I-P Edition

RP-1616

Load Calculation Applications Manual

Second Edition

Jeffrey D. Spitler

A complete reference including

- Heat transfer processes and analysis
- New data and methods
- Applications-oriented, step-by-step examples
- Heat balance and radiant time series methods

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About the Author

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He has worked with a wide range of research sponsors, including ASHRAE, the U.S. Department of Energy, the Federal Highway Administration, York International Corporation, and ClimateMaster. He is a past president of the International Building Performance Simulation Association and is an ASHRAE Fellow.

Spitler has served on several ASHRAE technical committees and standing committees. He currently serves on ASHRAE Technical Committee 6.8, Geothermal Heat Pump and Energy Recovery Applications, and the Conferences and Expositions Committee. He has authored or coauthored more than 120 technical papers and six books, including the *Annotated Guide to Load Calculation Models and Algorithms*.

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Contents

Preface

This manual is the fourth in a series of load calculation manuals published by ASHRAE. The first in the series, *Cooling and Heating Load Calculation Manual,* by William Rudoy and Joseph Cuba, was published in 1980. A second edition, by Faye McQuiston and myself, was published in 1992 and focused on new developments in the transfer function method and the cooling load temperature difference method. Subsequent to the second edition, ASHRAE Technical Committee 4.1, Load Calculations Data and Procedures, commissioned additional research. This research led to the adaptation of the heat balance method for use in load calculation procedures and development of the radiant time series method (RTSM) as the recommended simplified procedure. Both methods were presented in the third volume of this series—*Cooling and Heating Load Calculation Principles,* by Curtis Pedersen, Daniel Fisher, Richard Liesen, and myself.

The *Load Calculation Applications Manual*, also sponsored by TC 4.1, builds on the past three, and some parts are taken directly from previous versions. New developments in data and methods have led to numerous revisions. This manual, intended to be more applications-oriented, includes extensive step-by-step examples for the RTSM.

This work, more so than many technical books, represents the work of many individuals, including the following:

- Authors, named above, of the previous three versions
- Numerous ASHRAE volunteers and researchers who have developed material for the ASHRAE Handbook that has now been incorporated
- Members of the Project Monitoring Subcommittee, including Chris Wilkins, Steve Bruning, Larry Sun, and Bob Doeffinger, who have provided extensive comments, guidance, and direction
- My graduate student, Bereket Nigusse, who has developed most of the spreadsheets underlying the examples and whose doctoral research has led to a number of developments in the RTSM that are incorporated into this manual

The contributions of all of these individuals are gratefully acknowledged.

Jeffrey D. Spitler, PhD, PE

Preface to the Second Edition

To the casual observer, the need for a new load calculation manual may not be self-evident. Yet, changes in lighting and equipment commonly used in buildings require new data, new methods that are more widely applicable have become available, and other newer data have become available since the first edition was originally published in 2008. These new data and methods have been produced by ASHRAE-funded research and by volunteers working on ASHRAE technical committees (TCs). These effort include the following:

- TC 4.1, Load Calculation Data and Procedures, and their contractors (RP-1482) have produced new internal heat gain data for office equipment.
- TC 4.1 and TC 4.5, Fenestration, and their contractors (RP-1311) have developed new methods and data for computing the effects of internal shading on solar heat gains.
- TC 4.1 and TC 5.10, Kitchen Ventilation, and their contractors (RP-1326) have produced a complete new data set on heat gains from kitchen equipment based on experimental measurements.
- TC 4.2, Climatic Information, and their contractors have produced new weather data (RP-1613) for over 6000 stations worldwide based on the years 1986–2010. TC 4.2 also produced a new ASHRAE clear-sky model (RP-1453) that is applicable worldwide—a significant improvement over the old model, which was only valid for the continental United States. TC 4.2 has also developed improved methods (RP-1363) for generating design day temperature profiles.
- TC 4.4, Building Materials and Building Envelope Performance, has provided a major revision of the building thermal properties data.

In addition to acknowledging the members of the above technical committees and their contractors, I would also like to thank the members of the Project Monitoring Subcommittee who have overseen this work: Steve Bruning, Jim Pegues, Bob Doeffinger, Larry Sun, and Chris Wilkins. Their oversight and suggestions have been invaluable.

I have been assisted on this project by three students at Oklahoma State University: a graduate student, Laura Southard, and two undergraduate students, Jimmy Kim and Amy Wong, who have helped with developing revised examples and source code for the changes to the accompanying spreadsheets.

Putting together this book from a set of the author's Word files was a big task requiring quite a bit of attention to detail. I greatly appreciate the work of the ASHRAE staff, especially Sarah Boyle, assistant editor of Special Publications, in editing and typesetting the book. Cindy Michaels, Managing editor of Special Publications, was also very helpful in getting me access to handbook chapters as soon as they became available. Thanks to both of you!

