Handbook of Smoke Control Engineering

Second Edition

John H. Klote
James A. Milke
Paul G. Turnbull
Ahmed Kashef
Duncan A. Phillips
Douglas H. Evans
William A. Webb
Michael J. Roth
Michael J. Ferreira

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Handbook of
Smoke Control Engineering

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Dr. John Klote is known throughout the world as an expert in smoke control due to his many books on the topic and his 19 years of fire research conducted at the U.S. National Institute of Standards and Technology in Gaithersburg, Maryland. For 11 years, Klote operated his own consulting company specializing in analysis of smoke control systems. Klote developed a series of smoke control seminars for ASHRAE and SFPE. Klote was the primary author of the ASHRAE books *Design of Smoke Control Systems for Buildings* (1983), *Design of Smoke Management Systems* (1992), *Principles of Smoke Management* (2002), and the first edition of *Handbook of Smoke Control Engineering* (2012). Klote is also the primary author of the 2007 ICC book *A Guide to Smoke Control in the 2006 IBC*. Klote also has authored more than 80 papers and articles on smoke control, smoke movement, CFD fire simulations, and other aspects of fire protection. He is a licensed professional engineer in Washington, DC. Klote earned his doctorate in mechanical engineering from George Washington University. Klote is a member of NFPA, a Fellow of SFPE, and a Fellow of ASHRAE. He is a member and past chair of ASHRAE Technical Committee (TC) 5.6, Control of Fire and Smoke, and he is a member emeritus of the NFPA Smoke Management Committee.

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Paul Turnbull has been actively involved in the development of codes and standards for smoke control systems for more than 35 years. For the first 10 years of his career, he was responsible for safety certifications of building controls, HVAC, fire alarm, and smoke control equipment. During this time, he became involved in the development of standards for smoke control systems and equipment. For the next 15 years, he specialized in the development and application of gateways that enabled fire alarm, security, and lighting control systems to be integrated with building controls in order to provide coordinated operations between these systems. For the past 15 years he has been involved in the development of room automation systems including HVAC, lighting, shade control, and life safety. He is an active member in several professional associations focused on control of fire and smoke. Paul holds a BS in Electrical Engineering and an MS in Computer Science. He is a member of ASHRAE TC 5.6, Control of Fire and Smoke, and the NFPA Smoke Management Committee.

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Douglas H. Evans

After 22 years as a Fire Protection Engineer with the Clark County (Nevada) Building Department, Douglas Evans, PE, FSFPE, founded DHE FPE LLC to provide specialized consulting services to the construction industry. In his position with Clark County, his primary focus was coordinating fire protection aspects for the mega-resorts on the Las Vegas Strip. Although this specialization requires a thorough understanding of most fire protection aspects, Evans is primarily recognized for his knowledge of combustible exterior facades, plastics/foam plastics as building materials, smoke management systems, unique interior features, product listings/applications for use on and within structures, and alternates/equivalences (performance-based designs) to prescriptive code requirements. During his career, Evans has authored multiple books on smoke management systems design, articles on various fire protection subjects in trade journals, and amendments that have been incorporated into the *International Building Code*® (IBC®). He has also given a number of professionally related presentations. Evans is a registered Fire Protection Engineer, a Fellow of SFPE, and a member of ICC and NFPA.

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fles City in Singapore; The Bank of China in Hong Kong; and the Johnson & Johnson World Headquarters in New Brunswick, New Jersey. In each case, the architectural design for the project required large multifloor and interconnected spaces. Each project required the application of basic principles of determining the fire size and performing smoke production calculations to determine appropriate exhaust and pressurization values to allow occupants to escape or reach a place of safety before they would be endangered.

Michael J. Roth

Dr. Michael Roth is a director and co-founder of Klimaat Consulting & Innovation Inc., an engineering firm focused on the modeling and analysis of climate for the built environment. In addition to the processing and publication of the climatic design information for ASHRAE, Roth has consulted on ventilation and smoke control design projects worldwide for more than 20 years, with a particular focus on CFD modeling. He is a licensed professional engineer and holds a BASc and an MASc in Mechanical Engineering from the University of Waterloo, Ontario, and a PhD in Earth and Ocean Sciences from the University of Victoria, British Columbia. He is a member of ASHRAE TC 4.2, Climatic Information.

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This book is dedicated to the memory of Harold (Bud) Nelson.

