

# Multiphase Science and Technology

Volume 1

---

G. F. Hewitt  
J. M. Delhaye  
N. Zuber

# MULTIPHASE SCIENCE AND TECHNOLOGY

## Volume 1

*Edited by*

**G. F. Hewitt**

Engineering Sciences Division and HTFS  
U. K. Atomic Energy Authority  
Harwell Laboratory, England

**J. M. Delhayé**

Centre d'Etudes Nucléaires de Grenoble  
Service des Transferts Thermiques  
Grenoble, France

**N. Zuber**

Division of Reactor Safety Research  
U. S. Nuclear Regulatory Commission  
Washington, D.C., U.S.A.

 **HEMISPHERE PUBLISHING CORPORATION**

Washington    New York    London

**DISTRIBUTION OUTSIDE THE UNITED STATES**

**McGRAW-HILL INTERNATIONAL BOOK COMPANY**

Auckland	Bogotá	Guatemala	Hamburg	Johannesburg	
Lisbon	London	Madrid	Mexico	Montreal	New Delhi
Panama	Paris	San Juan	São Paulo	Singapore	Sydney
Tokyo	Toronto				

## MULTIPHASE SCIENCE AND TECHNOLOGY, Volume 1

Copyright © 1982 by Hemisphere Publishing Corporation. All rights reserved.  
Printed in the United States of America. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher.

1 2 3 4 5 6 7 8 9 0 B C B C 8 9 8 7 6 5 4 3 2 1

### Library of Congress Cataloging in Publication Data

Main entry under title:

Multiphase science and technology.

Includes bibliographies and index.

Contents: v. 1. Spray cooling of hot surfaces / L. Bolle and J. C. Moureau—The spherical droplet in gaseous carrier streams / Georg Gyarmathy—Boiling in multicomponent fluids / R. A. W. Shock—[etc.]

1. Vapor-liquid equilibrium—Addresses, essays, lectures. 2. Ebullition—Addresses, essays, lectures. 3. Cooling—Addresses, essays, lectures. I. Hewitt, G. F. (Geoffrey Fredrick) II. Delhay, J. M., date III. Zuber, N.

TP156.E65M84 660.2'96 81-4527  
AACR2

ISBN 0-89116-222-4 (Hemisphere)  
ISBN 0-07-028428-8 (McGraw-Hill)  
ISSN 0276-1459

# MULTIPHASE SCIENCE AND TECHNOLOGY

## Editorial Advisory Board

D. AZIZ

Department of Chemical Engineering  
The University of Calgary  
Calgary T2N 1N4, Canada

S. BANERJEE

Department of Engineering Physics  
McMaster University  
Hamilton, Ontario, Canada

H. BRAUER

Technische Universität Berlin  
Institut für Chemieingenieurtechnik  
1 Berlin 10, RFA

J. C. CHARPENTIER

CPIC/ENSIC  
54042 Nancy Cedex, France

J. G. COLLIER

Atomic Energy Unit  
Harwell, Oxfordshire OX 11 0RA, UK

M. CUMO

Comitato per L'Energia Nucleare  
Centro Studi Nucleari della Casaccia  
Dipartimento Reattori Termici  
Rome, Italy

M GIOT

Département Thermodynamique  
et Turbomachines  
B-1348 Louvain la Neuve, Belgium

D. HASSON

Technion  
Department of Chemical Engineering  
Haifa, Israel

M. HIRATA

University of Tokyo  
Department of Mechanical Engineering  
Bunkyo-Ku  
Tokyo 113, Japan

A. KONORSKI

Instytut Maszyn Przepływowych  
80 - 952 Gdansk, Poland

S. S. KUTATELADZE

Institute of Thermophysics  
Novosibirsk 63 0090, USSR

K. R. LAWTHER

A.A.E.C. Research Establishment  
Private mail bag, Sutherland 2232  
NSW Australia

F. MARBLE

Jet Propulsion Center  
California Institute of Technology  
Pasadena, CA 91125, USA

F. MAYINGER

Institut für Verfahrenstechnik  
Technical University Hannover  
3000 Hannover, FRG