I would like to take the author's prerogative to note three longtime ASHRAE TC 4.1 members who passed away during 2011 and 2012. Lynn G. Bellenger was not only an active TC 4.1 member, but very active in all areas of ASHRAE, serving as the first female ASHRAE President in 2010 and 2011. Lynn was an encouragement to many society members.

Two other TC 4.1 stalwarts, Thomas B. Romine, Jr. and Curtis O. Pedersen, both passed away in July of 2012. Tom was a consulting engineer in Fort Worth, Texas who ably represented the viewpoint of the consulting engineer on the technical committee and helped me keep the end user in mind when I was working on some of the earlier load calculation manuals. Curt was a professor at the University of Illinois at

Urbana-Champaign, my PhD advisor, an investigator on several load calculation-related research projects, and proponent of using fundamental methods—i.e., the heat balance method—for load calculations. Both men have had a great impact on the load calculation methodologies presented in this book.

Jeffrey D. Spitler, PhD, PE

1
Introduction

This manual focuses on two methods for calculating cooling loads in nonresidential buildings—the heat balance method (HBM) and the radiant time series method (RTSM). The two methods presented are based on fundamental heat balance principles, directly so in the case of the HBM, and less directly so in the case of the RTSM. Both methods were first fully presented for use in design load calculations in the predecessor to this volume, *Cooling and Heating Load Calculation Principles* (Pedersen et al. 1998). Since that time, there have been a number of developments in the RTSM. This publication attempts to bring the previous volume up to date, incorporate new developments, and provide a more in-depth treatment of the method. This edition incorporates recent improvements in available data for weather, building materials, fenestration, and internal heat gains and improved methods for predicting clear-sky radiation, design day temperatures, and solar heat gains from fenestration.

This publication is accompanied by a set of spreadsheets and a set of weather files, which can be found at ashrae.org/lcam. The spreadsheets support the more complex examples in the book; the weather files provided the needed weather information to perform load calculations around the world. If the files or information at the link are not accessible, please contact the publisher.

1.1 Definition of a Cooling Load

When an HVAC system is operating, the rate at which it removes heat from a space is the instantaneous heat extraction rate for that space. The concept of a design cooling load derives from the need to determine an HVAC system size that, under extreme conditions, will provide some specified condition within a space. The space served by an HVAC system commonly is referred to as a *thermal zone* or just a *zone*. Usually, the indoor boundary condition associated with a cooling load calculation is a constant interior dry-bulb temperature, but it could be a more complex function, such as a thermal comfort condition. What constitutes extreme conditions can be interpreted in many ways. Generally, for an office it would be assumed to be a clear sunlit day with high outdoor wet-bulb and dry-bulb temperatures, high office occupancy, and a correspondingly high use of equipment and lights. Design conditions assumed for a cooling load determination are subjective. However, after the design conditions are agreed upon, the design cooling load represents the maximum—or peak heat extraction—rate under those conditions.

1.2 The Basic Design Questions

In considering the problem of design from the HVAC system engineer's viewpoint, a designer needs to address the following three main questions:

1. What is the required equipment size?
2. How do the heating/cooling requirements vary spatially within the building?
3. What are the relative sizes of the various contributors to the heating/cooling load?

The cooling load calculation is performed primarily to answer the second question, that is, to provide a basis for specifying the required airflow to individual spaces within the building. The calculation also is critical to professionally answering the first question. Answers to the third question help the designer make choices to improve the performance or efficiency of the design and occasionally may influence architectural designers regarding energy-sensitive consequences.

1.3 Overview of the ASHRAE Load Calculation Methods

1.3.1 Models and Reality

All calculation procedures involve some kind of model, and all models are approximate. The amount of detail involved in a model depends on the purpose of that model. This is the reality of modeling, which should describe only the variables and parameters that are significant to the problem at hand. The challenge is to ensure that no significant aspects of the process or device being modeled are excluded and, at the same time, that unnecessary detail is avoided.

A complete, detailed model of all of the heat transfer processes occurring in a building would be very complex and would be impractical as a computational model, even today. However, building physics researchers and practitioners generally agree that certain modeling simplifications are reasonable and appropriate under a broad range of situations. The most fundamental of these is that the air in the space can be modeled as well-stirred. This means there is an approximately uniform temperature throughout the space due to mixing. This modeling assumption is quite valid over a wide range of conditions. With that as a basis, it is possible to formulate fundamental models for the various heat transfer and thermodynamic processes that occur. The resulting formulation is called the HBM. There is an introduction to the general principles of the HBM in Chapter 2 and further description in Chapter 11.

