

Some Concepts in Evaporation and Their Origins*

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Dedicated to Professor August Guyer

Summary

Practical experience showed the need for quantitative data on the fouling of evaporator surfaces. This data was accumulated by means of an alternating and direct current resistance thermometer device developed for the purpose and applied in pilot scale experiments. The most important concept in fouling is the temperature of the wetted surface. Of decreasing importance are wetting of the surface, thinness of the stagnant liquid layer on the surface, and consistency of the liquid boiling.

These concepts were used by the author to create two new designs now in plant use. These are the expanding tube and Wurling evaporators. A control system has been successfully simulated to embody the concepts. This automatic system may be applicable to every design of forced circulation evaporator.

Introduction

Evaporation is probably the most important unit operation to food processors. Very large evaporation capacities are used in fruit and vegetable juice concentration, milk evaporation, sugar and syrup manufacturing, and distilled spirits production. A problem particularly troublesome to such industries, is the deposition on the hot surfaces of a burnt layer. This fouling involves destruction of some temperature-sensitive component of the food—not mere insolubilization of a salt, as in the case of calcium scaling. Fouling is therefore especially bad since it degrades the food as well as it reduces heat transfer rates.

A few years ago at the Western Regional Research Laboratory in Albany (California) we developed the

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flash entry evaporator design (BROWN *et al.*¹). In this design, water is evaporated during a single pass of foods flowing down inside long tubes, outside of which steam condenses. The food is preheated, usually by steam injection, so that some steam flashes off suddenly just as the liquid enters the tubes. In this way, high performance is attained through the use of very high two-phase velocities inside the tubes. A number of flash entry industrial evaporators based on our pilot model were installed. Some, particularly those evaporating tomato puree to higher concentrations, have been plagued with fouling (MORGAN *et al.*²). While trying to remedy this problem, we found very little guidance in literature and engineering experience of a sufficiently general nature to help answer the pressing questions. For example, to decrease fouling, should more steam be flashed from the feed to increase two-phase velocity and turbulence? Or should product be recirculated to increase the liquid velocity and mass flow rate? During plant scale operation, fouling always made steady state observation impossible. For these reasons we began a controlled study of fouling on the pilot scale.

Experimental Methods

The situation we began studying was the transfer of heat from condensing steam to a boiling liquid flowing inside a tube. Metal surface effects were found to effect fouling during a preliminary experiment (KILPATRICK and BREITWIESER³). Therefore only aged stainless steel surfaces were used. In this case, the heat transfer resistances from steam to tube, through the tube wall, and from tube to boiling liquid inside were all about equally important. This is shown in Figure 1 for a typical heat flux of 200,000 kcal/hr m² across a clean tube wall.

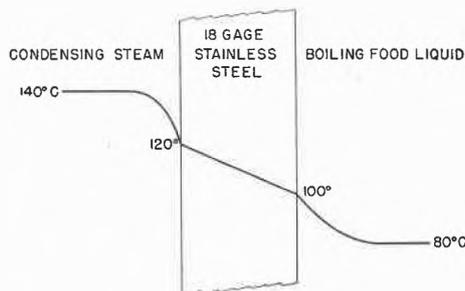


Fig. 1. Typical temperatures in a modern evaporator

To study only the resistance from the surface into the boiling liquid, surface temperatures and local heat fluxes were needed. Analysis showed that temperatures measured by a thermocouple, thermistor, or any point

temperature measuring device, would be unrepresentative due to the mere presence of the device. We therefore invented a method of measurement in which the heat transfer surface itself acted as a resistance thermometer (MORGAN and CARLSON⁴). In this technique, fouling is studied on the inside of a stainless steel tube enclosed in a steam jacket. The steam heat is transferred radially into the boiling liquid tube content from condensing steam outside. Electric currents were passed along the tube lengthwise. The voltage drops between various points were measured and calibrated against tube temperature, Figure 2. When direct current was