G. OOMS

Technische Hogeschool Delft  
Laboratorium voor Aero-en Hydrodynamica  
2628 Al Delft, The Netherlands

F. RESCH

Institut de Mécanique Statistique de la  
Turbulence  
13003 Marseille, France

L. E. SCRIVEN

Department of Chemical Engineering  
and Materials Science  
University of Minnesota  
Minneapolis, MN 55455, USA

G. V. TSIKLARI

Institute of High Temperature  
Krasnook Armenaya  
Moscow, USSR

M. WICKS

Shell Oil Company  
P. O. Box 3105  
Houston, TX 77001, USA



# Contents

Preface    xiii

## Chapter 1    Spray Cooling of Hot Surfaces    *L. Bolle and J. C. Moureau*    1

1	Introduction	1
1.1	Main Uses of Liquid Sprays	1
1.2	Previous Experimental Studies of Spray Cooling	4
1.2.1	Laboratory Measurements	4
1.2.2	Industrial Measurements	13
2	Main Characteristics of a Liquid Spray	16
2.1	Various Kinds of Atomizers	16
2.2	Macroscopic Characteristics of a Spray	22
2.2.1	Total Flow Rate and Related Parameters	22
2.2.2	Liquid Flow Rate Density ( $\dot{m}_l$ )	24
2.2.3	Dynamic Pressure of the Spray	25
2.3	Microscopic Characteristics of a Spray	29
2.3.1	Droplet Diameter Distribution	29
2.3.2	Droplet Velocity Distribution	36
2.3.3	Mean Velocity of Drops in a Spray	40
3	Hydrodynamic Behavior of Droplets Impinging on a Hot Plate	42
3.1	The Single Drop	42
3.1.1	Drop with $We > 80$	43
3.1.2	Drop with $We < 80$	47
3.2	The Liquid Spray	47
4	Heat Transfer during the Impact of a Drop	52
4.1	Existing Theoretical Models	52
4.1.1	The Sessile Drop	52
4.1.2	The Impinging Drop	57
4.2	A New Theoretical Model	67
4.2.1	Heat Transfer by Direct Contact	67
4.2.2	Heat Transfer through the Vapor Film	70
4.2.3	Heat Transfer Due to a Single Drop	71
5	Heat Transfer between a Hot Plate and a Spray: Theoretical Model and Experiments	72
5.1	Theoretical Evaluation of the Heat Exchange	72
5.2	Heat Transfer Measurements	73
5.2.1	Experimental Device	73
5.2.2	Wall Heat Flux Calculations	74
5.2.3	Heat Transfer Results	76
5.2.4	Comparison with Other Experimental Results	81
5.2.5	Efficiency of Spray Cooling	83
5.3	Comparison between Theoretical Model and Experiments	86
6	Conclusions	90
	Nomenclature	91
	References	92

