature at the exit of the evaporator tube.

Liquid Entrainment

The centrifugal vapor-liquid separator of the

pilot-scale evaporator performed well under normal operating conditions. Calculated vapor velocities in the separator ranged from 1.7 ft/sec at atmospheric pressure to 24 ft/sec at 28.5 inches of vacuum. These velocities are below the recommended design velocities for vapor-liquid separators (18).

The glass section of the separator was very convenient for visual inspection of entrainment during operation of the evaporator. At boiling temperatures higher than 130°F, little entrainment could be detected visually. At lower temperatures, especially below 100° F, the high vapor velocities caused a violent turbulence at the entrance of the separator and some liquid was entrained as mist in the vapor. The entrainment was evident in the condensate, which had a faint pink color when Concord grape juice was evaporated.

In an attempt to measure the liquid entrainment quantitatively, Concord grape juice was evaporated under various conditions and the condensate was analyzed for red color. The concentration of the red pigments in the condensate was measured in a Bausch and Lomb Spectronic 20 photometer, using dilute solution of grape juice for calibration. By this method, a minimum of 50 ppm of grape juice could be detected on the condensate. No entrainment was detected at boiling temperatures of 150° and 212-F.

The following entrainment, expressed as per cent of juice in the condensate, was found at lower temperatures: 0.02 to 0.10% (at 130° F), 0.02 to 0.15% (at 110°F), and 0.15 to 0.40% (at 90° F). It is evident from these measurements that liquid entrainment is caused by very high vapor velocities in the separator, which are the result of high evaporation rates and high vacuum. It is possible that entrainment may be reduced by baffles, arranged at appropriate locations in the separator.

Heat Transfer Coefficients

The over-all heat transfer coefficients obtained in evaporating water were similar to those reported in the literature, as in the evaporation of sea water in long tube falling film evaporators (17). In water desalination, the main objective of development is to reduce the cost of evaporation by improving heat transfer and heat economy. Heat transfer is improved by using new metals or alloys which are better heat conductors than stainless steel, and that resist corrosion. New metal treatments to promote nucleate boiling, and new shapes of the evaporating surface have also been proposed, resulting in substantial

increases of the heat transfer coefficients. Heat economy is accomplished by multiple-effect operation.

In the evaporation of fruit juices and other liquid foods, high heat transfer coefficients are desirable, but other considerations are of equal importance. These are related to the heat damage of the product and the cleaning and sanitizing of the evaporating equipment. Stainless steel is used extensively in the food industry, because it possesses most of the desired qualities, although it is not a very good heat conductor. Operating conditions in food evaporation are selected as a compromise of good heat transfer and minimum heat damage to the product.

The experimental heat transfer coefficients, obtained in the pilot-scale evaporator, for water and depectinized apple juice, were compared with the calculated coefficients, using heat transfer equations developed for falling films (3,6). The heat transfer coefficient for a film of water falling on a vertical wall is given by the equation

$$h_i = 120 (Re)^{1/3}$$

where the Reynolds number is

$$Re = \frac{4\Gamma}{\mu}$$

Thus, for water at 212°F, flowing at a mean liquid rate of 1.2 gpm,

$$\Gamma = \frac{W}{\pi D}$$

$$\text{or, } \Gamma = \frac{1.2 \times 8.3 \times 60 \times 12}{3.14 \times 1.87} = 1,200 \text{ lb/hr.ft.}$$

The viscosity of water at 212°F is $\mu = 0.285 \text{ cp} = 0.285 \times 2.42 = 0.685 \text{ lb/hr.ft.}$

$$Re = \frac{4 \times 1,200}{0.685} = 7,000 \text{ and } h_i = 120(7,000)^{1/3} = 2,300 \text{ Btu/hr.sq.ft.}^\circ \text{F.}$$

Assuming that the evaporator tube is clean (no scale), the over-all heat transfer coefficient (U) is calculated from the equation

$$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_s} + \frac{x}{k}$$

where h_s

is the steam side coefficient, assumed to be 1,500 Btu/hr.sq.ft.°F, x is the tube wall thickness (0.065 inch), and k is the thermal conductivity of stainless steel (105 Btu/hr.sq.ft.°F/inch). For

$$h_i = 2,300,$$

U becomes 570 Btu/hr.sq.ft.°F.