1.3.2 The Heat Balance Method

The processes that make up the heat balance model can be visualized using the schematic shown in Figure 1.1. It consists of four distinct processes:

1. Outside face heat balance
2. Wall conduction process
3. Inside face heat balance
4. Air heat balance

Figure 1.1 shows the heat balance process in detail for a single opaque surface. The shaded part of the figure is replicated for each of the surfaces enclosing the zone.

The process for transparent surfaces is similar to that shown but does not have the absorbed solar component at the outside surface. Instead, it is split into two parts: an inward-flowing fraction and an outward-flowing fraction. These fractional parts participate in the inside and outside face heat balances. The transparent surfaces, of course, provide the transmitted solar component that contributes to the inside heat balance.

The double-ended arrows indicate schematically where there is a heat exchange, and the single-ended arrows indicate where the interaction is one way. The formulation of the heat balance consists of mathematically describing the four major processes, shown as rounded blocks in the figure.

1.3.3 The Radiant Time Series Method

The RTSM is a relatively new method for performing design cooling load calculations. It is derived directly from the HBM and effectively replaced all other simplified (non-heat-balance) methods such as the transfer function method (TFM), the cooling

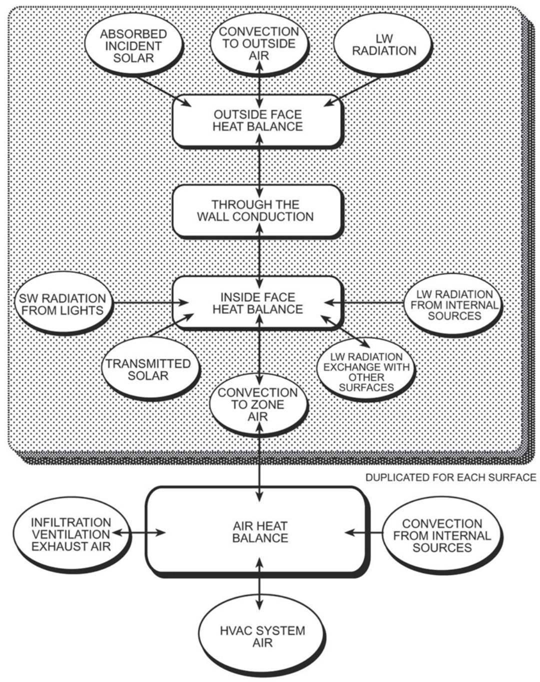

Figure 1.1 Schematic of heat balance process in a zone.
(Source: *Cooling and Heating Load Calculation Principles*, Figure 1.1).

load temperature difference/solar cooling load/cooling load factor method (CLTD/SCL/CLFM), and the total equivalent temperature difference/time averaging method (TETD/TAM). The RTSM was developed in response to a desire to offer a method that was rigorous yet did not require the iterative calculations of the previous methods. In addition, the periodic response factors and radiant time factors have clear physical meanings; when plotted, they allow the user to visually see the effects of damping and time delay on conduction heat gains and zone response.

The utility of the RTSM lies in the clarity, not the simplicity, of the procedure. Although the RTSM uses a “reduced” heat balance procedure to generate the radiant time series (RTS) coefficients, it is approximately as computationally intensive as the heat balance procedure upon which it is based. What the RTS method does offer is insight into the building physics without the computational rigor of the HBM, a sacrifice in accuracy that is surprisingly small in most cases. Previous simplified methods relied on room transfer function coefficients that completely obscured the actual heat transfer processes they modeled. The heat-balance-based RTS coefficients, on the other hand, provide some insight into the relationship between zone construction and the time dependence of the building heat transfer processes. The RTSM abstracts the building thermal response from the fundamentally rigorous heat balance and presents the effects of complex, interdependent physical processes in terms that are relatively easy to understand. The abstraction requires a number of simplifying assumptions and approximations. These are covered in Section 7.1. Figure 1.2 shows the computational procedure that defines the RTSM. A more detailed schematic is shown in Chapter 7.

In the RTSM, a conductive heat gain for each surface is first calculated using air-to-air response factors. The conductive heat gains and the internal heat gains are then split into radiant and convective portions. All convective portions are instantaneously converted to cooling loads and summed to obtain the fraction of the total hourly cooling load caused by convection.