**Chapter 2 The Spherical Droplet in Gaseous Carrier Streams: Review and Synthesis***George Gyarmathy* 99

後

1	Introduction	99
1.1	Purpose and Scope	99
1.2	Historical Outline	103
2	Statement of Problem, Dimensional Analysis	105
2.1	Definition of Sample, Basic Assumptions	105
2.2	Balance Equations	110
2.3	Nondimensional Parameters	115
2.3.1	Basic Physical Variables	115
2.3.2	Nondimensional Variables	117
2.3.3	Basic Set of Nondimensional Parameters	118
2.3.4	Discussion of the Nondimensional Parameters and Their Numerical Values	125
2.3.5	Relationships Concerning the Expansion Rate	129
2.3.6	Other Nondimensional Groups	130
2.3.7	Review and Comparison with Literature	132
3	Transfer of Heat, Mass, and Momentum to a Sphere	135
3.1	Assumptions and Introductory Remarks	135
3.2	Continuum Environment	138
3.2.1	General	138
3.2.2	Nusselt Number Expressions for Quiescent Media	139
3.2.3	Nusselt Number Expressions for Relative Flow	139
3.2.4	Other Effects	140
3.2.5	Review of the Crucial Parameters	143
3.3	Free-Molecule Environment	144
3.3.1	General	144
3.3.2	Accommodation Coefficients	145
3.3.3	Transfer Rates	147
3.3.4	Nusselt Number Expressions	149
3.3.5	Review of the Crucial Parameters	152
3.4	Multirange Expressions	153
3.4.1	General	153
3.4.2	The Cunningham Correction	154
3.4.3	Multirange Expressions for the Nusselt Numbers	156
3.4.4	The Stationary, Isothermal Sphere	157
3.4.5	Relative Flow and Other Corrections	158
3.4.6	Comparison with Experimental Data	158
3.4.7	Review of the Crucial Parameters	160
3.5	Applicability to Droplet Growth; Proximity Effects	160
3.5.1	Constancy of $r$ (Assumption IVa)	160
3.5.2	Constancy of $T_r$ and $p_r$ (Assumption IVb)	162
3.5.3	Constancy of Far Field Conditions (Assumption IVc)	162
3.5.4	Infinite Environment (Assumption IVd)	163
3.5.5	Body-Force Effects (Assumption IVe)	166
3.6	Heat Conduction in the Interior of the Droplets	166
3.7	Drift Velocity	169
4	Equilibrium and Stability of Droplets	171
4.1	Thermodynamic Equilibrium	171
4.2	Mechanical Stability	174

A2.4	Energy Balance	263	
A2.5	Comments on Temperature Definitions	266	
Appendix 3	Free Molecule Transfer Processes in Mixture Carriers	267	
A3.1	Mass Impingement Rate of Molecules	267	
A3.2	Heat Transfer	267	
A3.3	Mass Transfer	269	
A3.4	Momentum Transfer (Drag)	271	
Appendix 4	The Analysis of Droplet Surface Temperature	272	
A4.1	Discussion of Eq. (213)	272	
A4.2	Approximation for Vapor-Rich Carriers	274	
A4.3	Approximation for Cool, Lean Mixture Carriers	275	
A4.4	Synthesis of the Rich and Lean Approximations	275	
A4.5	Approximation for Hot, Lean Carriers	276	
A4.6	Error Analysis of the Approximations	276	
A4.7	The Case of Continuum Nonlinear Mass Transfer	277	
A4.8	Correction for Free Molecular Conditions	277	
Appendix 5	Biographic Notes Concerning the Non-Dimensional Named Groups Proposed	279	
<b>Chapter 3</b>	<b>Boiling in Multicomponent Fluids</b>	<i>R. A. W. Shock</i>	<b>281</b>
1	Introduction	281	
2	Phase Equilibrium	283	
3	Onset of Boiling	286	
3.1	Homogeneous Nucleation	286	
3.2	Heterogeneous Nucleation	287	
4	Bubble Growth Dynamics	295	
4.1	Introduction	295	
4.2	Free Bubbles	297	
4.3	Attached Bubbles	308	
5	Nucleate Boiling Heat Transfer	318	
5.1	Introduction	318	
5.2	Correlations	327	
5.2.1	General Form of Correlations	327	
5.2.2	Empirical Correlations	335	
5.2.3	Semiempirical Correlations	338	
6	Critical Heat Flux	341	
6.1	Introduction	341	
6.2	Thin Wires	342	
6.3	Large Heaters	347	
7	Film Boiling	350	
8	Flow Boiling and Evaporation	361	
9	Conclusions	368	
	Nomenclature	369	
	References	372	
	Appendix	383	



