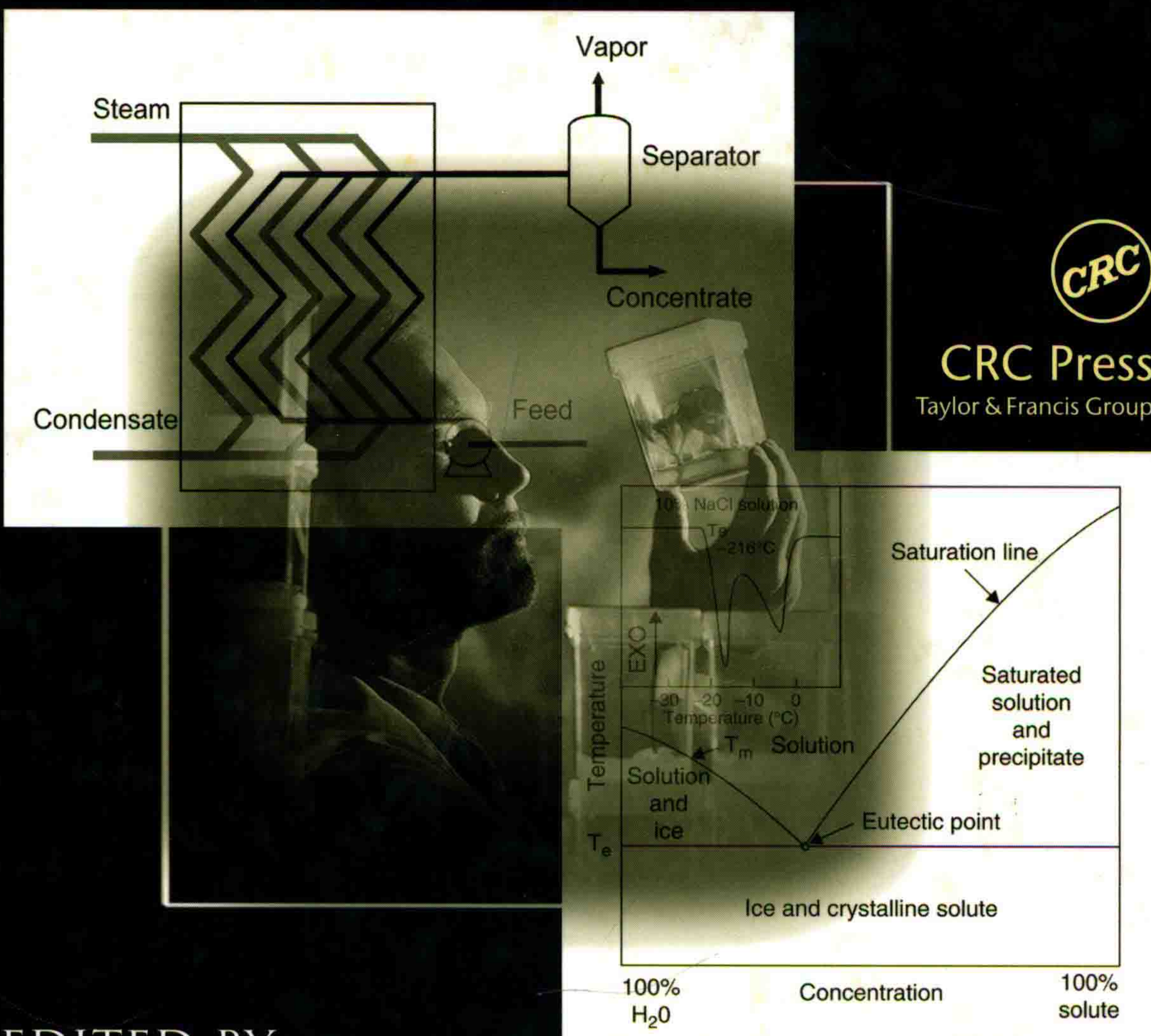
HANDBOOK OF FOOD ENGINEERING

SECOND EDITION



CRC Press
Taylor & Francis Group

EDITED BY

DENNIS R. HELDMAN
DARYL B. LUND

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an informa business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8247-5331-3 (Hardcover)
International Standard Book Number-13: 978-0-8247-5331-3 (Hardcover)
Library of Congress Card Number 2006010365

