UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

INTEL CORPORATION, GLOBALFOUNDRIES U.S., INC.,

AND MICRON TECHNOLOGY, INC.,

Petitioners,

v.

DANIEL L. FLAMM,

Patent Owner.

PTAB Case No. To Be Assigned

Patent No. RE40,264 E

DECLARATION OF SCOTT BENNETT, Ph.D.

27 September 2016

I, Scott Bennet, Ph.D., resident of Urbana, Illinois, hereby declare as follows:

I. Introduction and Qualifications

1. I have been retained by Perkins Coie LLP to provide my opinions concerning the public availability of certain documents at issue in *inter partes* review proceedings for U.S. Patent No. RE40,264 E.

2. My curriculum vitae is appended to this document as Appendix A. From 1956 to 1960, I attended Oberlin College, where I received an A.B. in English. I then attended Indiana University, where I received an M.A. in 1966 and a Ph.D. in 1967, both in English. In 1976, I received a M.S. in Library Science from the University of Illinois. I also served at the University of Illinois at Urbana-Champaign in two capacities. First, from 1967 to 1974, I was an Assistant Professor of English; then from 1974 to 1981, I was an Instructor, Assistant Professor, and Associate Professor of Library Science.

3. From 1981 to 1989, I served as the Assistant University Librarian for Collection Management, Northwestern University. From 1989 to 1994, I served as the Director of The Milton S. Eisenhower Library at The Johns Hopkins University. From 1994 to 2001, I served as the University Librarian at Yale University. In 2001, I retired from Yale University.

4. Since then, I have served in multiple capacities for various organizations, including as a consultant on library space planning from 2004 to the present, as a Senior Advisor for the library program of the Council of Independent Colleges from 2001 to 2009, as a member of the Wartburg College Library Advisory Board from 2004 to the present, and as a Visiting Professor at the Graduate School of Library and Information Science, University of Illinois at Urbana-Champaign, in the Fall of 2003. I was a founding partner of Prior Art Documentation Services, LLC, in 2015.

5. Over the course of my work as a librarian, professor, researcher, and author of numerous publications, I have had extensive experience with cataloging and online library management systems built around Machine-Readable Cataloging (MARC) standards. As a consultant, I have substantial experience in authenticating documents and establishing the date when they were available to persons exercising reasonable diligence.

6. In the course of more than fifty years of academic life, I have myself been an active researcher. I have collaborated with many individual researchers and, as a librarian, worked in the services of thousands of researchers at four prominent research universities. Members of my family are university researchers. Over the years, I have read some of the voluminous professional literature on the information seeking behaviors of academic researchers. And as an educator, I

have a broad knowledge of the ways in which students in a variety of disciplines learn to master the bibliographic resources used in their disciplines. In all of these ways, I have a general knowledge of the how researchers work.

7. My work in this matter is being billed at my standard consulting rate of $88 per hour. My compensation is not in any way contingent upon the outcome of this or any other *inter partes* review. I have no financial or personal interest in the outcome of this proceeding or any related litigation.

II. Scope of this Declaration

8. I am not a lawyer and I am not rendering an opinion on the legal question of whether any particular document is, or is not, a "printed publication" under the law.

9. I am, however, rendering my expert opinion on when and how each of the documents addressed herein was disseminated or otherwise made available to the extent that persons interested and ordinarily skilled in the subject matter or art, exercising reasonable diligence, could have located the documents before 4 December 1994.

10. I reserve the right to supplement my opinion in the future to respond to any arguments that the Patent Owner raises and to take into account new information as it becomes available.

III. Materials Considered in Forming My Opinion

11. In forming the opinions expressed in this declaration, I have reviewed the document and attachments referenced below. Each item is a type of material that experts in my field would reasonably rely upon to in forming their opinions.

> **Document 1. Frank R. Incropera and David P. DeWitt. Fundamentals of Heat and Mass Transfer, 3rd ed. New York, NY: Wiley, 1990.** Herein referred to as Incropera.

12. The following Attachments are true and accurate representations of library material and online documents and records, as they are identified below. All attachments were secured on 23-24September 2016. All URLs were available on 24 September 2016.

Attachment 1a: Statewide Illinois Library Catalog record for Incropera

Attachment 1b: University of Illinois at Urbana-Champaign Library catalog record for Incropera

Attachment 1c: Copy of Incropera from the University of Illinois at Urbana-Champaign Library

Attachment 1d: United States Copyright Office catalog record for Incropera

Attachment 1e: University of Illinois at Urbana-Champaign Library catalog record, in MARC format, for Incropera

Attachment 1f: École Polytechnique Fédérale de Lausanne (EPFL) Library catalog record, in MARC format, for Incropera

Attachment 1g: Scopus list of publications citing Incropera

Attachment 1h: Scopus index record for a publication citing Incropera

13. Helen Sullivan is a Managing Partner in Prior Art Documentation Services LLC (see http://www.priorartdocumentation.com/hellen-sullivan/ **)**. Her primarily responsibility in our partnership is to secure the bibliographic documentation used in attachments to our declarations. Ms. Sullivan secured all of the attachments listed above except for Attachment 1c, which I secured.

IV. Background Information

14. *Persons of ordinary skill in the art*. I am told by counsel that the subject matter of this proceeding relates to semiconductor processing.

15. I am told by counsel that persons of ordinary skill in this subject matter or art would have had (i) a Bachelor's degree in chemical engineering, materials science engineering, electrical engineering, physics, chemistry, or a similar field, and three or four years of work experience in semiconductor manufacturing or related fields; or (ii) a Master's degree in engineering, physics, chemistry, materials science, or a similar field and two or three years of work experience in semiconductor manufacturing or related fields; or (iii) a Ph.D. in engineering, physics, chemistry, materials science, or a similar field.

16. It is my opinion that such a person would have been engaged in in research, learning though study and practice in the field and possibly through

formal instruction the bibliographic resources relevant to his or her field. In the 1980s and 1990s such a person would have had access to a vast array of long-established print resources as well as to a rich and fast changing set of online resources providing indexing information, abstracts, and full text services.

17. *Library catalog records*. Libraries world-wide use the MARC format for catalog records; this machine readable format was developed at the Library of Congress in the 1960s.

18. MARC formatted records provide a variety of subject access points based on the content of the document being cataloged. All may be found in the MARC Fields 6XX. Particularly important are the MARC Field 600, which identifies personal names, and the MARC Field 650, which identifies topical terms. An ordinarily skilled researcher might discover material relevant to his or her topic by a search using the access points provided in the MARC Fields 6XX.

19. The MARC Field 040, subfield a, identifies the library or other entity that created the original catalog record for a given document and transcribed it into machine readable form. The MARC Field 008 identifies the date when this first catalog record was entered on the file. This date persists in all subsequent uses of the first catalog record, although newly and separately created records for the same document will show a new date.

20. WorldCat is the world's largest public online catalog, maintained by the Online Computer Library Center, Inc., or OCLC, and built with the records created by the thousands of libraries that are members of OCLC. WorldCat provides a user-friendly interface for the public to use MARC records; it requires no knowledge of MARC tags and codes. WorldCat records appear in many different catalogs, including the Statewide Illinois Library Catalog. The date a given catalog record was created (corresponding to the MARC Field 008) appears in some detailed WorldCat records as the Date of Entry.

21. When an OCLC participating institution acquires a document for which it finds no previously created record in OCLC, or when the institution chooses not to use an existing record, it creates a record for the document using OCLC's Connexion, the bibliographic system used by catalogers to create MARC records. Connexion automatically supplies the date of record creation in the MARC Field 008.

22. Once the MARC record is created by a cataloger at an OCLC participating member institution, it becomes available to other OCLC participating members in Connexion and to the public in WorldCat.

23. When a book has been cataloged, it will normally be made available to readers soon thereafter—normally within a few days or (at most) within a few weeks of cataloging.

24. *Indexing*. An ordinarily skilled researcher may discover material relevant to his or her topic in a variety of ways. One common means of discovery is to search for relevant information in an index of periodical and other publications. Having found relevant material, the researcher will then normally obtain it online, look for it in libraries, or purchase it from the publisher, a bookstore, or other provider. Sometimes, the date of a document's public accessibility will involve both indexing and library date information. Date information for indexing entries is, however, often unavailable. This is especially true for online indexes.

25. Indexing services commonly provide a list of the documents cited in the indexed publication. These services also often provide lists of publications that cite a given document. A citation of a document is evidence that the document was publicly available and in use by researchers as of the publication date of the citing document.

26. Prominent indexing services include:

27. Scopus. Produced by Elsevier, a major publisher, Scopus is the largest database of abstracts and citations of peer-reviewed literature. Its scope includes the social sciences, science, technology, medicine, and the arts. It includes 60 million records from more than 21,500 titles from some 5,000 international publishers. Coverage includes 360 trade publications, over 530 book

series, more than 7.2 million conference papers, and 116,000 books. Records date from 1823.

V. Consideration of individual documents

Document 1. Frank R. Incropera and David P. DeWitt. Fundamentals of Heat and Mass Transfer, 3rd ed. New York, NY: Wiley, 1990. Herein referred to as Incropera.

Authentication

28. Document 1 is a book written by Frank Incropera and David DeWitt, the 3rd edition of which was published in 1990 by Wiley.

29. Attachment 1a is a true and accurate copy of the Statewide Illinois Library Catalog record for Incropera. This record shows that Incropera is held by 308 libraries world-wide. An ordinarily skilled researcher would have no difficulty either identifying Incropera, using the many subject terms provided, or locating library copies of Incropera.

30. The University of Illinois at Urbana-Champaign Library is one library holding Incropera. Attachment 1b is a true and accurate copy of the University of Illinois at Urbana-Champaign Library catalog record for Incropera.

31. Attachment 1c is a true and accurate copy of the cover, title page, title page verso, table of contents, and Chapter 5 of Incropera from the University of Illinois at Urbana-Champaign Library. Attachment 1c is in a condition that creates no suspicion about its authenticity. Specifically, there are no visible alterations to

the document (aside from the header that identifies it), and Attachment 1c was found within the custody of a library – a place where if authentic it would likely be.

Public accessibility

32. Attachment 1d is a true and accurate copy of the United States Copyright Office catalog record for Incropera. It shows that Incropera was published by Wiley on 20 February 1990 and registered for copyright soon thereafter, on 14 May 1990. I conclude from this Copyright Office record that Incropera was available from the publisher on or soon after its 20 February 1990 publication date.

33. The verso of the Incropera title page in Attachment 1c includes cataloging-in-publication information for Incropera. Attachment 1e is a true and accurate copy of the University of Illinois at Urbana-Champaign Library catalog record, in MARC format, for Incropera. It shows in the MARC Field 040, subfield a, that the Library of Congress (OCLC code = DLC) first cataloged Incropera. The MARC Field 008 indicates this Library of Congress record was created on 25 July 1989, substantially before the publication of Incropera—as one would expect with cataloging-in-publication. I conclude from this MARC record that Incropera was bibliographically discoverable by 25 July 1989.

34. The library at the École Polytechnique Fédérale de Lausanne (EPFL) is another library holding Incropera. Attachment 1f is a true and accurate copy of the EPFL Library record, in MARC format, for Incropera. It shows in the MARC Field 040, subfield a, that the EPFL Library (OCLC code = EPFLB)[1] cataloged Incropera. The MARC Field 008 indicates this EPFL record was created on 6 September 1991. I conclude from this MARC record that Incropera was publicly available in at least one library by no later than 6 September 1991.

35. An ordinarily skilled research could also have discovered Incropera by citations to it in other publications. Attachment 1g is a true and accurate copy of a Scopus list of 92 documents citing Incropera. One of these citing publications is T. -H. Lyu and I. Mudawar, "Simultaneous Measurements of Thickness and Temperature Profile in a Wavy Liquid Film Heating Wall," Experimental Heat Transfer, 4,3 (July-September 1991): 217-233. Attachment 1h is a true and accurate copy of the Scopus index record for the Lyu and Mudawar paper, showing the citation of Incropera as the 8th document in the list of references.

Conclusion

36. Based on the evidence presented here—book publication, copyright registration, library cataloging, and citations—**it is my opinion that Incropera was bibliographically discoverable by 25 July 1989, was available from its**

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[1] The EPF-BC identifier found in the MARC Field, subfield a, is an obsolete code for the EPFL Library. Such obsolete codes are regularly found in older MARC records.

publisher on or soon after 20 February 1990, was publicly available in at least one library by 6 September 1991, and demonstrably in use by researchers by no later than July 1991.

VI. Attestation

37. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statement were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statement may jeopardize the validity of the application or any patent issued thereon.