5	Growth and Vaporization	175
5.1	Simplification of the Basic Equations	175
5.1.1	Outline of Approach	175
5.1.2	General Nonsteady Case	177
5.1.3	Partially Quasi-Steady Formulation	178
5.1.4	Quasi-Steady Formulation	179
5.2	The Surface Temperature of the Drop	180
5.2.1	Thermodynamic Parameters of the Droplet	180
5.2.2	Parameter Domains of Practical Interest	182
5.2.3	Discussion of the Equation Giving $T_r$	183
5.2.4	Iterative Calculation of $T_r$	185
5.2.5	The Caloric Effectiveness $Q$	187
5.2.6	Approximate Expressions for $Q$	187
5.2.7	Conclusions and Critical Remarks	191
5.3	Laws of Quasi-steady Droplet Growth	192
5.3.1	General Formulation	192
5.3.2	Simplified Growth Laws for Pure Vapor or Vapor-Rich Carriers	195
5.3.3	Simplified Growth Laws for Lean, Cold Carriers	197
5.3.4	Simplified Growth Laws for Lean, Hot Carriers	199
5.4	Outline of Calculation Procedure	200
6	Application	109
6.1	Time Constants	109
6.2	Spray Droplet Vaporization	209
6.3	The Influence of Droplet Size on Droplet Temperature	215
6.4	Analytic Solutions for Growth in Carriers of Constant Conditions	218
6.5	Entropy Production in Mist-Type Flows	223
6.5.1	Polytropic Loss Coefficients	223
6.5.2	Thermodynamic Disequilibrium	225
6.5.3	Mechanical Disequilibrium	228
6.5.4	Similarity Law of Entropy Production	230
7	Critical Discussion and Conclusions	231
7.1	Classification of Droplet Growth Theories	231
7.1.1	Fully Nonsteady Treatment	231
7.1.2	Partially Quasi-Steady Treatment	232
7.1.3	Quasi-Steady Formulation Using a Differential Equation for $T_r$	232
7.1.4	Quasi-Steady Theories Using an Algebraic Equation for $T_r$	233
7.2	Conclusions	235
7.3	Suggestions for Further Work	237
	Nomenclature	238
	References	244
	Appendix 1 Summary of Some Elementary Relationships and of Representative Materials Data	253
	A1.1 Carrier-Phase Composition	253
	A1.2 Carrier-Phase Mixture Properties	254
	A1.3 Vapor Pressure, Saturation Ratio, and Subcooling	255
	A1.4 Representative Materials Data	256
	Appendix 2 Balance Equations for the Two-Phase Fluid Sample	259
	A2.1 Definitions	259
	A2.2 Mass Balance	261
	A2.3 Momentum Balance	261

<b>Chapter 4</b>	<b>Contact Angles</b>	<i>Jacques Chappuis</i>	<b>387</b>
<b>1</b>	<b>Introduction</b>		<b>387</b>
1.1	Behavior of Liquids Relative to Solid Surfaces		<b>387</b>
1.2	Applications of Contact Angles		<b>388</b>
1.3	Theoretical Complexity and Present Standards of Understanding		<b>389</b>
1.4	Purpose and Scheme of the Chapter		<b>390</b>
<b>2</b>	<b>Liquid Surfaces</b>		<b>392</b>
2.1	Surface and Interfacial Tensions of Liquids, and Other Surface Thermodynamic Quantities		<b>392</b>
2.2	Surface Tension Related to the Molecular Structure of Liquids		<b>395</b>
2.3	Interfacial Tension Between Two Nonmiscible Liquids		<b>400</b>
2.4	Adsorption at Liquid Surfaces		<b>401</b>
2.5	Laplace's Law; The Condition of Mechanical Equilibrium of a Surface		<b>403</b>
2.6	Cylindrical Meniscii in the Gravitational Field		<b>404</b>
2.6.1	Cartesian Equation of the Curve $z = f(x)$		<b>406</b>
2.6.2	Parametric Equation of the Curve		<b>407</b>
2.6.3	Volume of the Meniscus		<b>409</b>
2.6.4	Elementary Work of Formation of a Cylindrical Meniscus		<b>410</b>
2.6.5	Total Work of Cylindrical Meniscus Formation		<b>412</b>
2.7	Axially Symmetrical Meniscii in the Gravitational Field		<b>412</b>
2.7.1	The Volume of an Axially Symmetrical Meniscus		<b>414</b>
2.8	Influence of a Liquid's Curvature on Its Vapor Tension		<b>415</b>
<b>3</b>	<b>Solid Surfaces</b>		<b>415</b>
3.1	Surface and Volume Stresses		<b>415</b>
3.2	Superficial Tension of Solids		<b>417</b>
3.3	Measurement of Surface Tension of Solids		<b>418</b>
3.4	Heterogeneity of Solid Surfaces		<b>418</b>
3.5	Roughness of Solid Surfaces		<b>419</b>
<b>4</b>	<b>Adsorption on Solid Surfaces</b>		<b>420</b>
4.1	General Characteristics of Adsorption		<b>420</b>
4.1.1	Definition of Adsorption		<b>420</b>
4.1.2	Specific Surface Area of Solids		<b>421</b>
4.1.3	Demonstration of Adsorption Phenomena at the Solid-Gas Interface		<b>421</b>
4.1.4	Demonstration of Adsorption Phenomena at the Solid-Liquid Interface		<b>421</b>
4.1.5	The Adsorption Mechanism		<b>421</b>
4.1.6	Physical Adsorption or Physisorption		<b>422</b>
4.1.7	Chemical Adsorption or Chemisorption		<b>423</b>
4.2	Adsorption of Gases on Solids		<b>423</b>
4.3	Adsorption from Solutions		<b>425</b>
4.4	Modification of the Surface Tension of Solids by Adsorption		<b>426</b>
<b>5</b>	<b>Contact Angles on Smooth and Homogeneous Solid Surfaces</b>		<b>427</b>
5.1	Young's Model		<b>427</b>
5.1.1	Thermodynamic Justification of Young's Equation		<b>428</b>
5.1.2	Quantities That May Come into Play in Young's Equation		<b>428</b>
5.2	Vectorial Justification of Young's Equation		<b>429</b>
5.2.1	Validity of Young's Vectorial Equation in the Absence of Gravity		<b>432</b>

5.3	Experimental Evidence of Young's Vectorial Model	432
5.4	Contact Angle of a Drop of Liquid on a Clean, Solid Surface, in a Vessel Containing No Other Gas Than the Liquid's Vapor	433
5.5	Adhesion Tension; Work of Wetting	434
5.6	Work of Adhesion; Work of Cohesion	437
5.7	Physical Significance of $W_A^\circ$ and $W_A$	439
5.8	Spreading Coefficient $S$	441
5.9	Reversible and Irreversible Processes in the Case of a Moving Three-Phase Line	441
5.9.1	An Irreversible Process	441
5.9.2	A Reversible Process	442
6	Hysteresis of Contact Angles on Real Solid Surfaces	443
6.1	Advancing and Receding Contact Angles	443
6.2	Surface Heterogeneity and Hysteresis	445
6.2.1	Model 1: A Horizontally-Striped Plate	445
6.2.2	Model 2: A Vertically-striped Plate	449
6.2.3	Model 3: A Surface of High Superficial Tension Interspersed with Small Patches of Low Tension	450
6.2.4	Application to Real Heterogeneous Surfaces	454
6.3	Surface Roughness and Hysteresis	454
6.3.1	Model 1: A Plate Presenting Inclined Horizontal Stripes	454
6.3.2	Model 2: A Plate Presenting Inclined Vertical Stripes	456
6.3.3	Application to Real Surfaces	457
6.4	Other Causes of Variation in Contact Angles: The Modifications of a Solid Surface after its Contact with a Liquid	458
6.5	Other Important Theories about Contact Angle Hysteresis	459
6.6	Conclusion and an Example of the Use of Results Obtained	460
6.6.1	Experimental Details	460
6.6.2	Experimental Results	460
6.6.3	Interpretation	461
7	The Wetting Tensiometer: Analysis of a Method of Measuring Contact Angles	462
7.1	Choice and Description of the Measuring Method	462
7.1.1	Choice of Method	462
7.1.2	Description of Method	463
7.2	Theoretical Analysis	464
7.2.1	Notation and Conventions	464
7.2.2	Nature of the Measured Forces	465
7.2.3	Height of the Meniscii	467
7.2.4	Case of Horizontal Edges	467
7.3	Physical Significance of the Recordings	468
7.3.1	Experimental Curves	468
7.3.2	Theoretical Curves	471
7.3.3	Theoretical Construction of a Curve	473
7.4	Practical Use	474
7.4.1	Choice of Samples	474
7.4.2	Choice and Influence of Liquid	475
7.4.3	Determination of Macroscopic Heterogeneity of Surface "Pollution"	475
7.4.4	Utilization of the Technique as a Test of Cleaning	477