Library of Congress Cataloging-in-Publication Data

Handbook of food engineering / [edited by] Dennis R. Heldman and Daryl B. Lund. -- 2nd ed.
p. cm. -- (Food science and technology ; 161)
Includes bibliographical references and index.
ISBN-13: 978-0-8247-5331-3 (acid-free paper)
ISBN-10: 0-8247-5331-3 (acid-free paper)
1. Food industry and trade--Handbooks, manuals, etc. I. Heldman, Dennis R. II. Lund, Daryl B. III. Series: Food science and technology (Taylor & Francis) ; 161.

TP370.4.H36 2007
664--dc22 2006010365

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http://www.crcpress.com

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SECOND EDITION

FOOD SCIENCE AND TECHNOLOGY

Preface

The primary mission of the second edition of the *Handbook of Food Engineering* is the same as the first. The most recent information needed for efficient design and development of processes used in the manufacturing of food products has been assembled, along with the traditional background on these processes. The audience for this handbook includes three groups: (1) practicing engineers in the food and related industries, (2) the student preparing for a career as a food engineer, and (3) other scientists and technologists seeking information about processes and the information needed in design and development of these processes. For the practicing engineer, the handbook assembles information needed for the design and development of a given process. For the student, the handbook becomes the primary reference needed to supplement textbooks used in the teaching of process design and development concepts. Other scientists and technologists should use the handbook to locate important information and physical data related to foods and food ingredients.

As in the first edition, the handbook assembles the most recent information on thermophysical properties of foods, rate constants about changes in food components during a process, and illustrations of the use of these properties and constants in process design. Researchers will be able to use the information as a guide in establishing the direction of future research on thermophysical properties and rate constants. In this edition, an appendix has been created to assemble tables and figures containing property data needed for the design of processes described in various chapters of the handbook.

Although the first three chapters focus primarily on properties of food and food ingredients, the chapters that follow are organized according to traditional unit operations associated with the manufacturing of foods. Two key chapters cover the basic concepts of transport and storage of liquids and solids, and the heating and cooling of foods and food ingredients. An additional background chapter focuses on basic concepts of mass transfer in foods. More specific unit operations on freezing, concentration, dehydration, thermal processing, and extrusion are discussed and analyzed in separate chapters. The chapter on membrane processes deals with liquid food concentration but provides the basis for other applications of membranes in food processing. The final chapters of the handbook cover the important topics of packaging and cleaning and sanitation.

The editors of this handbook hope that the information presented will continue to contribute to the evolution of food engineering as an interface between engineering and other food sciences. As demands for safe, high quality, nutritious and convenient foods continue to increase, the needs for the concepts presented will become more critical. In the near future, the applications of new science from molecular biology, nanotechnology, and nutritional biochemistry in food manufacturing will increase, and the role of engineering in process design and scale-up will be even more visible. At the same time, new process technologies will continue to emerge and require input from engineers for application, design, and development in food manufacturing. Ultimately, the use of engineering concepts should lead to the highest quality food products at the lowest possible cost.

The editors wish to acknowledge the authors and their significant contributions to the second edition of this handbook. These authors are among the leading scientists and engineers in the field

of food engineering. We are pleased to be associated with their contributions to this field and to the handbook.

Dennis R. Heldman
Daryl B. Lund

Editors

Dennis R. Heldman is a principal of Heldman Associates in Weston, Florida. He has been professor of food process engineering at Rutgers, The State University of New Jersey, the University of Missouri and Michigan State University. In addition, he has industry experience at the Campbell Soup Company, the National Food Processors Association and the Weinberg Consulting Group. Dr. Heldman is the author or co-author of over 140 journal articles, and the author, co-author or editor of over 10 textbooks, handbooks and encyclopedias. He is a fellow of the Institute of Food Technologists and the American Society of Agricultural Engineers. He served as president of the IFT, the Society for Food Science and Technology, an organization with over 20,000 members, from 2006–2007, and was elected fellow in the International Academy of Food Science & Technology in 2006. Dr. Heldman was awarded a BS (1960) and an MS (1962) from The Ohio State University, and a PhD (1965) from Michigan State University.