27 September 2016

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Scott Bennett, Ph.D.
Managing Partner
Prior Art Documentation Services LLC

Date

EXHIBIT A: RESUME

SCOTT BENNETT
Yale University Librarian Emeritus

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Urbana, Illinois 61801-4132
2scottb@prairienet.org
217-367-9896

EMPLOYMENT

Retired, 2001. Retirement activities include:

- Managing Partner in Prior Art Documentation Services, LLC, 2015-. This firm provides documentation services to patent attorneys; more information is available at http://www.priorartdocumentation.com
- Consultant on library space design, 2004- . This consulting practice is rooted in a research, publication, and public speaking program conducted since I retired from Yale University in 2001. I have served more than 50 colleges and universities in the United States and abroad with projects ranging in likely cost from under $50,000 to over $100 million. More information is available at http://www.libraryspaceplanning.com/
- Senior Advisor for the library program of the **Council of Independent Colleges**, 2001-2009
- Member of the Wartburg College Library Advisory Board, 2004-
- Visiting Professor, Graduate School of Library and Information Science, **University of Illinois at Urbana-Champaign**, Fall 2003

University Librarian, **Yale University**, 1994-2001

Director, The Milton S. Eisenhower Library, **The Johns Hopkins University**, Baltimore, Maryland, 1989-1994

Assistant University Librarian for Collection Management, **Northwestern University**, Evanston, Illinois, 1981-1989

Instructor, Assistant and Associate Professor of Library Administration**, University of Illinois at Urbana-Champaign**, 1974-1981

Assistant Professor of English, **University of Illinois at Urbana-Champaign**, 1967-1974

Woodrow Wilson Teaching Intern, **St. Paul's College**, Lawrenceville, Virginia, 1964-1965

EDUCATION

University of Illinois, M.S., 1976 (Library Science)
Indiana University, M.A., 1966; Ph.D., 1967 (English)
Oberlin College, A.B. magna cum laude, 1960 (English)

HONORS AND AWARDS

Morningside College (Sioux City, IA) Doctor of Humane Letters, 2010

American Council of Learned Societies Fellowship, 1978-1979; Honorary Visiting Research Fellow, Victorian Studies Centre**, University of Leicester**, 1979; **University of Illinois** Summer Faculty Fellowship, 1969

Indiana University Dissertation Year Fellowship and an **Oberlin College** Haskell Fellowship, 1966-1967; **Woodrow Wilson** National Fellow, 1960-1961

PROFESSIONAL ACTIVITIES

American Association for the Advancement of Science: Project on Intellectual Property and Electronic Publishing in Science, 1999-2001

American Association of University Professors: University of Illinois at Urbana-Champaign Chapter Secretary and President, 1975-1978; Illinois Conference Vice President and President, 1978-1984; national Council, 1982-1985, Committee F, 1982-1986, Assembly of State Conferences Executive Committee, 1983-1986, and Committee H, 1997-2001 ; Northwestern University Chapter Secretary/Treasurer, 1985-1986

Association of American Universities: Member of the Research Libraries Task Force on Intellectual Property Rights in an Electronic Environment, 1993-1994, 1995-1996

Association of Research Libraries: Member of the Preservation Committee, 1990-1993; member of the Information Policy Committee, 1993-1995; member of the Working Group on Copyright, 1994-2001; member of the Research Library Leadership and Management Committee, 1999-2001; member of the Board of Directors, 1998-2000

Carnegie Mellon University: Member of the University Libraries Advisory Board, 1994

Center for Research Libraries: Program Committee, 1998-2000

Johns Hopkins University Press: Ex-officio member of the Editorial Board, 1990-1994; Co-director of Project Muse, 1994

Library Administration and Management Association, Public Relations Section, Friends of the Library Committee, 1977-1978

Oberlin College: Member of the Library Visiting Committee, 1990, and of the Steering Committee for the library's capital campaign, 1992-1993; President of the Library Friends, 1992-1993, 2004-2005; member, Friends of the Library Council, 2003-

Research Society for Victorian Periodicals: Executive Board, 1971-1983; Co-chairperson of the Executive Committee on Serials Bibliography, 1976-1982; President, 1977-1982

A Selected Edition of W.D. Howells (one of several editions sponsored by the MLA Center for Editions of American Authors): Associate Textual Editor, 1965-1970; Center for Editions of American Authors panel of textual experts, 1968-1970

Victorian Studies: Editorial Assistant and Managing Editor, 1962-1964

Wartburg College: member, National Advisory Board for the Vogel Library, 2004-

Some other activities: Member of the **Illinois State Library** Statewide Library and Archival Preservation Advisory Panel; member of the **Illinois State Archives** Advisory Board; member of a committee advising the **Illinois Board of Higher Education** on the cooperative management of research collections; chair of a major collaborative research project conducted by the **Research Libraries Group** with support from Conoco, Inc.; active advisor on behalf of the **Illinois Conference AAUP** to faculty and administrators on academic freedom and tenure matters in northern Illinois.

Delegate to **Maryland Governor's Conference on Libraries and Information Service**; principal in initiating state-wide preservation planning in Maryland; principal in an effort to widen the use of mass deacidification for the preservation of library materials through cooperative action by the **Association of Research Libraries** and the **Committee on Institutional Cooperation**; co-instigator of a campus-wide information service for **Johns Hopkins University**; initiated efforts with the **Enoch Pratt Free Library** to provide information services to Baltimore's Empowerment Zones; speaker or panelist on academic publishing, copyright, scholarly communication, national and regional preservation planning, mass deacidification.

Consultant for the **University of British Columbia** (1995), **Princeton University** (1996), **Modern Language Association**, (1995, 1996), **Library of Congress** (1997), **Center for Jewish History** (1998, 2000-), **National Research Council** (1998); Board of Directors for the **Digital Library Federation**, 1996-2001; accreditation visiting team at **Brandeis University** (1997); mentor for **Northern Exposure to Leadership** (1997); instructor and mentor for ARL's **Leadership and Career Development Program** (1999-2000)

At the **Northwestern University Library**, led in the creation of a preservation department and in the renovation of the renovation, for preservation purposes, of the Deering Library book stacks.

At the **Milton S. Eisenhower Library**, led the refocusing and vitalization of client-centered services; strategic planning and organizational restructuring for the library; building renovation planning. Successfully completed a $5 million endowment campaign for the humanities collections and launched a $27 million capital campaign for the library.

At the **Yale University Library**, participated widely in campus-space planning, university budget planning, information technology development, and the promotion of effective teaching and learning; for the library has exercised leadership in space planning and renovation, retrospective conversion of the card catalog, preservation, organizational development, recruitment of minority librarians, intellectual property and copyright issues, scholarly communication, document delivery services among libraries, and instruction in the use of information resources. Oversaw approximately $70 million of library space renovation and construction. Was co-principal investigator for a grant to plan a digital archive for Elsevier Science.

Numerous to invitations speak at regional, national, and other professional meetings and at alumni meetings. Lectured and presented a series of seminars on library management at the **Yunnan University Library**, 2002. Participated in the 2005 International Roundtable for Library and Information Science sponsored by the **Kanazawa Institute of Technology** Library Center and the Council on Library and Information Resources.

PUBLICATIONS

"Putting Learning into Library Planning," *portal: Libraries and the Academy*, 15, 2 (April 2015), 215-231.

"How librarians (and others!) love silos: Three stories from the field " available at the Learning Spaces Collaborary Web site, http://www.pkallsc.org/

"Learning Behaviors and Learning Spaces," *portal: Libraries and the Academy,* 11, 3 (July 2011), 765-789.

"Libraries and Learning: A History of Paradigm Change," *portal: Libraries and the Academy,* 9, 2 (April 2009), 181-197. Judged as the best article published in the 2009 volume of *portal*.

"The Information or the Learning Commons: Which Will We Have?" *Journal of Academic Librarianship*, 34 (May 2008), 183-185. One of the ten most-cited articles published in JAL, 2007-2011.

"Designing for Uncertainty: Three Approaches," *Journal of Academic Librarianship*, 33 (2007), 165–179.

"Campus Cultures Fostering Information Literacy," *portal: Libraries and the Academy*, 7 (2007), 147-167. Included in Library Instruction Round Table Top Twenty library instruction articles published in 2007

"Designing for Uncertainty: Three Approaches," *Journal of Academic Librarianship*, 33 (2007), 165–179.

"First Questions for Designing Higher Education Learning Spaces," *Journal of Academic Librarianship*, 33 (2007), 14-26.

"The Choice for Learning," *Journal of Academic Librarianship*, 32 (2006), 3-13.

With Richard A. O'Connor, "The Power of Place in Learning," *Planning for Higher Education*, 33 (June-August 2005), 28-30

"Righting the Balance," in *Library as Place: Rethinking Roles, Rethinking Space* (Washington, DC: Council on Library and Information Resources, 2005), pp. 10-24

Libraries Designed for Learning (Washington, DC: Council on Library and Information Resources, 2003)

"The Golden Age of Libraries," in *Proceedings of the International Conference on Academic Librarianship in the New Millennium: Roles, Trends, and Global Collaboration*, ed. Haipeng Li (Kunming: Yunnan University Press, 2002), pp. 13-21. This is a slightly different version of the following item.

"The Golden Age of Libraries," *Journal of Academic Librarianship*, 24 (2001), 256-258

"Second Chances. An address . . . at the annual dinner of the Friends of the Oberlin College Library November 13 1999," Friends of the Oberlin College Library, February 2000

"Authors' Rights," *The Journal of Electronic Publishing* (December 1999), http://www.press.umich.edu/jep/05-02/bennett.html

"Information-Based Productivity," in *Technology and Scholarly Communication*, ed. Richard Ekman and Richard E. Quandt (Berkeley, 1999), pp. 73-94

"Just-In-Time Scholarly Monographs: or, Is There a Cavalry Bugle Call for Beleaguered Authors and Publishers?" *The Journal of Electronic Publishing* (September 1998), http://www.press.umich.edu/jep/04-01/bennett.html

"Re-engineering Scholarly Communication: Thoughts Addressed to Authors," *Scholarly Publishing*, 27 (1996), 185-196

"The Copyright Challenge: Strengthening the Public Interest in the Digital Age," *Library Journal*, 15 November 1994, pp. 34-37

"The Management of Intellectual Property," *Computers in Libraries*, 14 (May 1994), 18-20

"Repositioning University Presses in Scholarly Communication," *Journal of Scholarly Publishing*, 25 (1994), 243-248. Reprinted in *The Essential JSP. Critical Insights into the World of Scholarly Publishing. Volume 1: University Presses* (Toronto: University of Toronto Press, 2011), pp. 147-153

"Preservation and the Economic Investment Model," in *Preservation Research and Development. Round Table Proceedings, September 28-29, 1992*, ed. Carrie Beyer (Washington, D.C.: Library of Congress, 1993), pp. 17-18

"Copyright and Innovation in Electronic Publishing: A Commentary," *Journal of Academic Librarianship*, 19 (1993), 87-91; reprinted in condensed form in *Library Issues: Briefings for Faculty and Administrators*, 14 (September 1993)

with Nina Matheson, "Scholarly Articles: Valuable Commodities for Universities," *Chronicle of Higher Education*, 27 May 1992, pp. B1-B3

"Strategies for Increasing [Preservation] Productivity*," Minutes of the [119th] Meeting [of the Association of Research Libraries]* (Washington, D.C., 1992), pp. 39-40

"Management Issues: The Director's Perspective," and "Cooperative Approaches to Mass Deacidification: Mid-Atlantic Region," in *A Roundtable on Mass Deacidification*, ed. Peter G. Sparks (Washington, D.C.: Association of Research Libraries, 1992), pp. 15-18, 54-55

"The Boat that Must Stay Afloat: Academic Libraries in Hard Times," *Scholarly Publishing*, 23 (1992), 131-137

"Buying Time: An Alternative for the Preservation of Library Material," ACLS *Newsletter*, Second Series 3 (Summer, 1991), 10-11

"The Golden Stain of Time: Preserving Victorian Periodicals" in *Investigating Victorian Journalism*, ed. Laurel Brake, Alex Jones, and Lionel Madden (London: Macmillan, 1990), pp. 166-183

"Commentary on the Stephens and Haley Papers" in *Coordinating Cooperative Collection Development: A National Perspective*, an issue of *Resource Sharing and Information Networks*, 2 (1985), 199-201

"The Editorial Character and Readership of *The Penny Magazine*: An Analysis," *Victorian Periodicals Review*, 17 (1984), 127-141

"Current Initiatives and Issues in Collection Management*," Journal of Academic Librarianship*, 10 (1984), 257-261; reprinted in *Library Lit: The Best of 85*

"Revolutions in Thought: Serial Publication and the Mass Market for Reading" in *The Victorian Periodical Press: Samplings and Soundings*, ed. Joanne Shattock and Michael Wolff (Leicester: Leicester University Press, 1982), pp. 225-257

"Victorian Newspaper Advertising: Counting What Counts," *Publishing History*, 8 (1980), 5-18

"Library Friends: A Theoretical History" in *Organizing the Library's Support: Donors, Volunteers, Friends*, ed. D.W. Krummel, Allerton Park Institute Number 25 (Urbana: University of Illinois Graduate School of Library Science, 1980), pp. 23-32

"The Learned Professor: being a brief account of a scholar [Harris Francis Fletcher] who asked for the Moon, and got it," *Non Solus*, 7 (1980), 5-12

"Prolegomenon to Serials Bibliography: A Report to the [Research] Society [for Victorian Periodicals]," *Victorian Periodicals Review*, 12 (1979), 3-15

"The Bibliographic Control of Victorian Periodicals" in *Victorian Periodicals: A Guide to Research*, ed. J. Don Vann and Rosemary T. VanArsdel (New York: Modern Language Association, 1978), pp. 21-51

"John Murray's Family Library and the Cheapening of Books in Early Nineteenth Century Britain," *Studies in Bibliography*, 29 (1976), 139-166. Reprinted in Stephen Colclough and Alexis Weedon, eds., *The History of the Book in the West: 1800-1914*, Vol. 4 (Farnham, Surrey: Ashgate, 2010), pp. 307-334.

with Robert Carringer, "Dreiser to Sandburg: Three Unpublished Letters," *Library Chronicle*, 40 (1976), 252-256

"David Douglas and the British Publication of W. D. Howells' Works," *Studies in Bibliography*, 25 (1972), 107-124

as primary editor, W. D. Howells, *Indian Summer* (Bloomington: Indiana University Press, 1971)

"The Profession of Authorship: Some Problems for Descriptive Bibliography" in *Research Methods in Librarianship: Historical and Bibliographic Methods in Library Research*, ed. Rolland E. Stevens (Urbana: University of Illinois Graduate School of Library Science, 1971), pp. 74-85 edited with Ronald Gottesman, *Art and Error: Modern Textual Editing* (Bloomington: Indiana University Press, 1970)--also published in London by Methuen, 1970

"Catholic Emancipation, the *Quarterly Review*, and Britain's Constitutional Revolution," *Victorian Studies*, 12 (1969), 283-304

as textual editor, W. D. Howells, *The Altrurian Romances* (Bloomington: Indiana University Press, 1968); introduction and annotation by Clara and Rudolf Kirk

as associate textual editor, W. D. Howells, *Their Wedding Journey* (Bloomington: Indiana University Press, 1968); introduction by John Reeves

"A Concealed Printing in W. D. Howells," *Papers of the Bibliographic Society of America*, 61 (1967), 56-60

editor, *Non Solus*, A Publication of the University of Illinois Library Friends, 1974-1981

editor, Robert B. Downs Publication Fund, University of Illinois Library, 1975-1981

reviews, short articles, etc. in *Victorian Studies*, *Journal of English and German Philology*, *Victorian Periodicals Newsletter*, *Collection Management*, *Nineteenth-Century Literature*, *College & Research Libraries*, *Scholarly Publishing Today*, *ARL Newsletter*, *Serials Review*, *Library Issues*, *S[ociety for] S[cholarly] P[ublishing] Newsletter*, and *Victorian Britain: An Encyclopedia*

Attachment 1a: Statewide Illinois Library Catalog record for Incropera

WorldCat Detailed Record

- Click on a checkbox to mark a record to be e-mailed or printed in Marked Records.

WorldCat results for: (ti: fundamentals and ti: heat) and (ti: mass and ti: transfer) and dt= "bks" and yr: 1990. Record 1 of 18.

Prev 1 Next **Mark:**

Detailed Record | Add/View Comments

Fundamentals of heat and mass transfer /

Frank P **Incropera**; David P **DeWitt**

1990 **3rd ed.**
English Book Internet Resource xvi, 919, [53] pages : illustrations ; 24 cm
New York : Wiley, ; ISBN: 0471612464 9780471612469 9780471517290 0471517291

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Find Items About: Fundamentals of heat and mass transfer (1)

Title: **Fundamentals of heat and mass transfer /**

Author(s): Incropera, Frank P.
DeWitt, David P., 1934-2005.