Because of his many significant contributions when he worked at
General Services Administration (GSA) and
National Institute of Standards and Technology (NIST),
Bud is recognized as one of the great pioneers of fire protection engineering.
He also was the first chairman of the NFPA Smoke Management Committee.

Bud was always generous with his help and
positive suggestions to younger engineers.

How to Use this Book

Handbook of Smoke Control Engineering, Second Edition, is different from the first edition in that it has been printed in color and the layout has been changed to single column to accommodate people who are using the PDF version.

This handbook includes all the information in my previously published books on smoke control plus content on a number of other topics, and there are many example calculations included herein. This handbook can be used as a reference or as a textbook, with the teacher selecting the chapters or parts of chapters to be taught.

The book is organized in the classic handbook format to help engineers and other professionals who need to get information about a topic quickly. The Table of Contents and Index are provided so readers can quickly find what they need and go directly to their topic of interest. There is no introductory chapter; the most fundamental material is in the first chapters and applied material is in later chapters. The only departure from the handbook format is that, to help readers get the information quickly, the chapters do not include derivations of equations—these are provided in Appendix A to make the book more useful to scholars, teachers, and students. Unlike textbooks, some redundancy is needed in handbooks so that the chapters can be relatively independent. Such redundancy is minimized in this book to the extend possible. In some places, readers are referred to another section or chapter for more information.

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This handbook is accompanied by PDFs of climatic design data for most weather stations around the world and AtriumCalc, a Microsoft® Excel® application developed for analysis of atrium smoke control systems.

Preface

In 1973, the U.S. National Commission on Fire Prevention and Control presented their report, "America Burning," to President Nixon. The gist of the report was that the United States had the worst fire statistics of any country in the industrialized world. As a result, the U.S. Congress passed the Federal Fire Prevention and Control Act of 1974, leading to the formation of the U.S. Fire Administration, the National Fire Academy, the National Fire Incident Reporting System, and the Center for Fire Research within the National Bureau of Standards (NBS). ASHRAE and other societies responded. ASHRAE held several conferences on the subject and formed Technical Committee (TC) 5.6, Control of Fire and Smoke, which focused on developing smoke control technology.

In 1983, ASHRAE published *Design of Smoke Control Systems for Buildings*, authored by myself and John Fothergill. This book was the first attempt to consolidate and present practical information about smoke control design. Judging by the many favorable comments and suggestions about this first book, I feel that it was a success. The first publication was limited to systems that control smoke by means of the physical mechanisms of pressurization and airflow.

In 1992, ASHRAE published *Design of Smoke Management Systems*, authored by myself and Dr. James Milke and co-branded by SFPE. The term *smoke management* was used in the title of this publication to indicate that the physical mechanisms were expanded from pressurization and airflow to include compartmentation, dilution, and buoyancy. Based on heightened concerns about supplying combustion air to the fire, a caution was added about the use of airflow for smoke management.

In 2002, ASHRAE published *Principles of Smoke Management*, again authored by myself and Dr. Milke and co-branded by SFPE. This publication included the material of the two earlier books plus people movement in fire, hazard analysis, scale modeling, and computational fluid dynamics.

In 2012, ASHRAE published the first edition of *Handbook of Smoke Control Engineering*, and I was fortunate to have four coauthors. This handbook is co-branded by ICC, NFPA, and SFPE. Whereas the earlier books were aimed at both practicing engineers and students and derivations of equations were included in many of the chapters, this publication was in handbook form to make the material easier to use for engineers who want information on a specific topic quickly. To make the handbook useful to students and teachers, the derivations of equations were moved to Appendix A.

In this 2012 handbook the term *smoke control system* was used to mean an engineered system that includes all methods that can be used singly or in combination to modify smoke movement. This usage was consistent with that of the 2009 NFPA 92A, the 2012 NFPA 92, and most codes,

including *International Building Code*® (IBC®). This usage was a departure from the earlier ASHRAE smoke control books and earlier versions of NFPA 92A. The meaning of the term *smoke management system* was completely changed in the 2009 NFPA 92A, and this term was rarely used in the first edition of this handbook. Because these terms have different meanings in many publications, readers are cautioned to be careful about this terminology when reading different books, research papers, and articles.

This second edition of *Handbook of Smoke Control Engineering* has a similar format to the first edition, but it incorporates considerable new information based on research and engineering experience. New information includes the balanced approach to fire protection, the mechanisms of smoke control, a discussion of tall buildings, and system reliability. There new chapters include "Introduction to Smoke Control," "Advanced Atrium Topics," and "Wind Effects." The number of example calculations has also been increased.