Darryl B. Lund earned a BS (1963) in mathematics and a PhD (1968) in food science with a minor in chemical engineering at the University of Wisconsin-Madison. During 21 years at the University of Wisconsin, he was a professor of food engineering in the food science department serving as chair of the department from 1984–1987. He has contributed over 150 scientific papers, edited 5 books, and co-authored one major textbook in the area of simultaneous heat and mass transfer in foods, kinetics of reactions in foods, and food processing.

In 1988 he continued his administrative responsibilities by chairing the Department of Food Science at Rutgers University, and from December 1989 through July 1995 served as the executive dean of Agriculture and Natural Resources with responsibilities for teaching, research and extension at Rutgers University. In that position, among other achievements, he initiated a rigorous strategic planning process for Cook College and the New Jersey Agricultural Experiment Station, streamlined administrative services, fostered a review of the undergraduate curriculum and encouraged the faculty to develop a social contact for undergraduate instruction.

In August 1995, he joined the Cornell University faculty as the Ronald P. Lynch Dean of Agriculture and Life Sciences. During his tenure as dean of CALS, he initiated a strategic positioning process for the college that guided the college through 20% downsizing, promoted the Agriculture Initiative to gain increased state support for the Agricultural Experiment Station and Cooperative Extension, supported an initiative in genomics and overhaul of the biological sciences, fostered a review of undergraduate programs that led to major changes, and supported the adoption of electronic technologies for undergraduate teaching and distance education. In July 2000, Dr. Lund returned to the Department of Food Science as professor of food engineering.

In January 2001, Dr. Lund became the executive director of the North Central Regional Association of State Agricultural Experiment Station Directors. In this position he facilitates interstate collaboration on research and a greater integration between research and extension in the twelve-state region.

Among many awards in recognition of personal achievement, he is a recipient of the ASAE/DFISA Food Engineering Award, the IFT International Award and Carl R. Fellers Award, and the Irving Award from the American Distance Education Consortium. He is an elected fellow of the Institute of Food Technologists, elected fellow of the Institute of Food Science and Technology (UK), and charter inductee in the International Academy of Food Science and Technology.

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1 Rheological Properties of Foods

Hulya Dogan and Jozef L. Kokini

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1.1 INTRODUCTION

Rheological properties are important to the design of flow processes, quality control, storage and processing stability measurements, predicting texture, and learning about molecular and conformational changes in food materials (Davis, 1973). The rheological characterization of foods provides important information for food scientists, ingredient selection strategies to design, improve, and optimize their products, to select and optimize their manufacturing processes, and design packaging and storage strategies. Rheological studies become particularly useful when predictive relationships for rheological properties of foods can be developed which start from the molecular architecture of the constituent species.

Reliable and accurate steady rheological data are necessary to design continuous-flow processes, select and size pumps and other fluid-moving machinery and to evaluate heating rates during engineering operations which include flow processes such as aseptic processing and concentration (Holdsworth, 1971; Sheath, 1976), and to estimate velocity, shear, and residence-time distribution in food processing operations including extrusion and continuous mixing.

Viscoelastic properties are also useful in processing and storage stability predictions. For example, during extrusion, viscoelastic properties of cereal flour doughs affect die swell and extrudate expansion. In batch mixing, elasticity is responsible for the *rod climbing phenomenon*, also known as the *Weissenberg effect* (Bird et al., 1987). To allow for elastic recovery of dough during cookie making, the dough is cut in the form of an ellipse which relaxes into a perfect circle.

Creep and small-amplitude oscillatory measurements are useful in understanding the role of constituent ingredients on the stability of oil-in-water emulsions. Steady shear and creep measurements help identify the effect of ingredients that have stabilizing ability, such as gums, proteins, or other surface-active agents (Fischbach and Kokini, 1984).