Publication: New York : Wiley,
Edition: 3rd ed.

Year: 1990

Description: xvi, 919, [53] pages : illustrations ; 24 cm

Language: English

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Fundamentals of heat and mass transfer /

Frank P. Incropera, David P. DeWitt.

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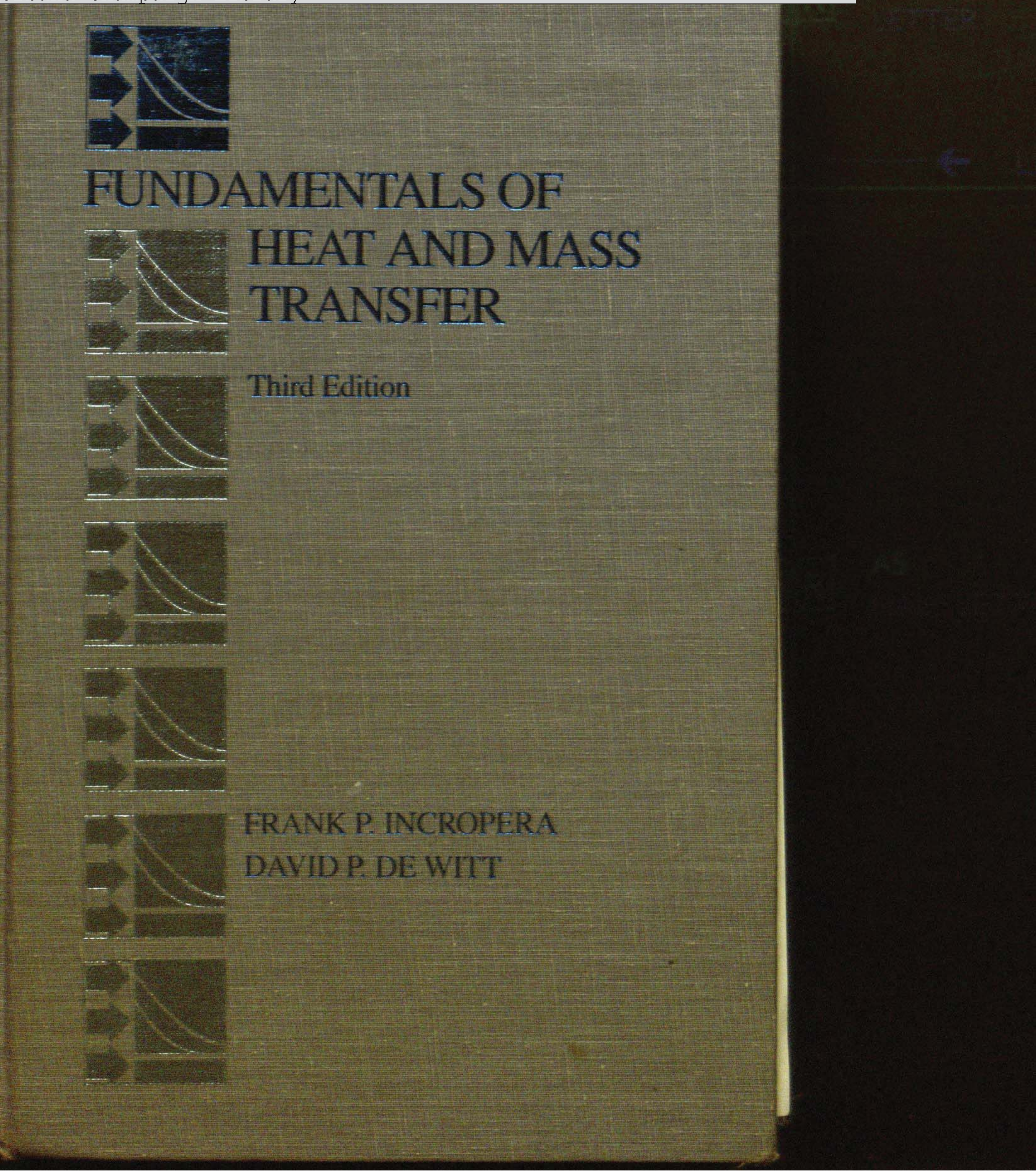

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THIRD EDITION

FUNDAMENTALS OF HEAT AND MASS TRANSFER

FRANK P. INCROPERA
DAVID P. DEWITT
School of Mechanical Engineering
Purdue University

WILEY
JOHN WILEY & SONS
New York • Chichester • Brisbane • Toronto • Singapore

Dedicated to those wonderful women in our lives,

Amy, Andrea, Debbie, Donna, Jody, Karen, Shaunna, and Terri

who, through the years, have blessed us with their love, patience, and understanding.

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PREFACE

With the passage of approximately nine years since publication of the first edition, this text has been transformed from the status of a newcomer to a mature representative of heat transfer pedagogy. Despite this maturation, however, we like to think that, while remaining true to certain basic tenets, our treatment of the subject is constantly evolving.

Preparation of the first edition was strongly motivated by the belief that, above all, a first course in heat transfer should do two things. First, it should instill within the student a genuine appreciation for the physical origins of the subject. It should then establish the relationship of these origins to the behavior of thermal systems. In so doing, it should develop methodologies which facilitate application of the subject to a broad range of practical problems, and it should cultivate the facility to perform the kind of engineering analysis which, if not exact, still provides useful information concerning the design and/or performance of a particular system or process. Requirements of such an analysis include the ability to discern relevant transport processes and simplifying assumptions, identify important dependent and independent variables, develop appropriate expressions from first principles, and introduce requisite material from the heat transfer knowledge base. In the first edition, achievement of this objective was fostered by couching many of the examples and end-of-chapter problems in terms of actual engineering systems.

The second edition was also driven by the foregoing objectives, as well as by input derived from a questionnaire sent to over 100 colleagues who used, or were otherwise familiar with, the first edition. A major consequence of this input was publication of two versions of the book, *Fundamentals of Heat and Mass Transfer* and *Introduction to Heat Transfer*. As in the first edition, the *Fundamentals* version included mass transfer, providing an integrated treatment of heat, mass and momentum transfer by convection and separate treatments of heat and mass transfer by diffusion. The *Introduction* version of the book was intended for users who embraced the treatment of heat transfer but did not wish to cover mass transfer effects. In both versions, significant improvements were made in the treatments of numerical methods and heat transfer with phase change.

In this latest edition, changes have been motivated by the desire to expand the scope of applications and to enhance the exposition of physical principles. Consideration of a broader range of technically important problems is facilitated by increased coverage of existing material on thermal contact resistance, fin performance, convective heat transfer enhancement, and compact heat exchangers, as well as by the addition of new material on submerged jets (Chapter 7) and free convection in open, parallel plate channels (Chapter 9). Submerged jets are widely used for industrial cooling and drying operations, while free convection in parallel plate channels is pertinent to passive cooling and heating systems. Expanded discussions of physical principles are concentrated in the chapters on single-phase convection (Chapters 7 to 9) and relate, for example, to forced convection in tube banks and to free convection on plates and in cavities. Other improvements relate to the methodology of performing a first law analysis, a more generalized lumped capacitance analysis, transient conduction in semi-infinite media, and finite-difference solutions.

In this edition, the old Chapter 14, which dealt with multimode heat transfer problems, has been deleted and many of the problems have been transferred to earlier chapters. This change was motivated by recognition of the importance of multimode effects and the desirability of impacting student consciousness with this importance at the earliest possible time. Hence, problems involving more than just a superficial consideration of multimode effects begin in Chapter 7 and increase in number through Chapter 13.

The last, but certainly not the least important, improvement in this edition is the inclusion of nearly 300 new problems. In the spirit of our past efforts, we have attempted to address contemporary issues in many of the problems. Hence, as well as relating to engineering applications such as energy conversion and conservation, space heating and cooling, and thermal protection, the problems deal with recent interests in electronic cooling, manufacturing, and material processing. Many of the problems are drawn from our accumulated research and consulting experiences; the solutions, which frequently are not obvious, require thoughtful implementation of the *tools* of heat transfer. It is our hope that in addition to reinforcing the student's understanding of principles and applications, the problems serve a motivational role by relating the subject to real engineering needs.

Over the past nine years, we have been fortunate to have received constructive suggestions from many colleagues throughout the United States and Canada. It is with pleasure that we express our gratitude for this input.

West Lafayette, Indiana

FRANK P. INCROPERA
DAVID P. DEWITT

CONTENTS

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CHAPTER 5

TRANSIENT CONDUCTION

In our treatment of conduction we have gradually considered more complicated conditions. We began with the simple case of one-dimensional, steady-state conduction with no internal generation, and we subsequently considered complications due to multidimensional and generation effects. However, we have not yet considered situations for which conditions change with time.

We now recognize that many heat transfer problems are time dependent. Such *unsteady*, or *transient*, problems typically arise when the boundary conditions of a system are changed. For example, if the surface temperature of a system is altered, the temperature at each point in the system will also begin to change. The changes will continue to occur until a *steady-state* temperature distribution is reached. Consider a hot metal billet that is removed from a furnace and exposed to a cool airstream. Energy is transferred by convection and radiation from its surface to the surroundings. Energy transfer by conduction also occurs from the interior of the metal to the surface, and the temperature at each point in the billet decreases until a steady-state condition is reached. Such time-dependent effects occur in many industrial heating and cooling processes.

To determine the time dependence of the temperature distribution within a solid during a transient process, we could begin by solving the appropriate form of the heat equation, for example, Equation 2.13. Some cases for which solutions have been obtained are discussed in Sections 5.4 to 5.8. However, such solutions are often difficult to obtain, and where possible a simpler approach is preferred. One such approach may be used under conditions for which temperature gradients within the solid are small. It is termed the *lumped capacitance method*.

5.1 THE LUMPED CAPACITANCE METHOD

A simple, yet common, transient conduction problem is one in which a solid experiences a sudden change in its thermal environment. Consider a hot metal forging that is initially at a uniform temperature T_i and is quenched by immersing it in a liquid of lower temperature $T_\infty < T_i$ (Figure 5.1). If the quenching is said to begin at time $t = 0$, the temperature of the solid will

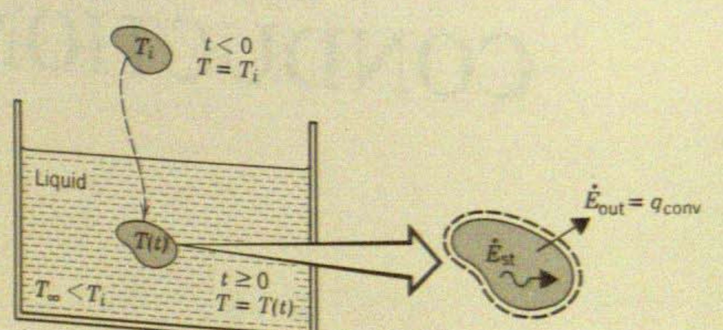


Figure 5.1 Cooling of a hot metal forging.

decrease for time $t > 0$, until it eventually reaches T_∞. This reduction is due to convection heat transfer at the solid–liquid interface. The essence of the lumped capacitance method is the assumption that the temperature of the solid is *spatially uniform* at any instant during the transient process. This assumption implies that temperature gradients within the solid are negligible.

From Fourier's law, heat conduction in the absence of a temperature gradient implies the existence of infinite thermal conductivity. Such a condition is clearly impossible. However, although the condition is never satisfied exactly, it is closely approximated if the resistance to conduction within the solid is small compared with the resistance to heat transfer between the solid and its surroundings. For now we assume that this is, in fact, the case.

In neglecting temperature gradients within the solid, we can no longer consider the problem from within the framework of the heat equation. Instead, the transient temperature response is determined by formulating an overall energy balance on the solid. This balance must relate the rate of heat loss at the surface to the rate of change of the internal energy. Applying Equation 1.11a to the control volume of Figure 5.1, this requirement takes the form

$$-\dot{E}_{\text{out}} = \dot{E}_{\text{st}} \tag{5.1}$$

or

$$-hA_s(T - T_\infty) = \rho V c \frac{dT}{dt} \tag{5.2}$$

Introducing the temperature difference

$$\theta \equiv T - T_\infty \tag{5.3}$$

and recognizing that $(d\theta/dt) = (dT/dt)$, it follows that

$$\frac{\rho V c}{hA_s} \frac{d\theta}{dt} = -\theta$$

Separating variables and integrating from the initial condition, for which $t = 0$ and $T(0) = T_i$, we then obtain

$$\frac{\rho V c}{hA_s} \int_{\theta_i}^{\theta} \frac{d\theta}{\theta} = -\int_0^t dt$$

where

$$\theta_i \equiv T_i - T_\infty \tag{5.4}$$

Evaluating the integrals it follows that

$$\frac{\rho V c}{hA_s} \ln \frac{\theta_i}{\theta} = t \tag{5.5}$$

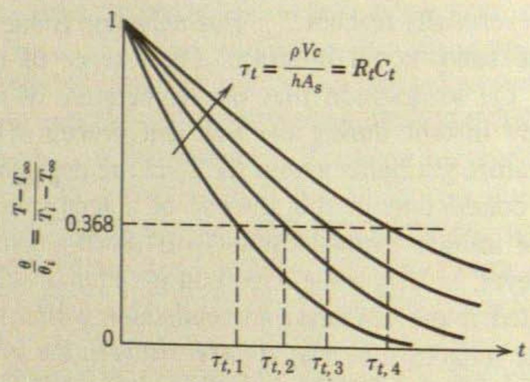


Figure 5.2 Transient temperature response of lumped capacitance solids corresponding to different thermal time constants τ_t.

or

$$\frac{\theta}{\theta_i} = \frac{T - T_\infty}{T_i - T_\infty} = \exp\left[-\left(\frac{hA_s}{\rho V c}\right)t\right] \tag{5.6}$$

Equation 5.5 may be used to determine the time required for the solid to reach some temperature T, or, conversely, Equation 5.6 may be used to compute the temperature reached by the solid at some time t.

The foregoing results indicate that the difference between the solid and fluid temperatures must decay exponentially to zero as t approaches infinity. This behavior is shown in Figure 5.2. From Equation 5.6 it is also evident that the quantity $(\rho V c/hA_s)$ may be interpreted as a *thermal time constant*. This time constant may be expressed as

$$\tau_t = \left(\frac{1}{hA_s}\right)(\rho V c) = R_t C_t \tag{5.7}$$

where R_t is the resistance to convection heat transfer and C_t is the *lumped thermal capacitance* of the solid. Any increase in R_t or C_t will cause a solid to respond more slowly to changes in its thermal environment and will increase the time required to reach thermal equilibrium ($\theta = 0$).