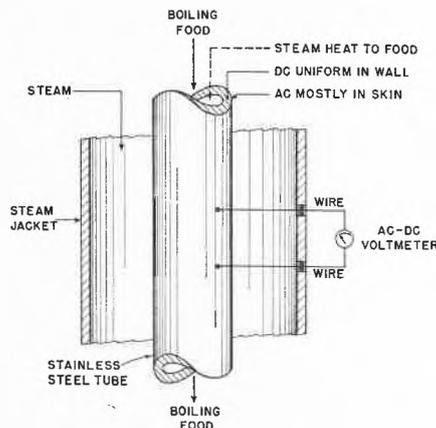


Fig. 2. Skin effect measurement of surface temperatures

used, the voltages represented the radial average wall temperatures. When 2000 cycle per second alternating current was used, the voltages represented temperatures very near the outside surface of the tubular conductor because of the skin effect of high frequency currents in circular conductors. The difference between DC and AC voltages was related to heat flux. Radial average wall temperature and heat flux observations could therefore be used to calculate inside surface temperatures. In this way, resistance to heat transfer, or its inverse, h_L , could be observed rapidly in the boiling liquid film alone. Vapor fraction present could be calculated by summing up the heat flux rate for all points upstream from the test section, knowing inlet and outlet compositions.

We collected data on fouling of various liquids in this way (MORGAN and CARLSON⁵). We found that a standard cleaning procedure could restore the surface to the same clean value after each fouling experience. This clean value, h_0 , was best indicated by extrapolation of the coefficient, h_L , back to time zero, Figure 3.

At any time since clean, the decrease in liquid coefficient, h_L , can be interpreted as increase in a fouling coefficient, h_F .

$$\frac{1}{h_L} = \frac{1}{h_0} + \frac{1}{h_F}$$

¹ A. H. BROWN, M. E. LAZAR, T. WASSERMAN, G. S. SMITH, and M. W. COLE, *Ind. Eng. Chem.* 43 (1951) 2949.

² A. I. MORGAN jr., T. WASSERMAN, A. H. BROWN, and G. S. SMITH, *Food Technol.* 13 (1959) 232.

³ P. W. KILPATRICK and E. BREITWIESER, *Ind. Eng. Chem.* 53 (1961) 119.

⁴ A. I. MORGAN jr. and R. CARLSON, *J. Heat Transfer* 1961 (May) 105.

⁵ A. I. MORGAN jr. and R. A. CARLSON, *Food Technol.* 14 (1960) 594.

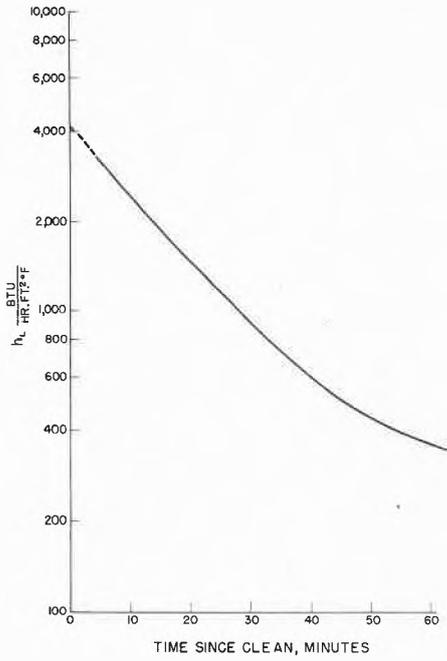


Fig. 3. Variation of liquid coefficient of heat transfer with time

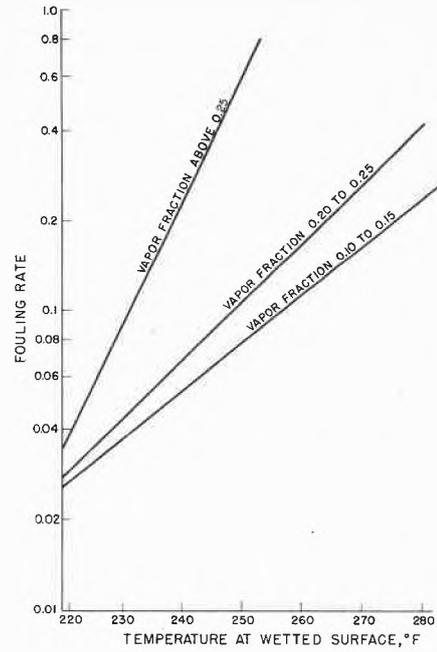


Fig. 5. Effect of vapor fraction on fouling rate of tomato juice

The rate of change of this coefficient is referred to as the fouling rate. In Figures 4, 5, and 6, the units of fouling rate happen to be $\text{hr ft}^2 \text{ }^\circ\text{F}$ per Btu/min and the temperatures are those for the wetted surface, whether this surface be bare metal or fouled material.