8	Interpretation of Contact Angle Values	477
8.1	Existence of an Equation of State	477
8.2	The Importance of $\pi_e$ in Different Cases	478
8.3	The Choice of Proper Experimental Results	479
8.4	Analysis of Results	480
8.5	Critical Analysis of Zisman's Interpretation	484
8.6	Other Important Theories in the Literature	485
8.7	The Author's New Interpretation	486
8.8	Conclusions to Be Drawn from Our Interpretation	490
8.8.1	The Expression of $W_A^0$	490
8.8.2	The Expression of $\gamma_{SL}$	490
8.8.3	The Significance of $\gamma_0$ and $\gamma_C$	490
8.8.4	The Measurement of $\pi_e$	491
8.9	Recapitulation of Conclusions Drawn from PTFE Data	491
8.10	Extension of the Theory to Other Solids	491
9	Nonequilibrium Contact Angles	494
	Nomenclature	495
	References	500
	Subject Index	507

## Preface

This is the first volume of *Multiphase Science and Technology*, a new international series of books intended to fill an existing gap and bring together materials from different fields such as nuclear energy, chemical processing, petroleum, meteorology, civil engineering, and energetics. The objectives of the series are to provide authoritative overviews of important areas in multiphase systems. The chapters published in the series are systematic and tutorial presentations of the state of knowledge in various areas. The editors hope that the nonspecialist reader can gain an up-to-date idea of the present stage of development in a given area.

Chapter 1 deals with the spray cooling of hot surfaces and is coauthored by Professor Léon Bolle and Doctor Jean-Claude Moureau. Professor L. Bolle has been with the Catholic University of Louvain, Belgium, since 1972 and is currently working on industrial energetics. A former student of Professor L. Bolle, Doctor J. C. Moureau received his doctorate in applied sciences in 1978 and is now in charge of nuclear safety at the Belgian Ministry of Health and Welfare.

The behavior of a droplet in a carrier stream is then examined in Chapter 2, by Doctor George Gyarmathy, Manager of the Turbomachinery R & D laboratories in the Brown Boveri Company, Baden, Switzerland. Doctor G. Gyarmathy has been involved in the theory of wet steam turbine and condensation for the past twenty years and is a recognized expert in these areas.

Chapter 3 is devoted to boiling phenomena in multicomponent fluids. Doctor R. A. W. Shock, the author, works for Heat Transfer and Fluid Flow Service at Harwell, UK. He is a specialist in the design of vertical thermosiphon reboilers and in crystallization.

Wall nucleation depends upon contact angles and wettability phenomena, the subject reviewed by Doctor Jacques Chappuis, Ecole Centrale de Lyon, France, in Chapter 4. Doctor J. Chappuis is currently on a sabbatical year at the Department of Mechanical Engineering of the University of Toronto.

These four chapters constitute the first volume of *Multiphase Science and Technology*. We would like to thank all the authors and reviewers for their outstanding contributions. And we would like also to express our special indebtedness to Mrs. Pauline Wilkes, who did a careful and patient job in typing this book.

*The Editors*



# Spray Cooling of Hot Surfaces

L. Bolle and J. C. Moureau  
Universite Catholique de Louvain, Belgium

## 1 INTRODUCTION

### 1.1 Main Uses of Liquid Sprays

A dispersion of small liquid drops in a continuous gaseous phase is generally called a liquid spray. This dispersion has also received various other names according to the dimensions of the droplets produced. Some authors, such as Fortier (1967), distinguish between mist and cloud. A mist is a dispersion including drops smaller than  $10^{-1} \mu\text{m}$ , whereas a cloud refers to a dispersion of larger particles. Others call an aerosol a dispersion of submicrometer particles and a mist much larger drops, for example, drops with a diameter of  $150 \mu\text{m}$ . It is therefore necessary to make clear that, in this chapter, we consider as liquid spray a dispersion of liquid particles with diameters ranging from about  $20 \mu\text{m}$  up to about  $1 \text{ mm}$ .