It is useful to note that the foregoing behavior is analogous to the voltage decay that occurs when a capacitor is discharged through a resistor in an electrical RC circuit. Accordingly, the process may be represented by an *equivalent thermal circuit*, which is shown in Figure 5.3. With the switch closed the solid is charged to the temperature θ_i. When the switch is opened, the energy that is stored in the solid is discharged through the thermal resistance and the temperature of the solid decays with time. This analogy suggests that RC electrical circuits may be used to determine the transient behavior of thermal systems. In fact, before the advent of digital computers, RC circuits were widely used to simulate transient thermal behavior.

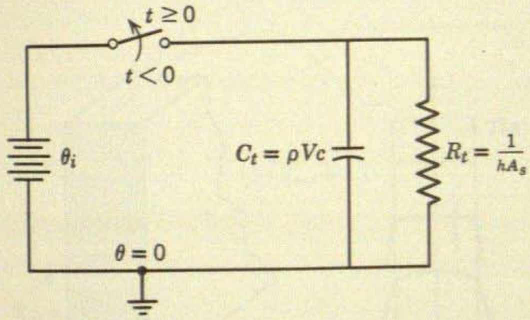


Figure 5.3 Equivalent thermal circuit for a lumped capacitance solid.

To determine the total energy transfer Q occurring up to some time t, we simply write

$$Q = \int_0^t q\,dt = hA_s \int_0^t \theta\,dt$$

Substituting for θ from Equation 5.6 and integrating, we obtain

$$Q = (\rho V c)\theta_i \left[1 - \exp\left(-\frac{t}{\tau_t}\right)\right] \tag{5.8a}$$

The quantity Q is, of course, related to the change in the internal energy of the solid, and from Equation 1.11b

$$-Q = \Delta E_{st} \tag{5.8b}$$

For quenching Q is positive and the solid experiences a decrease in energy. Equations 5.5, 5.6, and 5.8a also apply to situations where the solid is heated ($\theta < 0$), in which case Q is negative and the internal energy of the solid increases.

5.2 VALIDITY OF THE LUMPED CAPACITANCE METHOD

From the foregoing results it is easy to see why there is a strong preference for using the lumped capacitance method. It is certainly the simplest and most convenient method that can be used to solve transient conduction problems. Hence it is important to determine under what conditions it may be used with reasonable accuracy.

To develop a suitable criterion consider steady-state conduction through the plane wall of area A (Figure 5.4). Although we are assuming steady-state conditions, this criterion is readily extended to transient processes. One surface is maintained at a temperature $T_{s,1}$ and the other surface is exposed to a fluid of temperature $T_\infty < T_{s,1}$. The temperature of this surface will be some

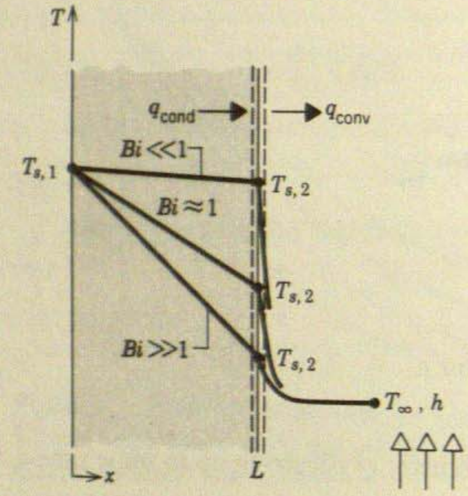


Figure 5.4 Effect of Biot number on steady-state temperature distribution in a plane wall with surface convection.

intermediate value, $T_{s,2}$, for which $T_\infty < T_{s,2} < T_{s,1}$. Hence under steady-state conditions the surface energy balance, Equation 1.12, reduces to

$$\frac{kA}{L}(T_{s,1} - T_{s,2}) = hA(T_{s,2} - T_\infty)$$

where k is the thermal conductivity of the solid. Rearranging, we then obtain

$$\frac{T_{s,1} - T_{s,2}}{T_{s,2} - T_\infty} = \frac{(L/kA)}{(1/hA)} = \frac{R_{cond}}{R_{conv}} = \frac{hL}{k} \equiv Bi \tag{5.9}$$

The quantity (hL/k) appearing in Equation 5.9 is a *dimensionless parameter*. It is termed the *Biot number*, and it plays a fundamental role in conduction problems that involve surface convection effects. According to Equation 5.9 and as illustrated in Figure 5.4, the Biot number provides a measure of the temperature drop in the solid relative to the temperature difference between the surface and the fluid. Note especially the conditions corresponding to $Bi \ll 1$. The results suggest that, for these conditions, it is reasonable to *assume* a uniform temperature distribution across a solid at any time during a transient process. This result may also be associated with interpretation of the Biot number as a ratio of thermal resistances, Equation 5.9. *If $Bi \ll 1$, the resistance to conduction within the solid is much less than the resistance to convection across the fluid boundary layer*. Hence the assumption of a uniform temperature distribution is reasonable.

We have introduced the Biot number because of its significance to transient conduction problems. Consider the plane wall of Figure 5.5, which is initially at a uniform temperature T_i and experiences convection cooling when it is immersed in a fluid of $T_\infty < T_i$. The problem may be treated as one dimensional in x, and we are interested in the temperature variation with position and time, $T(x, t)$. This variation is a strong function of the Biot

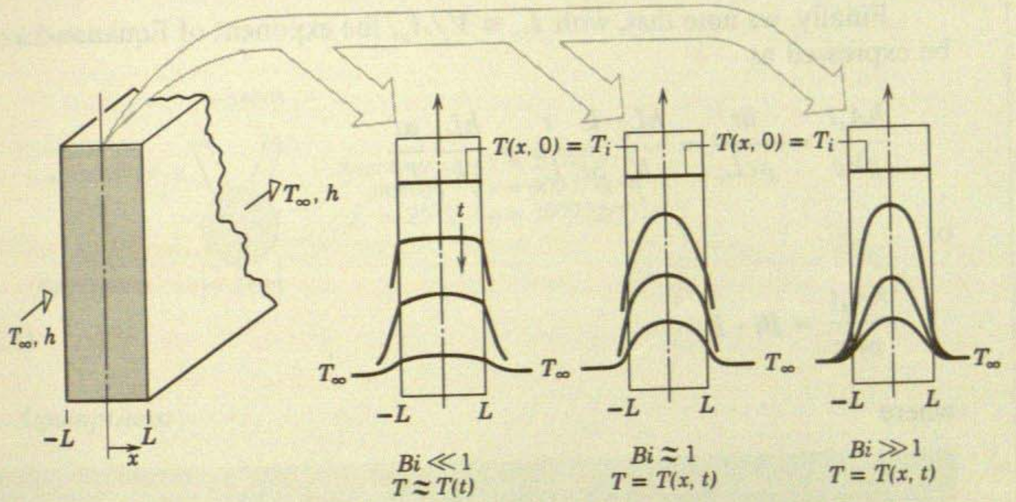


Figure 5.5 Transient temperature distribution for different Biot numbers in a plane wall symmetrically cooled by convection.

number, and three conditions are shown in Figure 5.5. For $Bi \ll 1$ the temperature gradient in the solid is small and $T(x, t) \approx T(t)$. Virtually all the temperature difference is between the solid and the fluid, and the solid temperature remains nearly uniform as it decreases to T_∞. For moderate to large values of the Biot number, however, the temperature gradients within the solid are significant. Hence $T = T(x, t)$. Note that for $Bi \gg 1$, the temperature difference across the solid is now much larger than that between the surface and the fluid.

We conclude this section by emphasizing the importance of the lumped capacitance method. Its inherent simplicity renders it the preferred method for solving transient conduction problems. Hence, when confronted with such a problem, *the very first thing that one should do is calculate the Biot number*. If the following condition is satisfied

$$Bi = \frac{hL_c}{k} < 0.1 \qquad (5.10)$$

the error associated with using the lumped capacitance method is small. For convenience, it is customary to define the *characteristic length* of Equation 5.10 as the ratio of the solid's volume to surface area, $L_c \equiv V/A_s$. Such a definition facilitates calculation of L_c for solids of complicated shape and reduces to the half-thickness L for a plane wall of thickness $2L$ (Figure 5.5), to $r_o/2$ for a long cylinder, and to $r_o/3$ for a sphere. However, if one wishes to implement the criterion in a conservative fashion, L_c should be associated with the length scale corresponding to the maximum spatial temperature difference. Accordingly, for a symmetrically heated (or cooled) plane wall of thickness $2L$, L_c would remain equal to the half-thickness L. However, for a long cylinder or sphere, L_c would equal the actual radius r_o, rather than $r_o/2$ or $r_o/3$.

Finally, we note that, with $L_c \equiv V/A_s$, the exponent of Equation 5.6 may be expressed as

$$\frac{hA_s t}{\rho V c} = \frac{ht}{\rho c L_c} = \frac{hL_c}{k}\frac{k}{\rho c}\frac{t}{L_c^2} = \frac{hL_c}{k}\frac{\alpha t}{L_c^2}$$

or

$$\frac{hA_s t}{\rho V c} = Bi \cdot Fo \qquad (5.11)$$

where

$$Fo \equiv \frac{\alpha t}{L_c^2} \qquad (5.12)$$

is termed the Fourier number. It is a *dimensionless time*, which, with the Biot number, characterizes transient conduction problems. Substituting Equation 5.11 into 5.6, we obtain

$$\frac{\theta}{\theta_i} = \frac{T - T_\infty}{T_i - T_\infty} = \exp(-Bi \cdot Fo) \qquad (5.13)$$

EXAMPLE 5.1

A thermocouple junction, which may be approximated as a sphere, is to be used for temperature measurement in a gas stream. The convection coefficient between the junction surface and the gas is known to be $h = 400\ \text{W/m}^2 \cdot \text{K}$, and the junction thermophysical properties are $k = 20\ \text{W/m} \cdot \text{K}$, $c = 400\ \text{J/kg} \cdot \text{K}$, and $\rho = 8500\ \text{kg/m}^3$. Determine the junction diameter needed for the thermocouple to have a time constant of 1 s. If the junction is at 25°C and is placed in a gas stream that is at 200°C, how long will it take for the junction to reach 199°C?

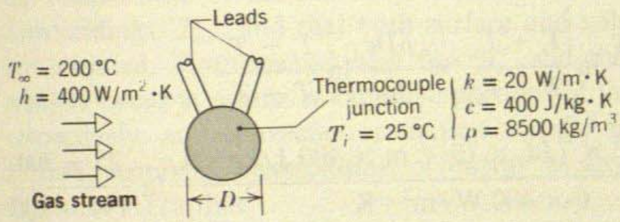
SOLUTION

Known: Thermophysical properties of thermocouple junction used to measure temperature of a gas stream.

Find:

1. Junction diameter needed for a time constant of 1 s.
2. Time required to reach 199°C in gas stream at 200°C.

Schematic:



Assumptions:

1. Temperature of junction is uniform at any instant.
2. Radiation exchange with the surroundings is negligible.
3. Losses by conduction through the leads are negligible.
4. Constant properties.

Analysis:

1. Because the junction diameter is unknown, it is not possible to begin the solution by determining whether the criterion for using the lumped capacitance method, Equation 5.10, is satisfied. However, a reasonable approach is to use the method to find the diameter and to then determine whether the criterion is satisfied. From Equation 5.7 and the fact that $A_s = \pi D^2$ and $V = \pi D^3/6$ for a sphere, it follows that

$$\tau_t = \frac{1}{h\pi D^2} \times \frac{\rho \pi D^3}{6} c$$

Rearranging and substituting numerical values,

$$D = \frac{6h\tau_t}{\rho c} = \frac{6 \times 400 \text{ W/m}^2 \cdot \text{K} \times 1 \text{ s}}{8500 \text{ kg/m}^3 \times 400 \text{ J/kg} \cdot \text{K}} = 7.06 \times 10^{-4} \text{ m} \quad \triangleleft$$

With $L_c = r_o/3$ it then follows from Equation 5.10 that

$$Bi = \frac{h(r_o/3)}{k} = \frac{400 \text{ W/m}^2 \cdot \text{K} \times 3.53 \times 10^{-4} \text{ m}}{3 \times 20 \text{ W/m} \cdot \text{K}} = 2.35 \times 10^{-4}$$

Accordingly, Equation 5.10 is satisfied (for $L_c = r_o$, as well as for $L_c = r_o/3$) and the lumped capacitance method may be used to an excellent approximation.

2. From Equation 5.5 the time required for the junction to reach $T = 199°C$ is

$$t = \frac{\rho(\pi D^3/6)c}{h(\pi D^2)} \ln \frac{T_i - T_\infty}{T - T_\infty} = \frac{\rho D c}{6h} \ln \frac{T_i - T_\infty}{T - T_\infty}$$

$$t = \frac{8500\ \text{kg/m}^3 \times 7.06 \times 10^{-4}\ \text{m} \times 400\ \text{J/kg} \cdot \text{K}}{6 \times 400\ \text{W/m}^2 \cdot \text{K}} \ln \frac{25 - 200}{199 - 200}$$

$$t = 5.2\ \text{s} \approx 5\tau_t$$ ◁

Comments: Heat losses due to radiation exchange between the junction and the surroundings and conduction through the leads would necessitate using a smaller junction diameter to achieve the desired time response.

5.3 GENERAL LUMPED CAPACITANCE ANALYSIS

Although transient conduction in a solid is commonly initiated by convection heat transfer to or from an adjoining fluid, other processes may induce transient thermal conditions within the solid. For example, a solid may be separated from large surroundings by a gas or vacuum. If the temperatures of the solid and surroundings differ, radiation exchange could cause the internal thermal energy, and hence the temperature, of the solid to change. Temperature changes could also be induced by applying a heat flux at a portion, or all, of the surface and/or by initiating thermal energy generation within the solid. Surface heating could, for example, be applied by attaching a film or sheet electrical heater to the surface, while thermal energy could be generated by passing an electrical current through the solid.