In order to study effects of liquid composition on fouling rates, we observed tomato macerates of different

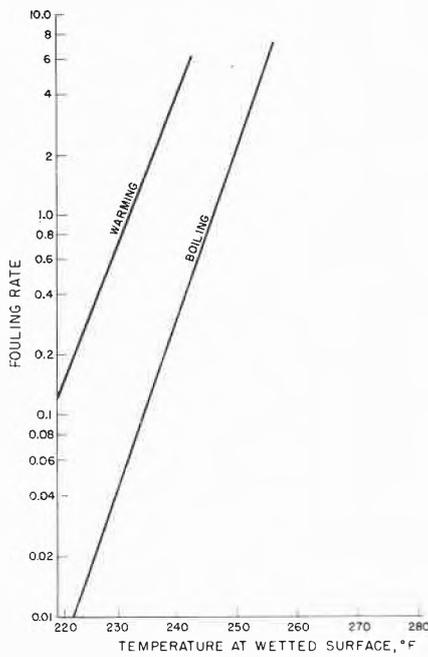


Fig. 4. Effect of boiling on fouling rate of tomato paste

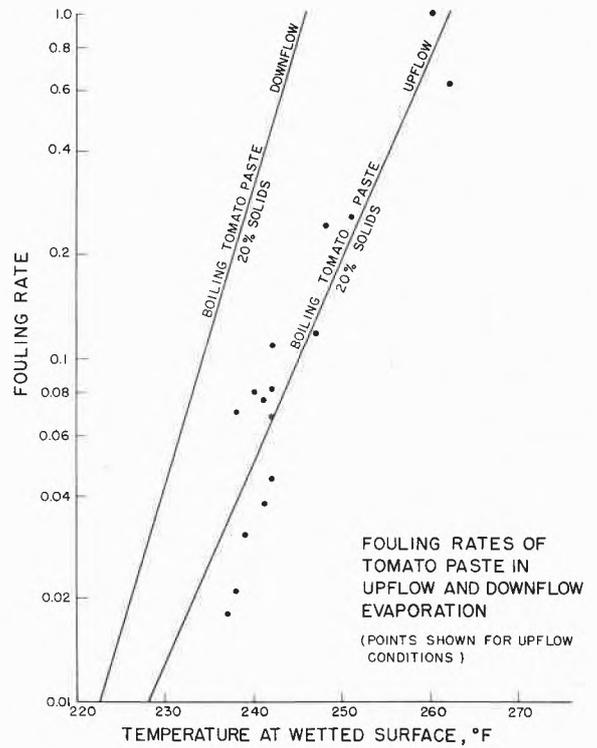


Fig. 6. Effect of flow direction on fouling rate of tomato juice

concentrations and histories. We also observed a synthetic liquid in which we varied the protein, fiber, pectin, etc., contents (MORGAN and WASSERMAN⁶).

⁶ A. I. MORGAN jr. and T. WASSERMAN, *Food Technol.* 13 (1959) 691.

Results

Operating variables were studied for their relative effects on fouling rates of fruit and vegetable purees. The most important factor is temperature of the wetted surface. Of decreasing importance are direction of flow, presence or absence of local boiling, vapor fraction, mass flow rate, and smoothness of metal surface.

The results for tomato juices and purees are shown in Figures 4, 5, and 6. The secondary factors of the presence of local boiling, vapor fraction, and flow direction are plotted in each case against fouling rate for each level of the major factor, temperature of the wetted surface. In these figures, the temperature used is adjusted to account for the temperature drop through the fouled layer on the hot surface.

The temperature dependence of fouling rates can be treated in an Arrhenius plot to obtain the activation energy of the fouling reaction. This activation energy varies between 50 and 70 kcal/g mole. This is in the center of the rather wide range of activation energies for protein denaturation.

Further information on the chemistry of fouling is provided by analysis of fouled layers from various foods. All these showed sugar, fiber, pectin, and ash values reflecting those of the solids of the food being evaporated. In each case, however, the Kjeldahl nitrogen values were much higher in the foul than those in the food. In one case, grape juice, there was 15 times as much apparent protein in the foul as in the grape solids.