This handbook also provides the following data and tools for free download:

- PDFs of climatic design data for most weather stations around the world, which engineers can use for smoke control design and which allows them to produce wind roses for the stations of their choice
- AtriumCalc, which is a Microsoft® Excel® application developed for analysis of atrium smoke control systems and used for calculating the equations within the handbook

These files can be found online. If the files or information at the link are not accessible, please contact the publisher.

This handbook and its predecessors are different from other design books in a number of respects. This handbook is written in both English units (also called I-P for inch-pound) and SI units so that it can be used by a wide audience. Physical descriptions are worked into the text as simple explanations of how particular mechanisms, processes, or events happen.

As with the earlier books, I hope that this handbook is of value to the engineering community. I invite readers to send me their suggestions and comments through ASHRAE.

Dr. John H. Klote, PE

Acknowledgments

This handbook would not have been possible without the support of ASHRAE. In addition to publishing books about smoke control, ASHRAE has funded a considerable body of smoke control research from the 1980s to the present. Of course, a debt is owed to the ASHRAE editorial staff.

Acknowledgment is made to the many members of ASHRAE TC 5.6, Control of Fire and Smoke, who made constructive comments on this handbook and the preceding five ASHRAE smoke control publications. There are so many people that it is not possible to remember everyone, but the ones who come to mind are Jack Buckley, Jim Buckley, John Clark, Larry Felker, George Hadjisophocleous, Amir Jokar, Yoon Ko, Gary Lougheed, Richard Masters, Peter McDonnell, George Tamura, Paul Turnbull, and William Webb. All of these engineers were very helpful, but a special thanks goes to Paul Turnbull for his especially valuable comments about all TC 5.6 smoke control publications. Special thanks are due to Kevin McGrattan of the National Institute of Standards and Technology (NIST), who provided valuable comments and suggestions about Chapter 21, "Computational Fluid Dynamics."

In the early years of smoke control (1970s and 1980s), smoke control presentations were made in the United States and Canada by William Schmidt, Brooks Semple, and Robert Taylor, who were informally known the Smokey Trio. Schmidt was an engineer, but Semple and Taylor did not have technical backgrounds. Of course, the Smokey Trio's presentations were weak on technical information, but they were very interesting and spread the word about smoke control. Also, the Smokey Trio was very active in ASHRAE TC 5.6 in the early years of smoke control.

In the 1970s and 1980s, oxygen consumption calorimeters were developed by many researchers around the world. These calorimeters made it possible to measure the heat release rate (HRR) of many burning materials. At the National Institute of Standards and Technology (NIST), Willian Parker developed the equations to calculate the HRR from an oxygen consumption calorimeter for many applications.

Acknowledgment must be made to the many engineers and scientists who have conducted the research that is the foundation of modern smoke control technology. These researchers are too many to mention here, but many of their efforts are referenced in the text. It should be mentioned that I personally owe much to NIST for the opportunity of doing fire research there for 19 years.

The content of this handbook is heavily dependent on extensive smoke control research conducted at National Research Council Canada (NRC). Much of this research has been conducted at NRC's Experimental Fire Tower near Ottawa by many researchers, including George Tamura,

Gary Lougheed, and Yoon Ko. George Tamura and I conducted a joint U.S. and Canadian project that included work at the NRC's Experimental Fire Tower.

In the last few decades of the twentieth century, many zone fire models were developed around the world. CFAST is NIST's flagship zone fire model that can be downloaded from NIST at no cost. CFAST has been upgraded and maintained at NIST by Richard Peacock, Paul Reneke, and Glenn Forney.

In 2000, the computational fluid dynamics (CFD) model, Fire Dynamics Simulator (FDS), was released to the public. Kevin McGrattan developed FDS specifically for fire research and fire engineering applications. Glenn Forney developed Smokeview, which is a model for visualizing FDS simulations. Both FDS and Smokeview can be downloaded from NIST at no cost.

Also at NIST, George Walton developed CONTAM, which was the first network model that had a graphical interface. This graphical interface made CONTAM an outstanding improvement over earlier network models. CONTAM can be downloaded from NIST at no cost. After Walton retired, CONTAM has been upgraded and maintained at NIST by W. Stuart Dols and Brian Polidoro.

Dr. John H. Klote, PE