Figure 5.6 depicts a situation for which thermal conditions within a solid may be simultaneously influenced by convection, radiation, an applied surface

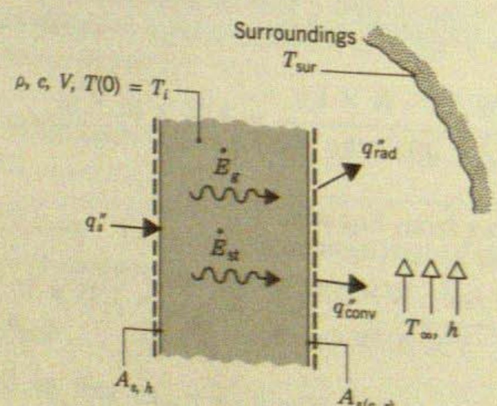


Figure 5.6 Contral surface for general lumped capacitance analysis.

heat flux, and internal energy generation. It is presumed that, initially ($t = 0$), the temperature of the solid (T_i) differs from that of the fluid, T_∞, and the surroundings, T_{sur}, and that both surface and volumetric heating (q_s'' and $\dot{q}$) are initiated. The imposed heat flux q_s'' and the convection–radiation heat transfer occur at mutually exclusive portions of the surface, $A_{s(h)}$ and $A_{s(c,r)}$, respectively, and convection–radiation transfer is presumed to be *from* the surface. Applying conservation of energy at any instant t, it follows from Equation 1.11a that

$$q_s'' A_{s,h} + \dot{E}_g - (q''_{conv} + q''_{rad}) A_{s(c,r)} = \rho V c \frac{dT}{dt} \tag{5.14}$$

or, from Equations 1.3a and 1.7,

$$q_s'' A_{s,h} + \dot{E}_g - \left[h(T - T_\infty) + \varepsilon\sigma\left(T^4 - T_{sur}^4\right)\right] A_{s(c,r)} = \rho V c \frac{dT}{dt} \tag{5.15}$$

Unfortunately, Equation 5.15 is a nonlinear, first-order, nonhomogeneous, ordinary differential equation which cannot be integrated to obtain an exact solution.[1] However, exact solutions may be obtained for simplified versions of the equation. For example, if there is no imposed heat flux or generation and convection is either nonexistent (a vacuum) or negligible relative to radiation, Equation 5.15 reduces to

$$\rho V c \frac{dT}{dt} = -\varepsilon A_{s,r}\sigma\left(T^4 - T_{sur}^4\right) \tag{5.16}$$

Separating variables and integrating from the initial condition to any time t, it follows that

$$\frac{\varepsilon A_{s,r}\sigma}{\rho V c}\int_0^t dt = \int_{T_i}^{T} \frac{dT}{T_{sur}^4 - T^4} \tag{5.17}$$

Evaluating both integrals and rearranging, the time required to reach the temperature T becomes

$$t = \frac{\rho V c}{4\varepsilon A_{s,r}\sigma T_{sur}^3}\left\{\ln\left|\frac{T_{sur} + T}{T_{sur} - T}\right| - \ln\left|\frac{T_{sur} + T_i}{T_{sur} - T_i}\right| + 2\left[\tan^{-1}\left(\frac{T}{T_{sur}}\right) - \tan^{-1}\left(\frac{T_i}{T_{sur}}\right)\right]\right\} \tag{5.18}$$

This expression cannot be used to evaluate T explicitly in terms of t, T_i, and T_{sur}, nor does it readily reduce to the limiting result for $T_{sur} = 0$ (radiation to

[1] An approximate, finite-difference solution may be obtained by *discretizing* the time derivative (Section 5.9) and *marching* the solution out in time.

deep space). Returning to Equation 5.17, it is readily shown that, for $T_{sur} = 0$,

$$t = \frac{\rho V c}{3\varepsilon A_{s,r}\sigma}\left(\frac{1}{T^3} - \frac{1}{T_i^3}\right) \tag{5.19}$$

An exact solution to Equation 5.15 may also be obtained if radiation may be neglected and h is independent of time. Introducing a reduced temperature, $\theta \equiv T - T_\infty$, where $d\theta/dt = dT/dt$, Equation 5.15 reduces to a linear, first-order, nonhomogeneous differential equation of the form

$$\frac{d\theta}{dt} + a\theta - b = 0 \tag{5.20}$$

where $a \equiv (hA_{s,c}/\rho Vc)$ and $b \equiv [(q_s'' A_{s,h} + \dot{E}_g)/\rho Vc]$. Although Equation 5.20 may be solved by summing its homogeneous and particular solutions, an alternative approach is to eliminate the nonhomogeneity by introducing the transformation

$$\theta' \equiv \theta - \frac{b}{a} \tag{5.21}$$

Recognizing that $d\theta'/dt = d\theta/dt$, Equation 5.21 may be substituted into (5.20) to yield

$$\frac{d\theta'}{dt} + a\theta' = 0 \tag{5.22}$$

Separating variables and integrating from 0 to t (θ_i' to θ'), it follows that

$$\frac{\theta'}{\theta_i'} = \exp(-at) \tag{5.23}$$

or substituting for θ' and θ,

$$\frac{T - T_\infty - (b/a)}{T_i - T_\infty - (b/a)} = \exp(-at) \tag{5.24}$$

Hence,

$$\frac{T - T_\infty}{T_i - T_\infty} = \exp(-at) + \frac{b/a}{T_i - T_\infty}[1 - \exp(-at)] \tag{5.25}$$

As it must, Equation 5.25 reduces to (5.6) when $b = 0$ and yields $T = T_i$ at $t = 0$. As $t \to \infty$, Equation 5.25 reduces to $(T - T_\infty) = (b/a)$, which could also be obtained by performing an energy balance on the control surface of Figure 5.6 for steady-state conditions.

5.4 SPATIAL EFFECTS

Situations frequently arise for which the lumped capacitance method is inappropriate, and alternative methods must be used. Regardless of the particular form of the method, we must now cope with the fact that gradients within the medium are no longer negligible.

In their most general form, transient conduction problems are described by the heat equation, Equation 2.13 for rectangular coordinates or Equations 2.20 and 2.23, respectively, for cylindrical and spherical coordinates. The solution to these partial differential equations provides the variation of temperature with both time and the spatial coordinates. However, in many problems, such as the plane wall of Figure 5.5, only one spatial coordinate is needed to describe the internal temperature distribution. With no internal generation and the assumption of constant thermal conductivity, Equation 2.13 then reduces to

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{5.26}$$

To solve Equation 5.26 for the temperature distribution $T(x, t)$, it is necessary to specify an *initial* condition and two *boundary conditions*. For the typical transient conduction problem of Figure 5.5, the initial condition is

$$T(x,0) = T_i \tag{5.27}$$

and the boundary conditions are

$$\left.\frac{\partial T}{\partial x}\right|_{x=0} = 0 \tag{5.28}$$

and

$$-k\left.\frac{\partial T}{\partial x}\right|_{x=L} = h\left[T(L,t) - T_\infty\right] \tag{5.29}$$

Equation 5.27 presumes a uniform temperature distribution at time $t = 0$; Equation 5.28 reflects the *symmetry requirement* for the midplane of the wall; and Equation 5.29 describes the surface condition experienced for time $t > 0$. From Equations 5.26 to 5.29, it is evident that, in addition to depending on x and t, temperatures in the wall also depend on a number of physical parameters. In particular

$$T = T(x, t, T_i, T_\infty, L, k, \alpha, h) \tag{5.30}$$

The foregoing problem may be solved analytically or numerically. These methods will be considered in subsequent sections, but first it is important to note the advantages that may be obtained by *nondimensionalizing* the governing equations. This may be done by arranging the relevant variables into suitable *groups*. Consider the dependent variable T. If the temperature difference $\theta \equiv T - T_\infty$ is divided by the *maximum possible temperature difference* $\theta_i \equiv T_i - T_\infty$, a dimensionless form of the dependent variable may be defined as

$$\theta^* \equiv \frac{\theta}{\theta_i} = \frac{T - T_\infty}{T_i - T_\infty} \tag{5.31}$$

Accordingly, θ^* must lie in the range $0 \leq \theta^* \leq 1$. A dimensionless spatial coordinate may be defined as

$$x^* \equiv \frac{x}{L} \tag{5.32}$$

where L is the half-thickness of the plane wall, and a dimensionless time may be defined as

$$t^* \equiv \frac{\alpha t}{L^2} \equiv Fo \tag{5.33}$$

where t^* is equivalent to the dimensionless *Fourier number*, Equation 5.12.

Substituting the definitions of Equations 5.31 to 5.33 into Equations 5.26 to 5.29, the heat equation becomes

$$\frac{\partial^2 \theta^*}{\partial x^{*2}} = \frac{\partial \theta^*}{\partial Fo} \tag{5.34}$$

and the initial and boundary conditions become

$$\theta^*(x^*, 0) = 1 \tag{5.35}$$

$$\left.\frac{\partial \theta^*}{\partial x^*}\right|_{x^*=0} = 0 \tag{5.36}$$

and

$$\left.\frac{\partial \theta^*}{\partial x^*}\right|_{x^*=1} = -Bi\,\theta^*(1, t^*) \tag{5.37}$$

where the Biot number is $Bi \equiv hL/k$. In dimensionless form the functional dependence may now be expressed as

$$\theta^* = f(x^*, Fo, Bi) \tag{5.38}$$

Recall that this functional dependence, without the x^* variation, was obtained for the lumped capacitance method, as shown in Equation 5.13.

Comparing Equations 5.30 and 5.38, the considerable advantage associated with casting the problem in dimensionless form becomes apparent.

Equation 5.38 implies that *for a prescribed geometry, the transient temperature distribution is a universal function of x^*, Fo, and Bi*. That is, the *dimensionless solution* assumes a prescribed form that does not depend on the particular value of T_i, T_∞, L, k, α, or h. Since this generalization greatly simplifies the presentation and utilization of transient solutions, the dimensionless variables are used extensively in subsequent sections.

5.5 THE PLANE WALL WITH CONVECTION

Exact, analytical solutions to transient conduction problems have been obtained for many simplified geometries and boundary conditions and are well documented in the literature [1–4]. Several mathematical techniques, including the method of separation of variables (Section 4.2), may be used for this purpose, and typically the solution for the dimensionless temperature distribution, Equation 5.38, is in the form of an infinite series. However, except for very small values of the Fourier number, this series may be approximated by a single term and the results may be represented in a convenient graphical form.

5.5.1 Exact Solution

Consider the *plane wall* of thickness $2L$ (Figure 5.7*a*). If the thickness is small relative to the width and height of the wall, it is reasonable to assume that conduction occurs exclusively in the x direction. If the wall is initially at a uniform temperature, $T(x, 0) = T_i$, and is suddenly immersed in a fluid of $T_\infty \neq T_i$, the resulting temperatures may be obtained by solving Equation 5.34 subject to the conditions of Equations 5.35 to 5.37. Since the convection conditions for the surfaces at $x^* = \pm 1$ are the same, the temperature distribution at any instant must be symmetrical about the midplane ($x^* = 0$). An

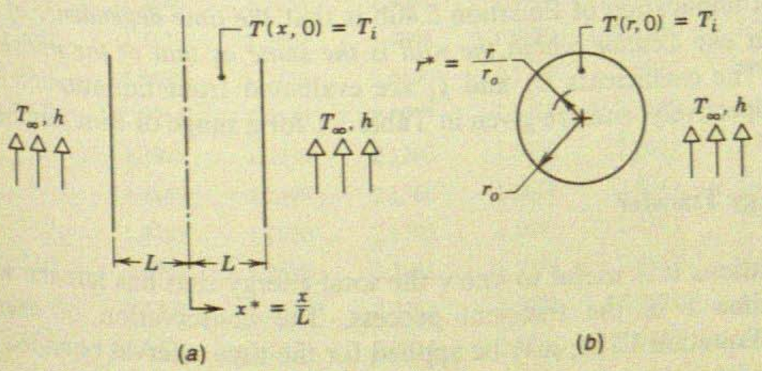


Figure 5.7 One-dimensional systems with an initial uniform temperature subjected to sudden convection conditions. (*a*) Plane wall. (*b*) Infinite cylinder or sphere.

exact solution to this problem has been obtained and is of the form [2]

$$\theta^* = \sum_{n=1}^{\infty} C_n \exp\left(-\zeta_n^2 Fo\right) \cos\left(\zeta_n x^*\right) \tag{5.39a}$$

where the coefficient C_n is

$$C_n = \frac{4 \sin \zeta_n}{2\zeta_n + \sin(2\zeta_n)} \tag{5.39b}$$

and the discrete values (*eigenvalues*) of ζ_n are positive roots of the transcendental equation

$$\zeta_n \tan \zeta_n = Bi \tag{5.39c}$$

The first four roots of this equation are given in Appendix B.3.

5.5.2 Approximate Solution

It can be shown (Problem 5.24) that for values of $Fo \geq 0.2$, the infinite series solution, Equation 5.39a, can be approximated by the first term of the series. Invoking this approximation, the dimensionless form of the temperature distribution becomes

$$\theta^* = C_1 \exp\left(-\zeta_1^2 Fo\right) \cos\left(\zeta_1 x^*\right) \tag{5.40a}$$

or

$$\theta^* = \theta_o^* \cos\left(\zeta_1 x^*\right) \tag{5.40b}$$

where θ_o^* represents the midplane $(x^* = 0)$ temperature

$$\theta_o^* = C_1 \exp\left(-\zeta_1^2 Fo\right) \tag{5.41}$$

An important implication of Equation 5.40b is that *the time dependence of the temperature at any location within the wall is the same as that of the midplane temperature*. The coefficients C_1 and ζ_1 are evaluated from Equations 5.39b and 5.39c, respectively, and are given in Table 5.1 for a range of Biot numbers.

5.5.3 Total Energy Transfer

In many situations it is useful to know the total energy that has left the wall up to any time t in the transient process. The conservation of energy requirement, Equation 1.11b, may be applied for the time interval bounded by the initial condition $(t = 0)$ and time $t > 0$

$$E_{in} - E_{out} = \Delta E_{st} \tag{5.42}$$

Table 5.1 Coefficients us[...]
to the series so[...]

	PLANE WALL	
Bi[a]	ζ_1 (rad)	C_1
0.01	0.0998	1.0017
0.02	0.1410	1.0033
0.03	0.1732	1.0049
0.04	0.1987	1.0066
0.05	0.2217	1.0082
0.06	0.2425	1.0098
0.07	0.2615	1.0114
0.08	0.2791	1.0130
0.09	0.2956	1.0145
0.10	0.3111	1.0160
0.15	0.3779	1.0237
0.20	0.4328	1.0311
0.25	0.4801	1.0382
0.30	0.5218	1.0450
0.4	0.5932	1.0580
0.5	0.6533	1.0701
0.6	0.7051	1.0814
0.7	0.7506	1.0919
0.8	0.7910	1.1016
0.9	0.8274	1.1107
1.0	0.8603	1.1191
2.0	1.0769	1.1795
3.0	1.1925	1.2102
4.0	1.2646	1.2287
5.0	1.3138	1.2402
6.0	1.3496	1.2479
7.0	1.3766	1.2532
8.0	1.3978	1.2570
9.0	1.4149	1.2598
10.0	1.4289	1.2620
20.0	1.4961	1.2699
30.0	1.5202	1.2717
40.0	1.5325	1.2723
50.0	1.5400	1.2727
100.0	1.5552	1.2731

[a] $Bi = hL/k$ for the plane wall a[...]