Table 1. Effects of Composition on Fouling Rate

	Decrease of boiling coefficient after 30 minutes (%)
Tomato juice	28
Full synthetic	33
Synthetic without fiber	2
Synthetic without pectin	8
Synthetic without protein	10
Synthetic with coarser fiber	57

The synthetic feed we evaporated closely resembled tomato puree in the way it fouled. Table 1 shows the results of making various changes in the synthetic feed. Omission of either fiber, pectin, or protein greatly reduced fouling, fiber having the greatest effect. Changing the size of the fiber, and consequently the fluid consistency, by substituting 100 mesh wood flour for 200 mesh, the fouling was very greatly increased. Fruit puree fouling is protein denaturation complicated with the consistency effects of fiber and pectin.

Concepts: The results could be interpreted in terms of four main concepts for evaporation of decreasing importance.

1. The solid surface must be as cool as possible.
2. The surface should be completely wetted.
3. The stagnant layer of liquid on the surface should be as thin as possible.
4. The liquid consistency should be as low as possible.

None of these concepts are particularly surprising. The quantification and interrelationships did, however, lead us to several useful results.

Practical Results

A. Expanding Tube Evaporation: An immediate result of the foregoing, was our expanding tube design of a single pass upflow forced circulation evaporator (Figure 7).

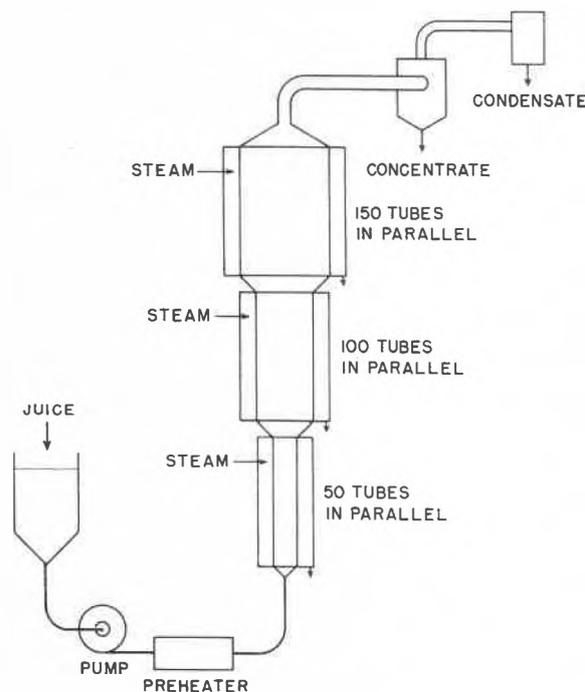


Fig. 7. Expanding tube evaporator

The use of upflow keeps the walls wetted, provided that vapor velocity does not become too great. This is accomplished by increasing the number of tubes as vapor fraction increases. The same size tube, usually 20 mm, is used throughout because larger tubes cannot be maintained in the annular flow regime. This flow is needed for complete wall wetting. Tube number is chosen by means of vapor velocity versus fouling rate data.

Several plant-scale expanding tube evaporators have so far been installed, one for pineapple juice (ROBE⁷), and one for apple juice. These are outstanding in freedom from fouling. The products are excellent because of the very short residence time in the single pass equipment.

B. Wurling Evaporator: Another result was a totally different evaporator design for use on thick liquids

⁷ K. ROBE, *Food Proc. & Marketing* 1966 (September).