Dilute solution viscoelastic properties of biopolymeric materials such as carbohydrates and protein can be used to characterize their three-dimensional configuration in solution. Their configuration affects their functionality in many food products. It is possible to predict better and improve the flow behavior of food polymers through an understanding of how the molecular structure of polymers affects their rheological properties (Liguori, 1985). Examples can be found in the improvement of

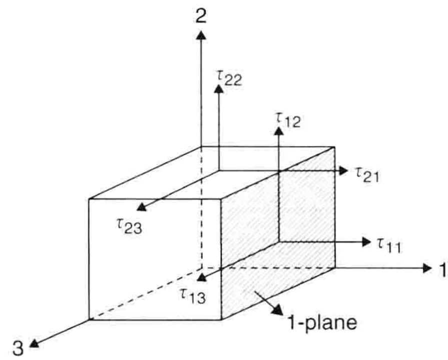

FIGURE 1.1 Stress components on a cubical material element.

the consistency and stability of emulsions by using polymers with enhanced surface activity and greater viscosity and elasticity.

This chapter will review recent advances in basic rheological concepts, methods of measurement, molecular theories, linear and nonlinear constitutive models, and numerical simulation of viscoelastic flows.

1.2 BASIC CONCEPTS

1.2.1 Stress and Strain

Rheology is the science of the deformation and flow of matter. Rheological properties define the relationship between stress and strain/strain rate in different types of shear and extensional flows. The stress is defined as the force F acting on a unit area A. Since both force and area have directional as well as magnitude characteristics, stress is a second order tensor and typically has nine components. Strain is a measure of deformation or relative displacement and is determined by the displacement gradient. Since displacement and its relative change both have directional properties, strain is also a second order tensor with nine components.

A rheological measurement is conducted on a given material by imposing a well-defined stress and measuring the resulting strain or strain rate or by imposing a well-defined strain or strain rate and by measuring the stress developed. The relationship between these physical events leads to different kinds of rheological properties.

When a force F is applied to a piece of material (Figure 1.1), the total stress acting on any infinitesimal element is composed of two fundamental classes of stress components (Darby, 1976):

Normal stress components, applied perpendicularly to the plane (τ_{11}, τ_{22}, τ_{33})
Shear stress components, applied tangentially to the plane (τ_{12}, τ_{13}, τ_{21}, τ_{23}, τ_{31}, τ_{32})

There are a total of nine stress components acting on an infinitesimal element (i.e., two shear components and one normal stress component acting on each of the three planes). Individual stress components are referred to as τ_{ij}, where i refers to the plane the stress acts on, and j indicates the direction of stress component (Bird et al., 1987). The stress tensor can be written as a matrix of nine components as follows:

$$\tau = \begin{bmatrix} \tau_{11} & \tau_{12} & \tau_{13} \\ \tau_{21} & \tau_{22} & \tau_{23} \\ \tau_{31} & \tau_{32} & \tau_{33} \end{bmatrix}$$

In general, the stress tensor in the deformation of an incompressible material is described by three shear stresses and two normal stress differences:

Shear stresses:	$\tau_{12}(=\tau_{21})$	$\tau_{13}(=\tau_{31})$	$\tau_{23}(=\tau_{32})$
Normal stress differences:	$N_1 = \tau_{11} - \tau_{22}$	$N_2 = \tau_{22} - \tau_{33}$	

1.2.2 Classification of Materials

Rheological properties of materials are the result of their stress-strain behavior. Ideal solid (elastic) and ideal fluid (viscous) behaviors represent two extreme responses of a material (Darby, 1976).