Table 5.1 Coefficients used in the one-term approximation to the series solutions for transient one-dimensional conduction

	PLANE WALL		INFINITE CYLINDER		SPHERE	
Bi^{a}	ζ_1 (rad)	C_1	ζ_1 (rad)	C_1	ζ_1 (rad)	C_1
0.01	0.0998	1.0017	0.1412	1.0025	0.1730	1.0030
0.02	0.1410	1.0033	0.1995	1.0050	0.2445	1.0060
0.03	0.1732	1.0049	0.2439	1.0075	0.2989	1.0090
0.04	0.1987	1.0066	0.2814	1.0099	0.3450	1.0120
0.05	0.2217	1.0082	0.3142	1.0124	0.3852	1.0149
0.06	0.2425	1.0098	0.3438	1.0148	0.4217	1.0179
0.07	0.2615	1.0114	0.3708	1.0173	0.4550	1.0209
0.08	0.2791	1.0130	0.3960	1.0197	0.4860	1.0239
0.09	0.2956	1.0145	0.4195	1.0222	0.5150	1.0268
0.10	0.3111	1.0160	0.4417	1.0246	0.5423	1.0298
0.15	0.3779	1.0237	0.5376	1.0365	0.6608	1.0445
0.20	0.4328	1.0311	0.6170	1.0483	0.7593	1.0592
0.25	0.4801	1.0382	0.6856	1.0598	0.8448	1.0737
0.30	0.5218	1.0450	0.7465	1.0712	0.9208	1.0880
0.4	0.5932	1.0580	0.8516	1.0932	1.0528	1.1164
0.5	0.6533	1.0701	0.9408	1.1143	1.1656	1.1441
0.6	0.7051	1.0814	1.0185	1.1346	1.2644	1.1713
0.7	0.7506	1.0919	1.0873	1.1539	1.3525	1.1978
0.8	0.7910	1.1016	1.1490	1.1725	1.4320	1.2236
0.9	0.8274	1.1107	1.2048	1.1902	1.5044	1.2488
1.0	0.8603	1.1191	1.2558	1.2071	1.5708	1.2732
2.0	1.0769	1.1795	1.5995	1.3384	2.0288	1.4793
3.0	1.1925	1.2102	1.7887	1.4191	2.2889	1.6227
4.0	1.2646	1.2287	1.9081	1.4698	2.4556	1.7201
5.0	1.3138	1.2402	1.9898	1.5029	2.5704	1.7870
6.0	1.3496	1.2479	2.0490	1.5253	2.6537	1.8338
7.0	1.3766	1.2532	2.0937	1.5411	2.7165	1.8674
8.0	1.3978	1.2570	2.1286	1.5526	2.7654	1.8921
9.0	1.4149	1.2598	2.1566	1.5611	2.8044	1.9106
10.0	1.4289	1.2620	2.1795	1.5677	2.8363	1.9249
20.0	1.4961	1.2699	2.2881	1.5919	2.9857	1.9781
30.0	1.5202	1.2717	2.3261	1.5973	3.0372	1.9898
40.0	1.5325	1.2723	2.3455	1.5993	3.0632	1.9942
50.0	1.5400	1.2727	2.3572	1.6002	3.0788	1.9962
100.0	1.5552	1.2731	2.3809	1.6015	3.1102	1.9990

[a] $Bi = hL/k$ for the plane wall and hr_o/k for the infinite cylinder and sphere. See Figure 5.7.

Equating the energy transferred from the wall Q to E_{out} and setting $E_{\text{in}} = 0$ and $\Delta E_{\text{st}} = E(t) - E(0)$, it follows that

$$Q = -[E(t) - E(0)] \tag{5.43a}$$

or

$$Q = -\int \rho c[T(r,t) - T_i]\, dV \tag{5.43b}$$

where the integration is performed over the volume of the wall. It is convenient to nondimensionalize this result by introducing the quantity

$$Q_o = \rho c V(T_i - T_\infty) \tag{5.44}$$

which may be interpreted as the initial internal energy of the wall relative to the fluid temperature. It is also the *maximum* amount of energy transfer which could occur if the process were continued to time $t = \infty$. Hence, assuming constant properties, the ratio of the total energy transferred from the wall over the time interval t to the maximum possible transfer is

$$\frac{Q}{Q_o} = \int \frac{-[T(r,t) - T_i]}{T_i - T_\infty} \frac{dV}{V} = \frac{1}{V} \int (1 - \theta^*)\, dV \tag{5.45}$$

Employing the approximate form of the temperature distribution for the plane wall, Equation 5.40b, the integration prescribed by Equation 5.45 can be performed to obtain

$$\frac{Q}{Q_o} = 1 - \frac{\sin \zeta_1}{\zeta_1} \theta_o^* \tag{5.46}$$

where θ_o^* can be determined from Equation 5.41, using Table 5.1 for values of the coefficients C_1 and ζ_1.

5.5.4 Graphical Representations

Graphical representations of the *approximate* relations for the transient temperature distribution and energy transfer were first presented by Heisler [5] and Gröber et al. [6]. The graphs have been widely used for nearly four decades; in addition to offering computational convenience, they illustrate the functional dependence of the transient, dimensionless temperature distribution on the Biot and Fourier numbers.

Results for the plane wall are presented in Figures 5.8 to 5.10. Figure 5.8 may be used to obtain the *midplane* temperature of the wall, $T(0, t) = T_o(t)$, at any time during the transient process. If T_o is known for particular values of Fo and Bi, Figure 5.9 may be used to determine the corresponding temperature at any location *off the midplane*. Hence, Figure 5.9 must be used tting $E_{in} = 0$

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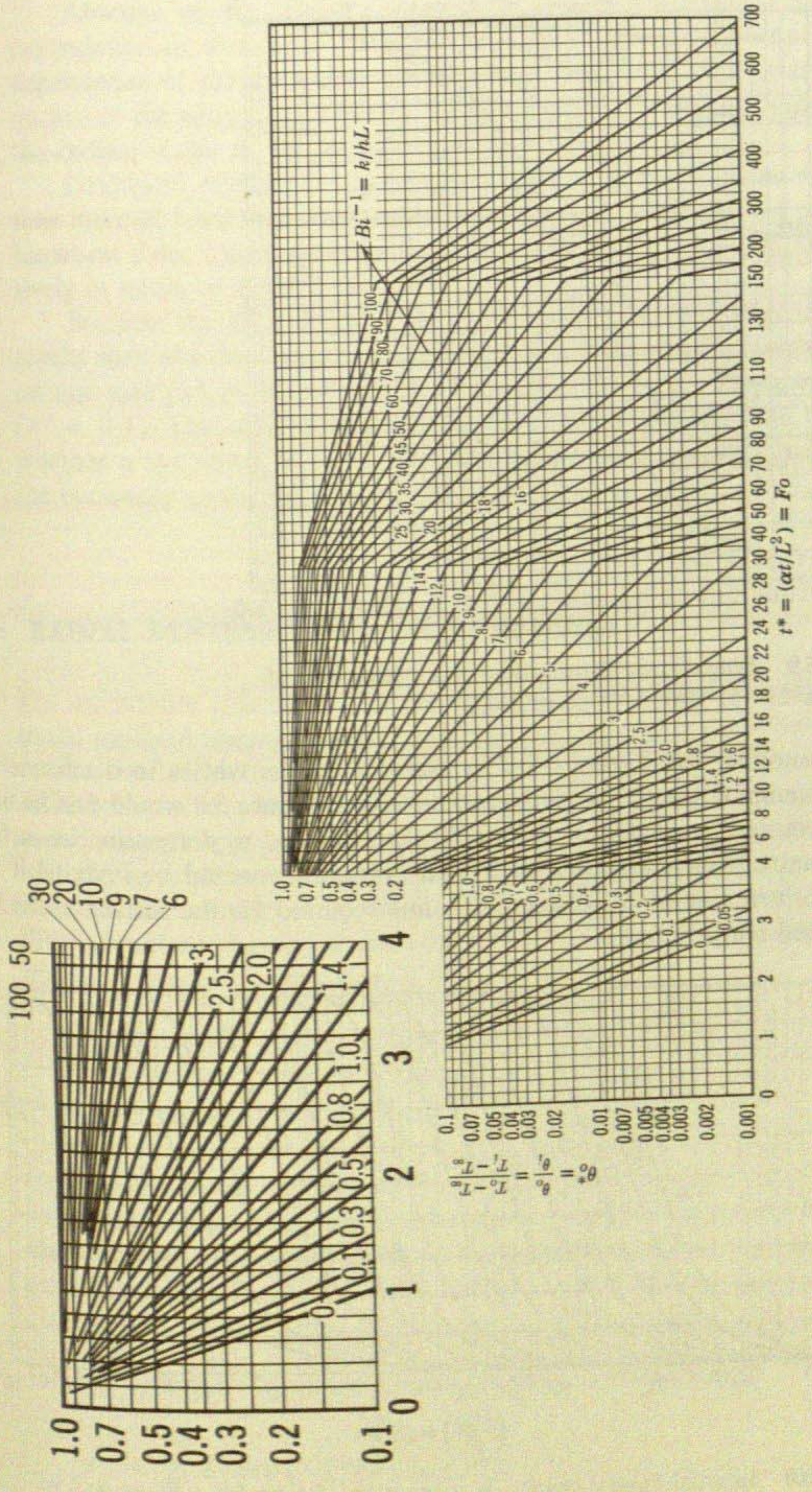


Figure 5.8 Midplane temperature as a function of time for a plane wall of thickness $2L$ [5]. Used with permission.

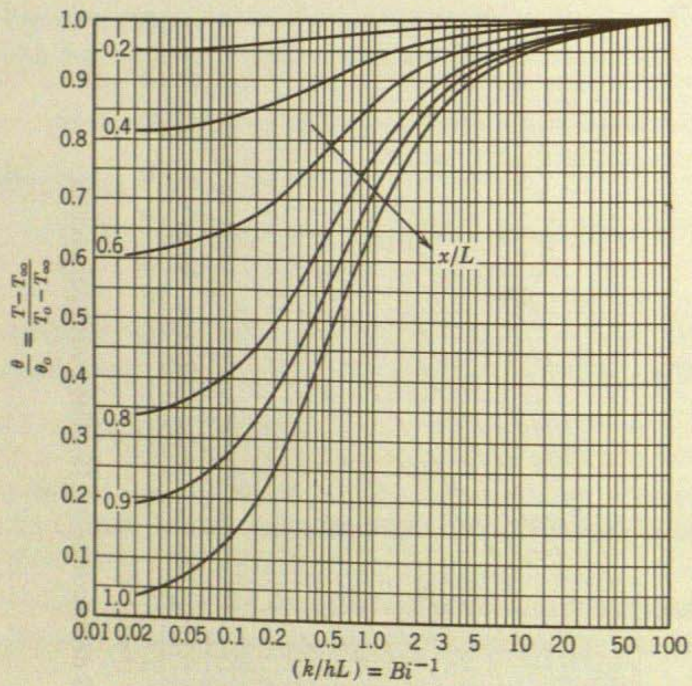


Figure 5.9 Temperature distribution in a plane wall of thickness $2L$ [5]. Used with permission.

in conjunction with Figure 5.8. For example, if one wishes to determine the surface temperature ($x^* = \pm 1$) at some time t, Figure 5.8 would first be used to determine T_o at t. Figure 5.9 would then be used to determine the surface temperature from knowledge of T_o. The procedure would be inverted if the problem were one of determining the time required for the surface to reach a prescribed temperature.

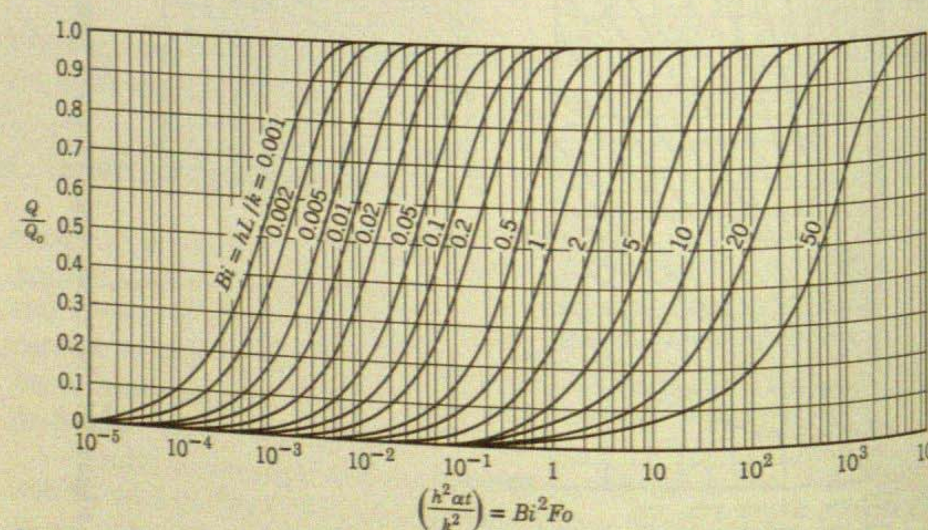


Figure 5.10 Internal energy change as a function of time for a plane wall of thickness $2L$ [6]. Adapted with permission.

Absence of the Fourier number in Figure 5.9 implies that the time dependence of any temperature off the midplane corresponds to the time dependence of the midplane temperature. This result is, of course, a consequence of the approximation that led to Equation 5.40b and is valid for all but the earliest stages of the transient process ($Fo \geq 0.2$).

Graphical results for the energy transferred from a plane wall over the time interval t are presented in Figure 5.10. These results were generated from Equation 5.46. The dimensionless energy transfer Q/Q_o is expressed exclusively in terms of Fo and Bi.

Because the mathematical problem is precisely the same, the foregoing results may also be applied to a plane wall of thickness L, which is insulated on one side ($x^* = 0$) and experiences convective transport on the other side ($x^* = +1$). This equivalence is a consequence of the fact that, regardless of whether a symmetrical or an adiabatic requirement is prescribed at $x^* = 0$, the boundary condition is of the form $\partial\theta^*/\partial x^* = 0$.

5.6 RADIAL SYSTEMS WITH CONVECTION

For an infinite cylinder or sphere of radius r_o (Figure 5.7b), which is at an initial uniform temperature and experiences a change in convective conditions, results similar to those of Section 5.5 may be developed. That is, an exact series solution may be obtained for the time dependence of the radial temperature distribution; a one-term approximation may be used for most conditions; and the approximation may be conveniently represented in graphical form. The infinite cylinder is an idealization that permits the assumption of one-dimensional conduction in the radial direction. It is a reasonable approximation for cylinders having $L/r_o \gtrsim 10$.

5.6.1 Exact Solutions

Exact solutions to the transient, one-dimensional form of the heat equation have been developed for the infinite cylinder and for the sphere. For a uniform initial temperature and convective boundary conditions, the solutions [2] are as follows.