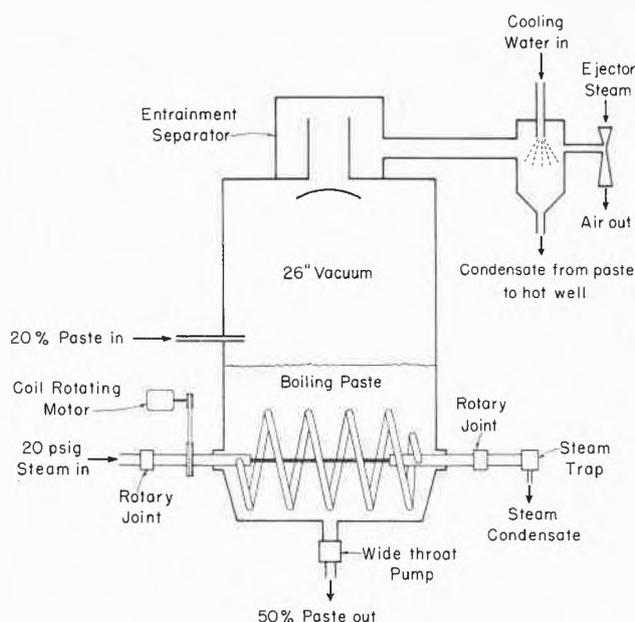


Fig. 8. Wurling Evaporator

(RANDALL *et al.*⁸). This design is shown in Figure 8. It consists of a rapidly rotating, steam-filled coil under the surface of a pool of food boiling in vacuum. Surface wetting is maintained by using a pool. Continuous operation is achieved by keeping the pool volume constant with dilute feed until the pool solids concentration is at the desired level. Product is then removed continuously. Temperatures are kept low by use of vacuum. The stagnant layer is reduced by maintaining local boiling and by the rapid rotation, preferably over 5 m/sec. For 50% solids, cold break tomato paste, the Wurling evaporator shows a higher evaporation rate, 250 kg/hr m², than a swept-film design under the same conditions (CARLSON⁹). The Wurling design is much cheaper to construct than the swept-film design for equivalent capacities.

Two plant-scale Wurling evaporators have so far been installed. One is making 50% tomato paste (HUTCHINGS¹⁰), and another is making fruit jams, jellies, and preserves. These industrial machines have confirmed our pilot scale results in regard to capacity, freedom from fouling, and economy of construction.

⁸ J. M. RANDALL, R. A. CARLSON, R. P. GRAHAM, and A. I. MORGAN jr., *Food Eng.* 1966 (March) 168.

⁹ R. A. CARLSON, J. M. RANDALL, R. P. GRAHAM, and A. I. MORGAN jr., *Food Technol.* 1966, in press.

¹⁰ I. J. HUTCHINGS and K. ROBE, *Food Process. & Marketing* 1966 (April) 108.

C. Evaporator Control: Our experimental results on fouling often defy generalization. For use in control of an existing evaporator, the data is too complex, at least for the hectic period of seasonal operation. We therefore sought an automatic control method. This control must maintain a constant output solids concentration despite sudden changes in incoming solids concentration and slower changes in heat exchange resistances due to fouling. We conceived of the scheme, shown in Figure 9, for this purpose. It is probably best applied to a single pass evaporator although it is completely applicable to any forced circulation design. A major object of this system is constant surface temperature despite varying evaporation demand. The evaporation variation is achieved by changing feed rate only. The relationship of mass flow rate to heat transfer and vapor fraction to heat transfer derived from our experiments suggest that this method is workable. We propose a derivative feed-forward signal from an inlet solids concentration sensor and an integrating feed-backward signal from a product solids concentration sensor, combined for control of feed rate.

This control system has been successfully simulated on our analogue computer (RANDALL¹¹). It achieved good product solids control in spite of step-wise changes in incoming feed solids and a slow increase in heat transfer resistance. We are now testing the method in nature on a pilot-scale evaporator consisting of a single 25 mm tube.

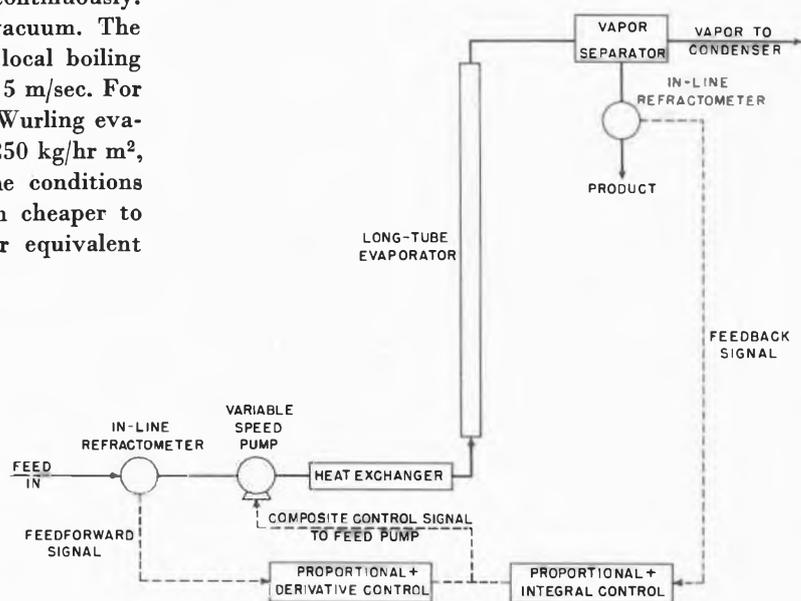


Fig. 9. Evaporator control system

¹¹ J. M. RANDALL, R. A. CARLSON, R. LEVY, and A. I. MORGAN jr., *Chem. Eng. Progr.* 1966, in press.