A process of disintegration of the liquid phase induces an increase in the interfacial surface area between the liquid and the medium into which it penetrates. This increase can be quite important: in some instances, the initial interfacial surface area can become several hundred times larger. Atomization can thus intensify the physical or chemical processes occurring at the interface, that is, mass, momentum, and energy transfers. This advantage is used in several industrial applications.

Liquid spraying is common in various fields: air conditioning and ventilation, gas absorption, washing and cleaning, fire protection, coating of surfaces, spray drying, combustion, cooling of hot gases, cooling of hot surfaces. This chapter is devoted to the study of this last application.

It is in the steel and metal works industry that one finds the most numerous uses of atomization in order to cool hot walls: cooling of slabs, rolled products, and cylinders in classical mills, and cooling of incandescent metal immediately after its exit from the mould in continuous casting units. In most instances, the amount of heat to be extracted from the metal is large: Fig. 1 shows, for the case of continuous casting, the variation of heat flux density  $\dot{q}_w$  in the secondary cooling zone of a rectangular slab.

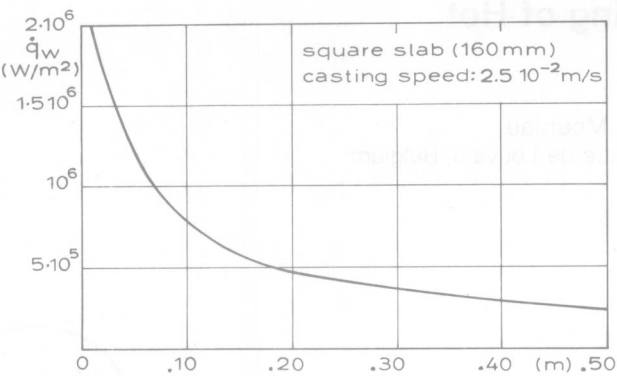


Fig. 1. Variation of the heat flux density as a function of distance to the casting level, according to Weinreich (1969).

Let us consider the typical example of the runout table of a hot strip mill. Between the last finishing stand and the coiling, cooling can be divided into three zones (Fig. 2):

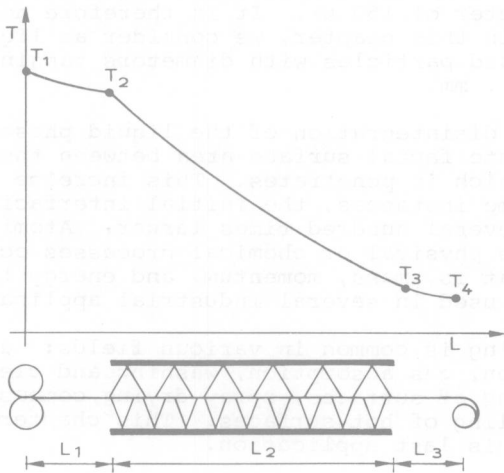


Fig. 2. Cooling zones on the runout table of a hot strip mill.

1. From the last mill to the beginning of the water cooling, the metal is in contact with air. Heat transfer is governed mainly by radiation with the environment, since the strip temperature is high (800 to 900°C).
2. Spray cooling produces an important drop in temperature along stretch  $L_2$ . The liquid aspersion is performed differently on the upper and lower sides of the strip. Above, water nozzles are generally mounted along successive rows at a distance of about 2 m from the strip: below, since the water must flow between the supporting rolls, the nozzles are placed nearer and usually have a lower flow rate. What kind of nozzles and how many should be displayed in order to achieve the desired cooling? At what pressure should they work? What is the optimal length  $L_2$ ? To all these questions, the answer given has sometimes been too empirical and approximate. Indeed, the fundamental problem — determination of the heat transfer coefficient between a hot wall and a water spray — has not been completely solved.
3. Between the end of the spray cooling and the coiling, the strip is again in contact mainly with air: again, radiative heat transfer is predominant.

From a metallurgical viewpoint, the velocity with which heat is extracted from the metal during water cooling is essential in order to obtain a good-quality product. It has been shown that, for low-alloy steels, high strength can be achieved without reducing ductility or weldability provided that the size of the grains can be reduced. One of the best ways to reach this goal is to control cooling during the austenite-ferrite transformation (Morgan et al., 1965, 1966).

For rolled wire rods, a drastic cooling without quenching is desirable. Furthermore, when spraying, the surface temperature risks being considerably lower than that of the center of the rod. Therefore, in order to avoid superficially quenched structures, one has to divide the spray cooling zone into several parts separated by air cooling zones. Indeed, this setup facilitates uniformization of the inside temperature of the rod. Figure 3 illustrates the method for a wire rod with a 5.5 mm diameter. Moreover, Couvreur (1971) insists on the necessity, in design calculations, of taking into account a variation of the surface heat transfer coefficient  $\alpha$  with the temperature of the rod. If, instead, one uses an averaged constant heat transfer coefficient, large discrepancies can appear. In Fig. 3, one sees a difference of about 100°C in the rod surface temperature when using constant and temperature-varying coefficients. This proves the usefulness of studies aiming to determine the exact parameters influencing heat transfer in such applications.

In nuclear power plants, spray cooling is one of the safety systems foreseen in case of accident. Schematically, two techniques exist: top spraying, that is, liquid spray onto the core from above; and bottom reflooding, that is, immersion from below. In the latter case, drops can sputter from the upper liquid level and impinge on hot walls. Many related publications — both theoretical and experimental — have described the phenomena occurring in various core configurations and possible incidents.

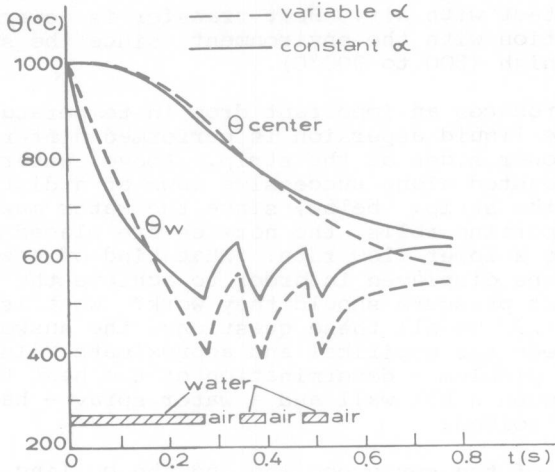


Fig. 3. Time evolution of the wire temperature, according to Couvreur (1971).

Yamanouchi (1968), for instance, has proposed a model for the evaluation of emergency spray cooling for a postulated loss of coolant accident (loca) in a boiling-water reactor. This model has been extended by several authors. Reviews of papers on spray cooling of light-water reactor cores have been published, among others, by Sawan and Carbon (1975). Moore et al. (1973) have studied spray emergency cooling of heavy-water reactors. In many of these texts, the liquid spray is considered only as a means to produce a liquid film flowing over the hot wall. It is the heat transfer between the film and the hot surface that is analyzed in detail and not the transfer due to the impacts of very many individual drops. Therefore, we shall not comment on these studies any further.

Besides the steel-making and nuclear industries, the chemical industry also uses liquid sprays in order to cool hot surfaces, for example, in the cooling of hot vessels and tanks.

Moreover, we think that liquid sprays could also be used in other fields. In 1973, Kawazoe and Kumamaru developed a new technique of spray cooling in order to improve the performance of the extrusion process of plastic-insulated telephone wires. New applications of spray cooling of hot surfaces are to be expected.

## 1.2 Previous Experimental Studies of Spray Cooling

One can distinguish in the literature two types of experimental work: results obtained in laboratories and measurements performed directly on industrial equipments. Theoretical models will be discussed later.

### 1.2.1 Laboratory Measurements

The main results published during the last 12 years are