An ideal solid material deforms instantaneously when a load is applied. It returns to its original configuration instantaneously (complete recovery) upon removal of the load. Ideal elastic materials obey Hooke's law, where the stress (τ) is directly proportional to the strain (γ). The proportionality constant (G) is called the modulus.

$$\tau = G\gamma$$

An ideal fluid deforms at a constant rate under an applied stress, and the material does not regain its original configuration when the load is removed. The flow of a simple viscous material is described by Newton's law, where the shear stress (τ) is directly proportional the shear rate ($\dot{\gamma}$). The proportionality constant (η) is called the Newtonian viscosity.

$$\tau = \eta\dot{\gamma}$$

Most food materials exhibit characteristics of both elastic and viscous behavior and are called viscoelastic. If viscoelastic properties are strain and strain rate independent, then these materials are referred to as linear viscoelastic materials. On the other hand if they are strain and strain rate dependent, than they are referred to as nonlinear viscoelastic materials (Ferry, 1980; Bird et al., 1987; Macosko, 1994).

A simple and classical approach to describe the response of a viscoelastic material is using mechanical analogs. Purely elastic behavior is simulated by springs and purely viscous behavior is simulated using dashpots. The Maxwell and Voigt models are the two simplest mechanical analogs of viscoelastic materials. They simulate a liquid (Maxwell) and a solid (Voigt) by combining a spring and a dashpot in series or in parallel, respectively. These mechanical analogs are the building blocks of constitutive models as discussed in Section 1.4 in detail.

1.2.3 Types of Deformation

1.2.3.1 Shear Flow

One of the most useful types of deformation for rheological measurements is simple shear. In simple shear, a material element is placed between two parallel plates (Figure 1.2) where the bottom plate is stationary and the upper plate is displaced in x-direction by Δx by applying a force F tangentionally to the surface A. The velocity profile in simple shear is given by the following velocity components:

$$v_x = \dot{\gamma}y, \quad v_y = 0, \quad \text{and} \quad v_z = 0$$

The corresponding shear stress is given as:

$$\tau = \frac{F}{A}$$

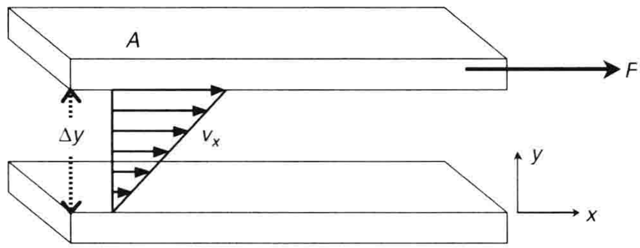

FIGURE 1.2 Shear flow.

If the relative displacement at any given point Δy is Δx, then the shear strain is given by

$$\gamma = \frac{\Delta x}{\Delta y}$$

If the material is a fluid, force applied tangentially to the surface will result in a constant velocity v_x in x-direction. The deformation is described by the strain rate ($\dot{\gamma}$), which is the time rate of change of the shear strain:

$$\dot{\gamma} = \frac{d\gamma}{dt} = \frac{d}{dt}\left(\frac{\Delta x}{\Delta y}\right) = \frac{dv_x}{dy}$$

Shear strain defines the displacement gradient in simple shear. The displacement gradient is the relative displacement of two points divided by the initial distance between them. For any continuous medium the displacement gradient tensor is given as:

$$\frac{\partial u_i}{\partial x_j} = \begin{bmatrix} \frac{\partial u_1}{\partial x_1} & \frac{\partial u_1}{\partial x_2} & \frac{\partial u_1}{\partial x_3} \\ \frac{\partial u_2}{\partial x_1} & \frac{\partial u_2}{\partial x_2} & \frac{\partial u_2}{\partial x_3} \\ \frac{\partial u_3}{\partial x_1} & \frac{\partial u_3}{\partial x_2} & \frac{\partial u_3}{\partial x_3} \end{bmatrix}$$

A nonzero displacement gradient may represent pure rotation, pure deformation, or both (Darby, 1976). Thus, each displacement component has two parts:

$$\frac{\partial u_i}{\partial x_j} = \underbrace{\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)}_{\text{Pure deformation}} + \underbrace{\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right)}_{\text{Pure rotation}}$$

Then the strain tensor (e_{ij}) can be defined as:

$$e_{ij} = \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

Similarly, the rotation tensor (r_{ij}) can be defined as:

$$r_{ij} = \left(\frac{\partial u_j}{\partial x_i} - \frac{\partial u_i}{\partial x_j}\right)$$