Infinite Cylinder In dimensionless form, the temperature is

$$\theta^* = \sum_{n=1}^{\infty} C_n \exp\left(-\zeta_n^2 Fo\right) J_0(\zeta_n r^*) \tag{5.47a}$$

where

$$C_n = \frac{2}{\zeta_n} \frac{J_1(\zeta_n)}{J_0^2(\zeta_n) + J_1^2(\zeta_n)} \tag{5.47b}$$

and the discrete values of ζ_n are positive roots of the transcendental equation

$$\zeta_n \frac{J_1(\zeta_n)}{J_0(\zeta_n)} = Bi \tag{5.47c}$$

The quantities J_1 and J_0 are Bessel functions of the first kind and their values are tabulated in Appendix B.4. Roots of the transcendental equation (5.47c) are tabulated by Schneider [2].

Sphere Similarly, for the sphere

$$\theta^* = \sum_{n=1}^{\infty} C_n \exp\left(-\zeta_n^2 Fo\right) \frac{1}{\zeta_n r^*} \sin\left(\zeta_n r^*\right) \tag{5.48a}$$

where

$$C_n = \frac{4[\sin(\zeta_n) - \zeta_n \cos(\zeta_n)]}{2\zeta_n - \sin(2\zeta_n)} \tag{5.48b}$$

and the discrete values of ζ_n are positive roots of the transcendental equation

$$1 - \zeta_n \cot \zeta_n = Bi \tag{5.48c}$$

Roots of the transcendental equation are tabulated by Schneider [2].

5.6.2 Approximate Solutions

For the infinite cylinder and sphere, Heisler [5] has shown that for $Fo \geq 0.2$, the foregoing series solutions can be approximated by a single term. Hence, as for the case of the plane wall, the time dependence of the temperature at any location within the radial system is the same as that of the centerline or centerpoint.

Infinite Cylinder The one-term approximation to Equation 5.47 is

$$\theta^* = C_1 \exp\left(-\zeta_1^2 Fo\right) J_0(\zeta_1 r^*) \tag{5.49a}$$

or

$$\theta^* = \theta_o^* J_0(\zeta_1 r^*) \tag{5.49b}$$

where θ_o^* represents the centerline temperature and is of the form

$$\theta_o^* = C_1 \exp\left(-\zeta_1^2 Fo\right) \tag{5.49c}$$

Values of the coefficients C_1 and ζ_1 have been determined and are listed in Table 5.1 for a range of Biot numbers.

Sphere From Equation 5.48a, the one-term approximation is

$$\theta^* = C_1 \exp\left(-\zeta_1^2 Fo\right) \frac{1}{\zeta_1 r^*} \sin(\zeta_1 r^*) \tag{5.50a}$$

or

$$\theta^* = \theta_o^* \frac{1}{\zeta_1 r^*} \sin(\zeta_1 r^*) \tag{5.50b}$$

where θ_o^* represents the center temperature and is of the form

$$\theta_o^* = C_1 \exp\left(-\zeta_1^2 Fo\right) \tag{5.50c}$$

Values of the coefficients C_1 and ζ_1 have been determined and are listed in Table 5.1 for a range of Biot numbers.

5.6.3 Total Energy Transfer

As in Section 5.5.3, an energy balance may be performed to determine the total energy transfer from the infinite cylinder or sphere over the time interval $\Delta t = t$. Substituting from the approximate solutions, Equations 5.49b and 5.50b, and introducing Q_o from Equation 5.44, the results are as follows.

Infinite Cylinder

$$\frac{Q}{Q_o} = 1 - \frac{2\theta_o^*}{\zeta_1} J_1(\zeta_1) \tag{5.51}$$

Sphere

$$\frac{Q}{Q_o} = 1 - \frac{3\theta_o^*}{\zeta_1^3}\left[\sin(\zeta_1) - \zeta_1 \cos(\zeta_1)\right] \tag{5.52}$$

Values of the center temperature θ_o^* are determined from Equation 5.49c or 5.50c, using the coefficients of Table 5.1 for the appropriate system.

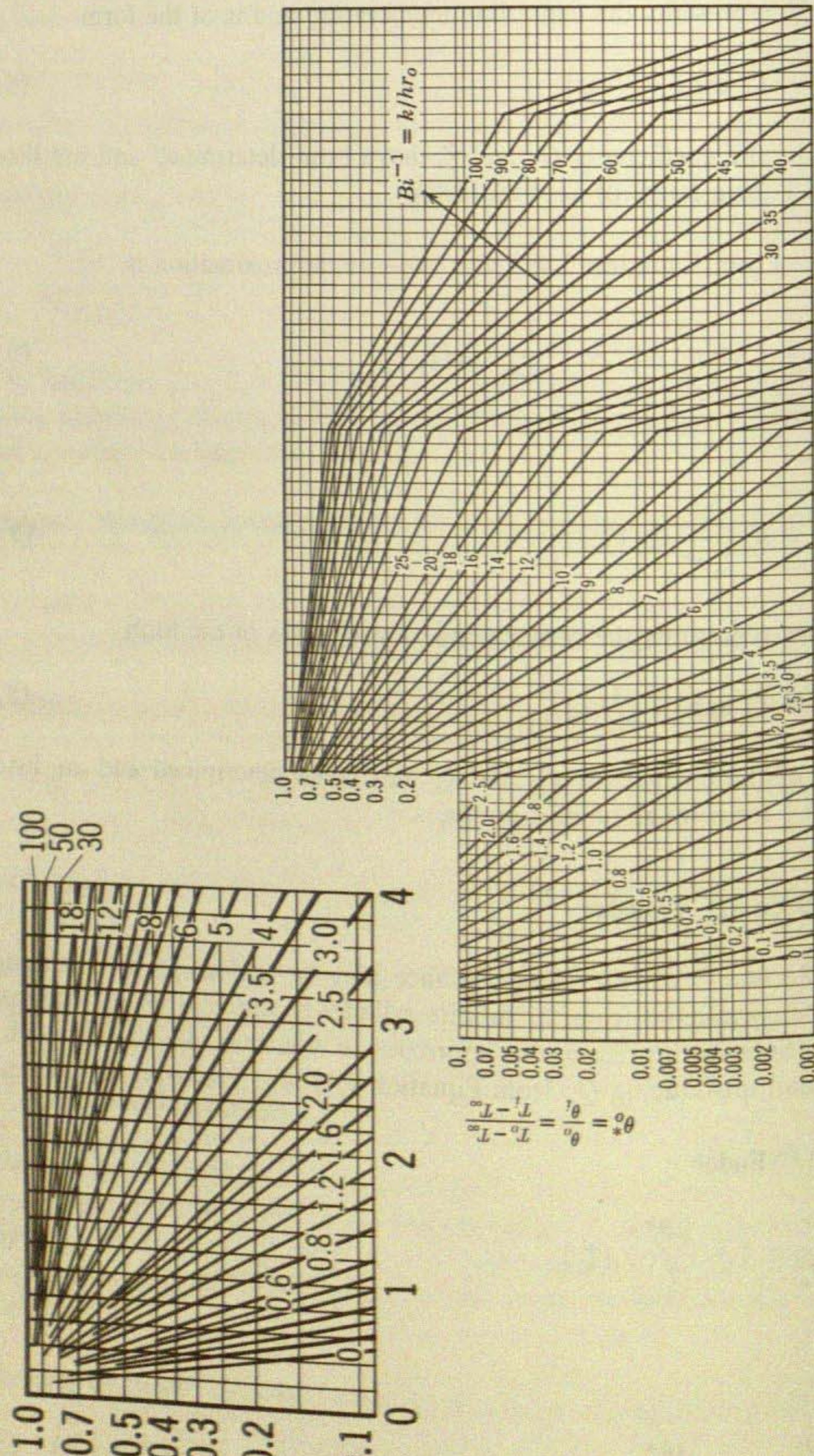


Figure 5.11 Centerline temperature as a function of time for an infinite cylinder of radius r_o [5]. Used with permission.

Figure 5.11 Centerline temperature as a function of time for an infinite cylinder of radius r_o [5]. Used with permission.

$(\alpha t/r_o^2) = Fo$

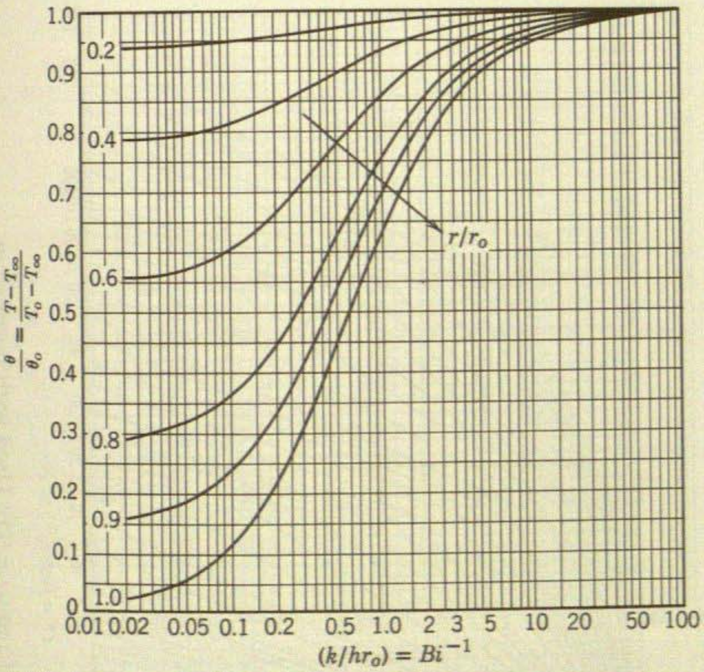


Figure 5.12 Temperature distribution in an infinite cylinder of radius r_o [5]. Used with permission.

5.6.4 Graphical Representation

Graphical representations similar to those for the plane wall (Figures 5.8 to 5.10) have also been generated by Heisler [5] and Gröber et al. [6] for an infinite cylinder and a sphere. Results for the infinite cylinder are presented in Figures 5.11 to 5.13, and those for the sphere are presented in Figures 5.14 to 5.16. *Note that, with respect to the use of these figures, the Biot number is*

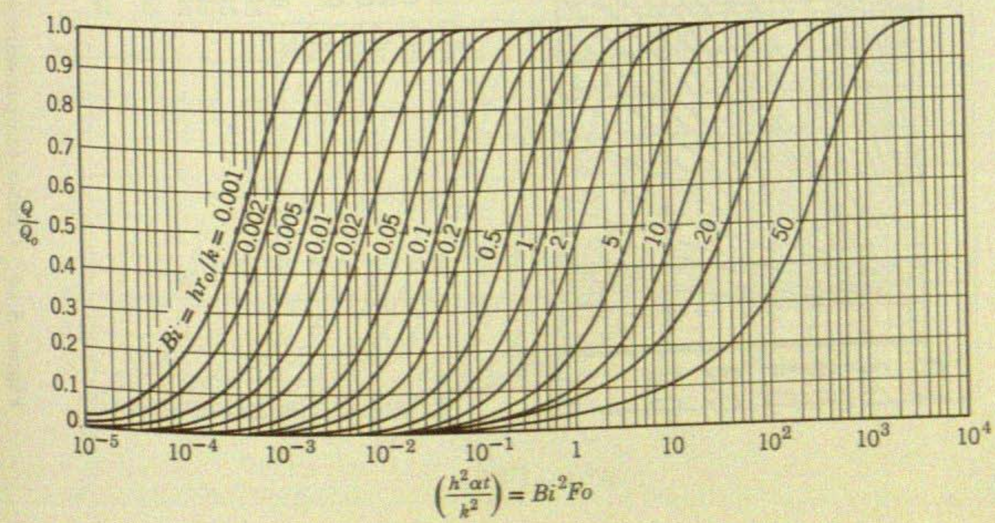


Figure 5.13 Internal energy change as a function of time for an infinite cylinder of radius r_o [6]. Adapted with permission.

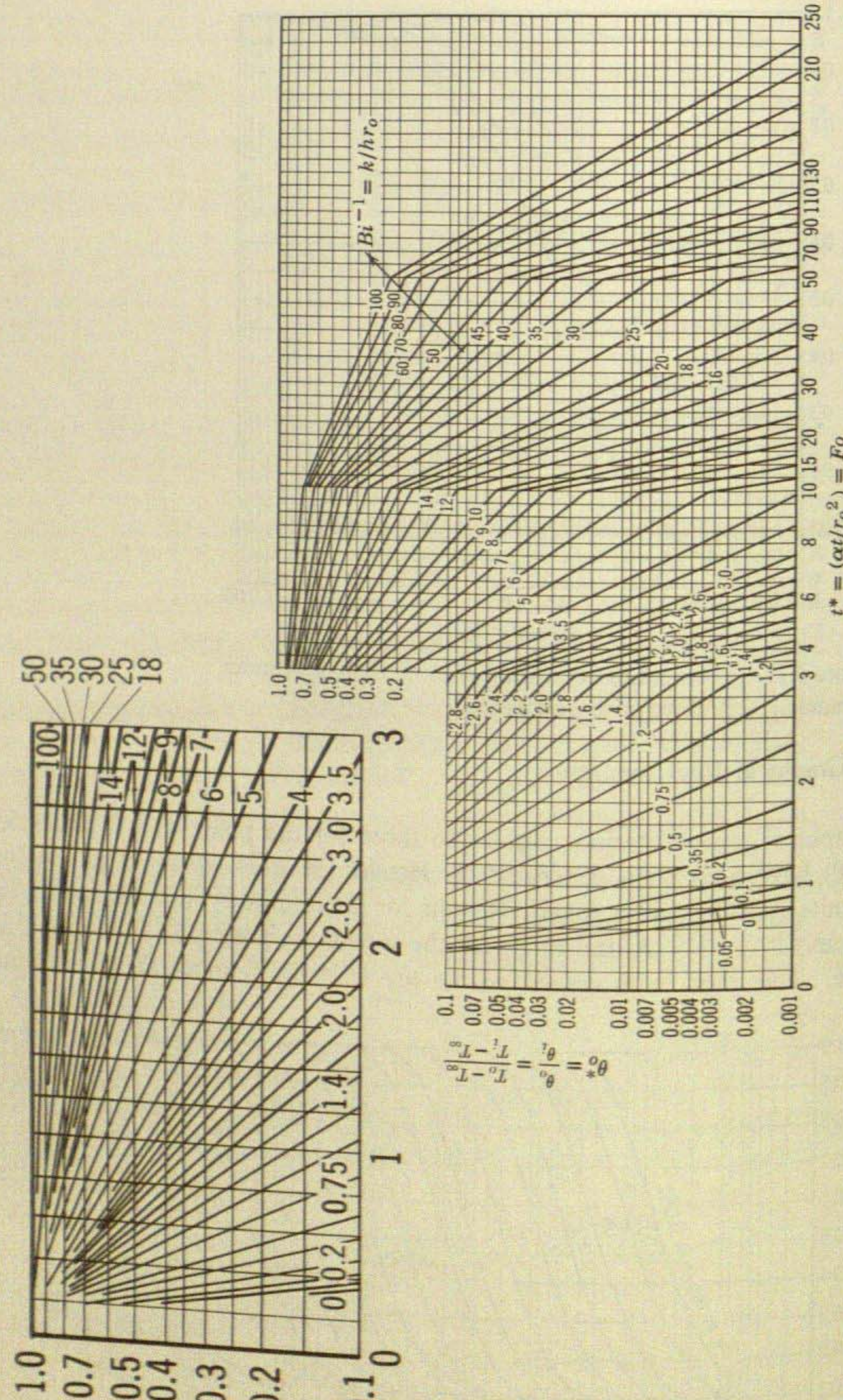


Figure 5.14 Center temperature as a function of time in a sphere of radius r_o [5]. Used with permission.

