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This Week's Citation Classic®

Ranz W E & Marshall W R, Jr. Evaporation from drops. Parts I & II. *Chem. Eng. Progr.* **48**:141-6; 173-80, 1952. [University of Wisconsin, Madison, WI]

An investigation was made of the factors influencing the rate of evaporation of pure liquid drops, and the rate of evaporation of water drops containing dissolved and suspended solids. Independent correlations of heat- and mass-transfer rates were obtained from drop temperatures measured with 0.5 mil thermocouples. Drop diameters ranged from 0.06 to 0.11 cm, and air temperatures up to 220°C. [The *SCI*® indicates that these papers have been cited in more than 525 and 415 publications, respectively.]

Rate Processes at a Spherical Boundary

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Drying of drops was one of several research projects offered to graduate students in a study of spray drying started at the University of Wisconsin by W.R. Marshall, Jr. (later dean of the Engineering College) when he first came to Madison from DuPont Research in 1947. As a cooperative student from the University of Cincinnati, whose engineering degree and education had been interrupted by World War II, I chose what I knew the least about and could learn the most about in the shortest time. It became a one-drop project because in those days one had to design and build an experimental apparatus from materials at hand, in particular, a horizontal microscope tube with traversing and focusing gear, a microscope camera, a microburet, and thin-wire thermocouples. Discovering a knack for building a cheap experimental apparatus, I designed and built other sets of equipment in case only one worked, it was a pleasure that many of these were used in later thesis projects.

In the matter of supporting theory, I am not one to waste time on noncritical literature searches, but the Frossiing paper[1] had to be consulted. I went to Pittsburgh to find the only copy in the US at the Carnegie Institute's library. It turned out to be a treatise-length paper in German. This I carefully translated myself to learn more German, having flunked the first try at the German exam, a graduate student requirement of the time. I passed the next exam easily and discovered years later that NASA did a translation of the same paper, not as good as mine because the translator was not doing experiments at the same time.

Since the study of single-drop drying came at a time when empirical correlations of the unit operations of chemical engineering had reached diminished returns and at the beginning of an era in which all molecular transport phenomena would be modeled scientifically and mathematically, publication of these papers invited repetitions, extensions, combinations, and intricate detailing. They represent an example of enough, but nottoo much, experiment and enough, but not too much, theory to understand a large class of practical and natural phenomena. I did not follow the paper trail personally after a subsequent article,[2] which showed how the boundary geometry of a single drop can be converted into that of a packed bed of many spheres and which was recognized by the Junior Award of the American Institute of Chemical Engineers. Years later someone told me that the design of water sprays for quenching a runaway nuclear reactor was based on the rate equation for a single drop, and I was afraid to ask if such an extension had ever survived an experimental verification.

A serious limitation on extended applications, unfortunately not emphasized in the original papers, has always been crude accounting (i.e., the use of the Df factor) for the radial convection at a spherical boundary caused by diffusion at the same boundary. Such intricacies and scientific rigor in describing simultaneous transfer phenomena were defined[3] in 1960 by a fellow graduate student with whom I shared graduate course studies in the late 1940s. Today in designing processes it is much more difficult to find a general model for a general class of phenomena. However, a miniaturized experiment, observed in real time, is always necessary to simplify the theoretical models to a tractable form for computations.

1. **Frössling N.** Übcr die Verdunstung fallender Tropfen (On the evaporation of falling drops). *Gerlands Beitr. Geophys.* 52:170-216, 1938. (Cited 180 times since 1945.)
2. **Ranz W E.** Friction and transfer coefficients for single panicles and packed beds. *Chem. Eng. Progr.* 48:247-53. 1952. (Cited 150 times.)
3. **Bird R B, Stewart W E & Lightfoot E N.** *Transport phenomena.* New York: Wiley. 1960. 780 p. (Cited 3,900 times.) [See also **Bird R B.** Citation Classic. (Thackray A. comp.) *Contemporary classics in engineering and applied science.* Philadelphia: ISI Press. 1986. p. 250]

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