A similar calculation for water at 130°F results in $U = 530 \text{ Btu/hr.sq.ft.}^\circ \text{F}$. The experimental values for water were 420 at 212°F, and 385 at

130° F. Evidently, the heat transfer equation gives values of U about 30 per cent higher than the experimental results.

For liquids other than water, the following equation has been suggested (6).

$$h_i = 0.01 \phi (Re)^{1/3} (Pr)^{1/3}$$

where Re is the Reynolds number, defined previously, Pr is the Prandtl number

$$Pr = \frac{C_p \mu}{-k}$$

and

$$\phi = \left(\frac{k^3 \rho^2 g}{\mu^2} \right)^{1/3}$$

The viscosity μ , the specific heat C_p , and the density ρ are taken at the liquid film temperature. The gravity constant g is taken in appropriate units.

Table 2 shows the calculated over-all heat transfer coefficients for the evaporation of depectinized apple juice at 130° F and at a mean liquid flow of 585 lb/hr.

The viscosities of the depectinized apple juice were determined experimentally (14). The thermal conductivities and the specific heats were taken from data of sucrose solutions at the same concentration (18). The steam-side heat transfer coefficient was taken as 1,500 Btu/hr.sq.ft.° F.

Table 2 shows that the calculated over-all heat transfer coefficients (U) were in good agreement with the experimental values up to about 40° Brix. At higher juice concentrations, the

calculated coefficients were significantly lower than the experimental values, and this deviation became very large above 50° Brix. It is apparent that the heat transfer equation for falling films is not applicable to liquids having viscosities higher than 3 cp, and it is, therefore, limited to dilute juices.

Values of the Reynolds number (Re) listed in Table 2 are useful as an index of the type of flow of the liquid film. In falling films turbulent flow prevails at Re values higher than 1,000 (1). At Re values between 1,000 and 25 the flow is laminar with rippling, and below 25 the flow is laminar. With depectinized apple juice the flow of liquid film on the evaporator wall is turbulent up to 40° Brix, and in this region, the heat transfer coefficient can be calculated from the heat transfer equation mentioned previously. At concentrations higher than 40° Brix, the flow becomes laminar with some rippling of the liquid film, and the heat transfer equation is not applicable.

Clarified juices are Newtonian fluids at all concentrations and temperature has a significant effect on viscosity, especially at high concentrations (14). From a heat transfer standpoint, it is desirable to evaporate the concentrated juices at the highest permissible temperature. This observation suggests that, in a multiple-effect evaporation of fruit juices, the flow of product and heat should be counter-current; i.e., the highest temperature should be applied to the most concentrated product.

Table 2. Heat Transfer Coefficients of Depectinized Apple Juice in the Falling Film Evaporator. Boiling Temperature, 130° F. Liquid Flow Rate, 585 lb/hr.

° Brix	20	40	50	60
μ , lb/hr.ft.	1.94	4.84	8.45	31.5
C_p , Btu/lb.° F	0.87	0.78	0.74	0.69
ρ , lb/cu.ft.	67	73	76	80
k , Btu/hr.sq.ft.° F/ft.	0.30	0.30	0.28	0.24
Re	2,450	985	560	150
Pr	5.62	12.5	20.4	90
ϕ	2,400	1,840	900	328
h_i , Btu/hr.sq.ft.° F	600	410	205	78
Calculated U	335	268	164	71
Experimental U	340	280	240	200

Non Newtonian Fluids

Cloudy fruit juices, containing suspended and colloidal particles, are usually pseudoplastic (non Newtonian) fluids. The same is true with other liquid suspensions and emulsions; e.g., soymilk. The pilot-scale evaporator was used successfully for the concentration of a number of these liquids. Satisfactory heat transfer coefficients were obtained which were comparable to those of clarified juices.

In evaporating pseudoplastic liquids, the boiling temperature and the jacket temperature should be chosen carefully, so that precipitation (scale formation) on the evaporator tube is minimized; this means, in general, temperatures lower than those used for clarified juices and water. The apparent viscosity of pseudoplastic liquids decreases only slightly at higher temperatures (14), and, therefore, a small improvement in heat transfer can be expected, if scale formation is neglected.

The apparent viscosity of pseudoplastic fluids decreases considerably at high shear rates. In the falling film evaporator, high shear rates are achieved by maintaining high liquid and vapor flow velocities in the evaporator tube. The relatively high heat transfer coefficients obtained in the evaporation of viscous pseudoplastic fluids can be explained on the basis of very high shear rates exerted on the liquid films. It is expected that a smaller diameter of the evaporator tube would result in higher heat transfer coefficients, due to higher liquid and vapor velocities.

High shear rates in the liquid film, which are desirable for improved heat transfer, are achieved also mechanically in the agitated film evaporators. Heat transfer coefficients obtained in the falling film evaporator were comparable to those reported for agitated film units (12). The agitated film evaporators can handle more viscous liquids, containing more suspended solids, without scale formation.

Vapor Turbulator

The Brock Turbulator (a twisted stainless steel ribbon) has been used successfully for improving heat transfer in tubular boilers. Some experimental work was performed to find out whether the Turbulator can increase the evaporative (heat transfer) capacity of the falling film evaporator.

A stainless steel ribbon, 8 feet long with 18 bends, was inserted in the evaporator tube, and water and apple juice were evaporated at various temperatures. Similar experiments were performed without the Turbulator. There was no improvement in evaporative capacity that could

be detected. In fact, in most cases, the heat transfer coefficients decreased significantly when the Turbulator was inserted in the evaporator tube. It was speculated that part of the liquid was diverted from the tube walls, and it flowed down the Turbulator, resulting in a decrease of heat transfer from the jacket to the evaporating liquid. It should be noted that the vapor velocities in the evaporator tube are generally high, and vapor turbulence does occur without the need of mechanical assistance.

NOMENCLATURE AND UNITS

C_p	= Specific heat of liquid film, Btu/lb.° F
D	= Internal diameter of evaporator tube, 1.87 inch
g	= Gravity constant, 4.17×10^8 ft/hr ²
h_i	= Heat transfer coefficient of evaporating film, Btu/hr.sq.ft.° F
h_s	= Heat transfer coefficient of condensing steam, Btu/hr.sq.ft.° F
k	= Thermal conductivity, Btu/hr.sq.ft.° F/inch
L	= Length of evaporator tube, 10 ft.
m	= Liquid film thickness, ft.
Pr	= Prandtl number, $\frac{C_p \mu}{k}$, dimensionless
Re	= Reynolds number, $\frac{4\Gamma}{\mu}$, dimensionless
Q	= Liquid hold-up volume, lb.
v	= Specific volume, cu.ft./lb.
V	= Linear liquid or vapor velocity, ft./sec.
x	= Thickness of tube wall, ft.
w	= Evaporation rate of water, lb./hr.
W	= Liquid feed rate, lb./hr.
Γ	= Liquid film flow rate, lb./hr.ft.
ΔT	= Temperature difference, ° F
λ	= Heat of vaporization of water, Btu/lb.
μ	= Liquid viscosity, lb./hr.ft. (1 cp = 2.42 lb./hr.ft.)
π	= 3.14
ρ	= liquid density, lb./cu.ft.

$$\Phi = \left(\frac{k^3 \rho^2 g}{\mu^2} \right)^{1/3}, \text{ Btu/hr.sq.ft.}^\circ \text{F}$$

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Editor's Note

This is a new series that replaces the former Research Circular series published by the New York State Agricultural Experiment Station at Geneva. It results from an intensive study made by a special committee, which recommended that all existing publication series be streamlined and modernized to better answer today's needs of both scientific and general audiences. It was thought important to identify each publication with its appropriate subject matter discipline, such as Biological Sciences, Food Sciences, or Plant Sciences, as well as with a departmental designation.