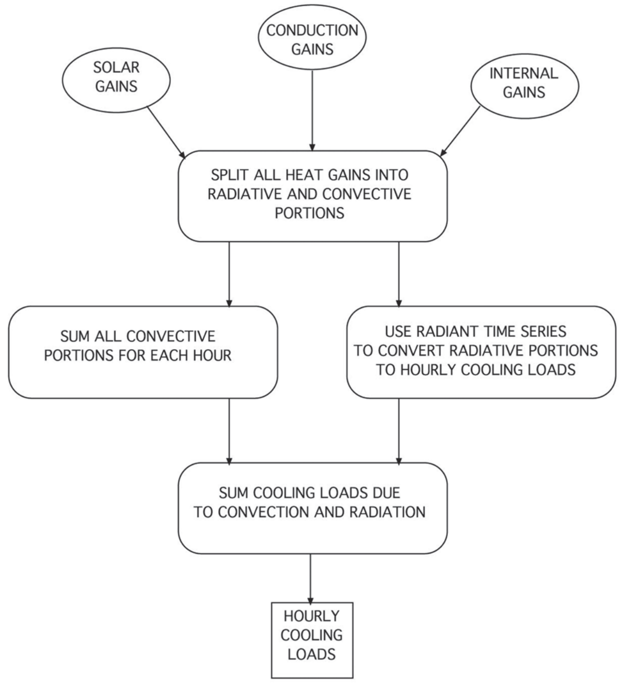

Figure 1.2 Schematic of the radiant time series method.
(Source: *Cooling and Heating Load Calculation Principles*, Figure 1.2).

Radiant heat gains from conduction, internal sources, and solar transmission are operated on by the RTS to determine the fraction of the heat gain that will be converted to a cooling load in current and subsequent hours. These fractional cooling loads are added to the previously calculated convective portions at the appropriate hour to obtain the total hourly cooling load.

1.4 Organization of the Manual

This manual is organized to roughly proceed from the general to the specific. Chapter 2 provides an overview of the heat transfer processes present in buildings and a brief discussion of how they are analyzed together in order to determine the building cooling load. Chapters 3–6 cover thermal properties, design conditions, infiltration, and internal heat gains—all of which are relevant to all load calculation methods. Chapters 7 and 8 cover the theory and application of the RTSM. Chapter 9 covers systems and psychrometrics, analyses of which are necessary to determine equipment sizes. Chapter 10 considers heating load calculations. Chapter 11 covers the HBM and its implementation.

Throughout the manual, numerous shaded examples are presented to illustrate various aspects of the RTSM. A number of the examples are performed using spreadsheets that are included in the supporting files online at www.ashrae.org/lcam.

References

Pedersen, C.O., D.E. Fisher, J.D. Spitler, and R.J. Liesen. 1998. *Cooling and Heating Load Calculation Principles*. Atlanta: ASHRAE.

2

Fundamentals of Heat Transfer and Thermodynamics

The cooling load is defined as the amount of heat that must be removed from the room air to maintain a constant room air temperature. Conversely, the heating load is the amount of heat that must be added to the room air. To determine these quantities, it is necessary to estimate the heat transmission into or out of the room. In turn, this requires analysis of all three modes of heat transfer—conduction, convection, and radiation— within the building envelope and between the building envelope and its surroundings. (Here, the term *building envelope* refers to the walls, roofs, floors, and fenestrations that make up the building.)

The three modes of heat transfer all occur simultaneously, and it is the simultaneous solution of all three modes of heat transfer that complicates the analysis. In practice, this simultaneous solution is done with a computer program either during the load calculation procedure (e.g., the heat balance method [HBM]) or prior to the load calculation procedure (all simplified load calculation procedures rely on tabulated factors that were developed with a simultaneous solution of all three modes of heat transfer).

Before concerning ourselves with the simultaneous solution, we should first consider the three modes independently. For convection and radiation, the treatment of the individual modes of heat transfer does not go far beyond what is taught in a first undergraduate course[1] in heat transfer. For steady-state conduction heat transfer, as used in heating load calculations, this is also the case. For transient conduction heat transfer, as used in cooling load calculations, the derivation of the solution procedure can be somewhat complex, although its application, in practice, is not very difficult.

Each of the three modes is discussed briefly below. Then, after considering the three modes of heat transfer, the simultaneous solution—based on the first law of thermodynamics—is briefly discussed.

2.1 Conduction—Steady State

Heat transfer through building walls and roofs is generally treated as a pure conduction heat transfer process, even though, for example, convection and radiation may be important in an internal air gap[2] in the wall. Conduction is the transfer of heat through a solid[3] via random atomic and molecular motion in response to a temperature gradient. Elements of the building envelope such as thermal bridges and corners distort the temperature gradients so that the heat flows in directions other than purely perpendicular to the envelope surfaces. Such heat flow is said to be multidimensional. For building load calculations, multidimensional conduction heat transfer is generally approximated as being one-dimensional; however, the approximations do take into account the impact of thermal bridges.[4] Heat loss from foundation elements is also multidimensional, but again, approximations are made that simplify the calculation procedure.

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1. Cf. Incropera and DeWitt (2001).
2. Even though heat transfer in an air gap is due to convection and radiation, it is approximated as being a conduction process with a fixed thermal resistance that is independent of the temperatures of the gap surfaces.
3. Technically, conduction also occurs in liquids and gases, too. But here we are only concerned with conduction in solids.
4. Appendix E covers the treatment of thermal bridges.