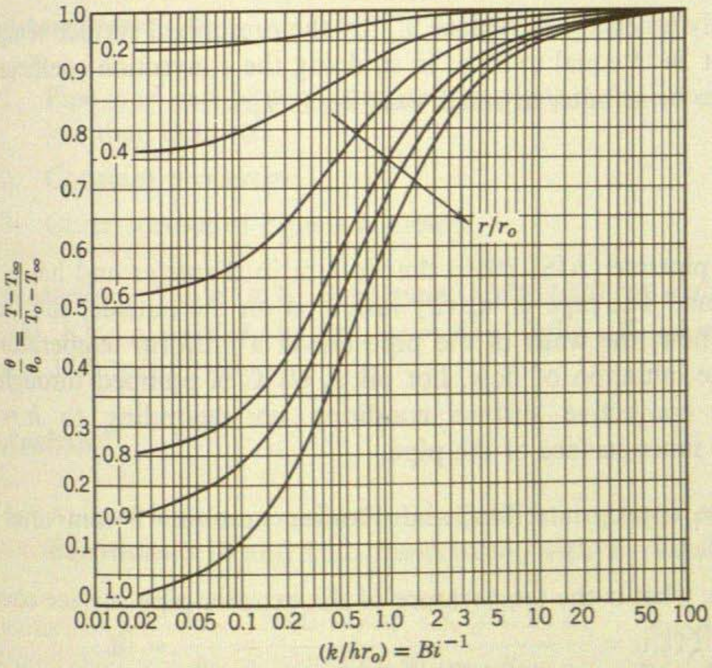


Figure 5.15 Temperature distribution in a sphere of radius r_o [5]. Used with permission.

defined in terms of r_o. In contrast recall that, for the lumped capacitance method, the characteristic length in the Biot number is customarily defined as $r_o/2$ for the cylinder and $r_o/3$ for the sphere.

In closing it should be noted that the *Heisler charts* may also be used to determine the transient response of a plane wall, an infinite cylinder, or a sphere subjected to a *sudden change in surface temperature*. For such a

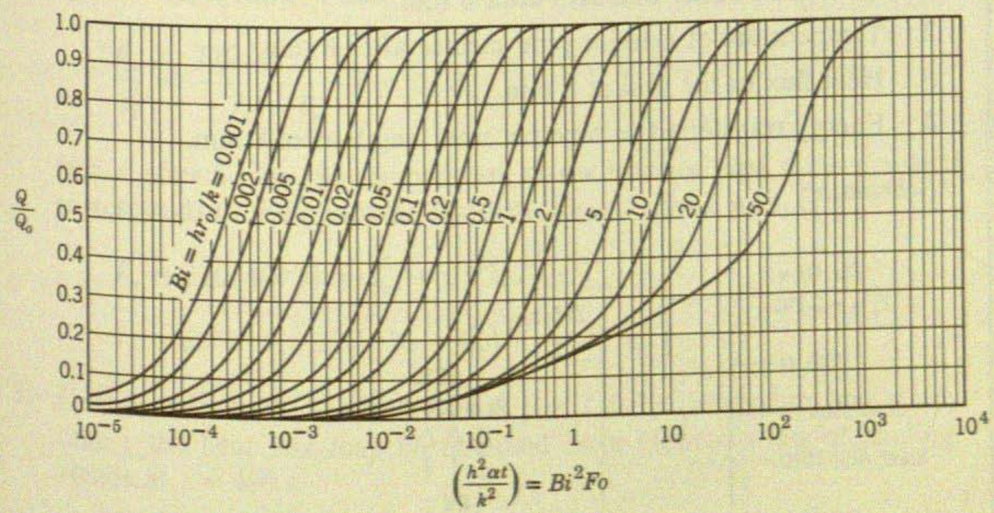


Figure 5.16 Internal energy change as a function of time for a sphere of radius r_o [6]. Adapted with permission.

Figure 5.14 Center temperature as a function of time in a sphere of radius r_o [5]. Used with permission.

$t^* = (\alpha t/r_o^2) = Fo$

condition it is only necessary to replace T_∞ by the prescribed surface temperature T_s and to set Bi^{-1} equal to zero. In so doing the convection coefficient is tacitly assumed to be infinite, in which case $T_\infty = T_s$.

EXAMPLE 5.2

Consider a steel pipeline (AISI 1010) that is 1 m in diameter and has a wall thickness of 40 mm. The pipe is heavily insulated on the outside, and before the initiation of flow, the walls of the pipe are at a uniform temperature of $-20°C$. With the initiation of flow, hot oil at 60°C is pumped through the pipe creating a convective surface condition corresponding to $h = 500$ $W/m^2 \cdot K$ at the inner surface of the pipe.

1. What are the appropriate Biot and Fourier numbers 8 min after the initiation of flow?
2. At $t = 8$ min, what is the temperature of the exterior pipe surface covered by the insulation?
3. What is the heat flux q'' (W/m^2) to the pipe from the oil at $t = 8$ min?
4. How much energy per meter of pipe length has been transferred from the oil to the pipe at $t = 8$ min?

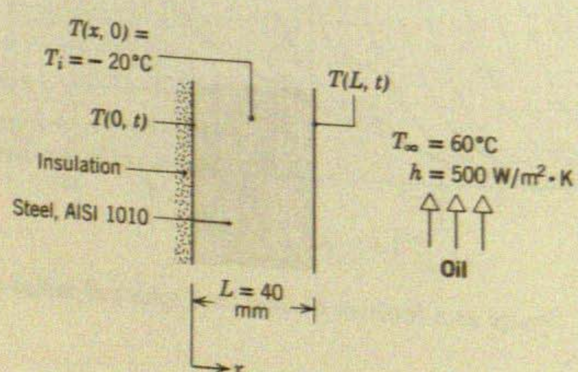
SOLUTION

Known: Wall subjected to sudden change in convective surface condition.

Find:

1. Biot and Fourier numbers after 8 min.
2. Temperature of exterior pipe surface after 8 min.
3. Heat flux to the wall at 8 min.
4. Energy transferred to pipe per unit length after 8 min.

Schematic:



Assumptions:

1. Pipe wall can be approximated as plane wall, since thickness is much less than diameter.
2. Constant properties.
3. Outer surface of pipe is adiabatic.

Properties: Table A.1, steel type AISI 1010 [$T = (-20 + 60)°C/2 \approx 300$ K]: $\rho = 7823$ kg/m³, $c = 434$ J/kg · K, $k = 63.9$ W/m · K, $\alpha = 18.8 \times 10^{-6}$ m²/s.

Analysis:

1. At $t = 8$ min, the Biot and Fourier numbers are computed from Equations 5.10 and 5.12, respectively, with $L_c = L$. Hence

$$Bi = \frac{hL}{k} = \frac{500\ \mathrm{W/m^2 \cdot K} \times 0.04\ \mathrm{m}}{63.9\ \mathrm{W/m \cdot K}} = 0.313 \qquad \triangleleft$$

$$Fo = \frac{\alpha t}{L^2} = \frac{18.8 \times 10^{-6}\ \mathrm{m^2/s} \times 8\ \mathrm{min} \times 60\ \mathrm{s/min}}{(0.04\ \mathrm{m})^2} = 5.64 \qquad \triangleleft$$

2. With $Bi = 0.313$, use of the lumped capacitance method is inappropriate. However, since transient conditions in the insulated pipe wall of thickness L correspond to those in a plane wall of thickness $2L$ experiencing the same surface condition, the desired results may be obtained from the charts for the plane wall. Using Figure 5.8, with $Bi^{-1} = 3.2$, it follows that

$$\frac{\theta_o}{\theta_i} = \frac{T(0,t) - T_\infty}{T_i - T_\infty} \approx 0.22$$

Hence after 8 min, the temperature of the exterior pipe surface, which corresponds to the midplane temperature of a plane wall, is

$$T_o = T(0, 480\ \mathrm{s}) \approx T_\infty + 0.22(T_i - T_\infty)$$

$$T_o = 60°\mathrm{C} + 0.22(-20 - 60)°\mathrm{C} \approx 42°\mathrm{C} \qquad \triangleleft$$

3. Heat transfer to the inner surface at $x = L$ is by convection, and at any time t the heat flux may be obtained from Newton's law of cooling. Hence at $t = 480$ s,

$$q''_x(L, 480\ \mathrm{s}) \equiv q''_L = h[T(L, 480\ \mathrm{s}) - T_\infty]$$

The surface temperature $T(L, 480$ s) may be obtained from Figure 5.9.

For the prescribed conditions

$$\frac{x}{L} = 1 \quad \text{and} \quad Bi^{-1} = 3.2$$

it follows that

$$\frac{\theta(L, 480\ \text{s})}{\theta_o(480\ \text{s})} = \frac{T(L, 480\ \text{s}) - T_\infty}{T_o(480\ \text{s}) - T_\infty} \approx 0.86$$

Hence

$$T(L, 480\ \text{s}) \approx T_\infty + 0.86[T_o(480\ \text{s}) - T_\infty]$$

$$T(L, 480\ \text{s}) \approx 60°\text{C} + 0.86[42 - 60]°\text{C} \approx 45°\text{C}$$

The heat flux at $t = 8$ min is then

$$q''_L = 500\ \text{W/m}^2 \cdot \text{K}\ (45 - 60)°\text{C} = -7500\ \text{W/m}^2 \quad \triangleleft$$

4. The energy transfer to the pipewall over the 8-min interval may be obtained from Figure 5.10 and Equation 5.44. With

$$Bi = 0.313 \qquad Bi^2 Fo = 0.55$$

it follows that

$$\frac{Q}{Q_o} \approx 0.78$$

Hence

$$Q \approx 0.78 \rho c V (T_i - T_\infty)$$

or with a volume per unit pipe length of $V' = \pi D L$,

$$Q' \approx 0.78 \rho c \pi D L (T_i - T_\infty)$$

$$Q' \approx 0.78 \times 7823\ \text{kg/m}^3 \times 434\ \text{J/kg} \cdot \text{K} \times \pi \times 1\ \text{m} \times 0.04\ \text{m}\ (-20 - 60)°\text{C}$$

$$Q' \approx -2.7 \times 10^7\ \text{J/m} \quad \triangleleft$$

Comments:

1. The minus sign associated with q'' and Q' simply implies that the direction of heat transfer is from the oil to the pipe (into the pipe wall).
2. Since $Fo > 0.2$, the one-term approximation can be used to calculate wall temperatures and the total energy transfer. The midplane tempera-

ture can be determined from Equation 5.41

$$\theta_o^* = \frac{T_o - T_\infty}{T_i - T_\infty} = C_1 \exp\left(-\zeta_1^2 Fo\right)$$

where, with $Bi = 0.313$, $C_1 = 1.047$ and $\zeta_1 = 0.531$ rad from Table 5.1. With $Fo = 5.64$,

$$\theta_o^* = 1.047 \exp\left[-(0.531 \text{ rad})^2 \times 5.64\right] = 0.214$$

This result is in good agreement with the value of 0.22 obtained from Figure 5.8. Hence,

$$T(0, 8 \text{ min}) = T_\infty + \theta_o^*(T_i - T_\infty) = 60°\text{C} + 0.214(-20 - 60)°\text{C} = 42.9°\text{C}$$

which is within 2% of the value determined from the Heisler chart.

3. Using the one-term approximation for the surface temperature, Equation 5.40b with $x^* = 1$ has the form

$$\theta^* = \theta_o^* \cos(\zeta_1)$$

$$T(L, t) = T_\infty + (T_i - T_\infty)\theta_o^* \cos(\zeta_1)$$

$$T(L, 8 \text{ min}) = 60°\text{C} + (-20 - 60)°\text{C} \times 0.214 \times \cos(0.531 \text{ rad})$$

$$T(L, 8 \text{ min}) = 45.2°\text{C}$$

which is within 1% of the value determined from the Heisler chart.

4. The total energy transferred during the transient process can be determined from the result associated with the one-term approximation, Equation 5.46.

$$\frac{Q}{Q_o} = 1 - \frac{\sin(\zeta_1)}{\zeta_1}\theta_o^*$$

$$\frac{Q}{Q_o} = 1 - \frac{\sin(0.531 \text{ rad})}{0.531 \text{ rad}} \times 0.214 = 0.80$$

which is within 3% of the value determined from the Gröber chart.

EXAMPLE 5.3

A new process for treatment of a special material is to be evaluated. The material, a sphere of radius $r_o = 5$ mm, is initially in equilibrium at 400°C in a furnace. It is suddenly removed from the furnace and subjected to a two-step cooling process.

Step 1 Cooling in air at 20°C for a period of time t_a until the center temperature reaches a critical value, $T_a(0, t_a) = 335°C$. For this situation, the convective heat transfer coefficient is $h_a = 10\ W/m^2 \cdot K$.

After the sphere has reached this critical temperature, the second step is initiated.

Step 2 Cooling in a well-stirred water bath at 20°C, with a convective heat transfer coefficient of $h_w = 6000\ W/m^2 \cdot K$.

The thermophysical properties of the material are $\rho = 3000\ kg/m^3$, $k = 20\ W/m \cdot K$, $c = 1000\ J/kg \cdot K$, and $\alpha = 6.66 \times 10^{-6}\ m^2/s$.

1. Calculate the time t_a required for step 1 of the cooling process to be completed.
2. Calculate the time t_w required during step 2 of the process for the center of the sphere to cool from 335°C (the condition at the completion of step 1) to 50°C.

SOLUTION

Known: Temperature requirements for cooling a sphere.

Find:

1. Time t_a required to accomplish desired cooling in air.
2. Time t_w required to complete cooling in water bath.

Schematic: