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The Art of Thermal Mass Modeling for Energy Conservation in Buildings, Part 1

ACI Spring 2012 Convention
March 18 – 21, Dallas, TX

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THERMAL MASS MODELING
HOW WE GOT TO WHERE WE ARE TODAY

Jeff S. Haberl, Ph.D., P.E., FASHRAE
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Chunliu Mao
March 2012
Dallas
Energy Systems Laboratory
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History: Building Energy Load Calculation Methods

What methods are currently used to size the building systems and analyze building energy use?

- Annual Building Energy Use Calculation Methods
  - Peak Heating Load Calculation
  - Peak Cooling Load Calculation
  - Annual Building Energy Use Calculation Methods
    - Forward
    - Inverse (Data-Driven)

How did the methods evolve from 1900 to Present?
How did these methods treat the use of thermal mass?

History: Pre 1900 - Important Developments

- Thermodynamics (Carnot, Joule, Thompson/Kelvin, Clausius, Gibbs)
- Heat Transfer (Newton, Fourier)
- Weather-reporting (Hooke, Le Roy)
- Electricity (Edison, Tesla)
- Material Science
  - Insulation
  - Metals, welding
- Inventions
  - Thermometer/Thermostat
  - Humidity Measurements
  - Barometer
  - Vacuum Pump
  - Refrigeration
  - Air Handling Units, centrifugal fans
  - Steam engine
  - Steam heating system

Distribution/Age of U.S. Commercial Buildings

New York City has thousands of new/old buildings
Same pattern for other U.S. cities, such as Chicago

- How are we going to create new high-performance buildings?
- Can we create high-performance buildings from existing buildings?
- What design methods were used to design existing buildings?
- How did the methods treat thermal mass?

History of ASHVE, ASRE, ASHAE, ASHRAE

American Society of Heating, Refrigerating and Air-Conditioning Engineers

- In 1894: ASHVE was established
- In 1895: ASHVE Transactions was first published
- In 1904: ASRE was established
- In 1905: ASRE Transactions was first published
- In 1915: Journal of ASHVE was first published
- In 1922: ASHVE Guide was first published
- In 1932: The Refrigerating and Data Book by ASRE was first published
- In 1954: ASHVE changed its name to ASHAE
- In 1959: ASHAE and ASRE merged and became ASHRAE
- In 1961: ASHRAE Guide and Data book was published
- In 1967: ASHRAE Handbook of Fundamentals was first published
- In 1972 ASHRAE Handbook
- In 1977 ASHRAE Handbook
- In 1981 ASHRAE Handbook
- In 1985 ASHRAE Handbook
- In 1989 ASHRAE Handbook
- In 1993 ASHRAE Handbook
- In 1997 ASHRAE Handbook
- In 2001 ASHRAE Handbook
- In 2005 ASHRAE Handbook
- In 2009 ASHRAE Handbook

CBECS Survey: U.S. Census Regions and Divisions

Source: http://www.eia.gov/emeu/cbecs/census_region.html
Observations:
- 52.3% of the buildings were built from 1970 to 1999
- 39.7% of the buildings were built in the South

Observations:
- 39.7% of buildings were built in the South
- 27.9% in the Midwest, 18.2% in the West and 14.2% in the Northeast

History: Pre 1945 – Guide Books

Guide Books:
- 1904 Frank E. Kidder: Architect’s and Builder’s Handbook
- 1922 ASHVE Guide
- 1932 The Refrigerating Data Book by ASRE
- 1938 Trane Air Conditioning Manual

History: Pre 1945 – Important Developments

Computer Development:
- 1822 - 1832: Charles Babbage and Joseph Clement produced the first Difference Engine
- 1815-1820: First computer programmer: Ada Lovelace
- In 1930, differential analyzer available
- In 1946, first large scale electronic, digital computer available: ENIAC

History: Pre 1945 – Important Developments

In 1848, Dr. John Gorrie invented his “ice machine”
In the late 1880s, "War of the Currents" began between Edison and Tesla.

Source: http://staff.fcps.net/rroyster/war.htm

Before that, air handling systems were steam-driven!

In 1904, "There appears to be no rule by which the architect can determine the size of the furnace that should be used to heat a given building other than by using the tables given by the various manufacturers……"
**History: Pre 1945 – Heating Load Calculation**

- In 1905, Stuart Cramer first used the term “air conditioning” for treating air in textile mills in N.C.
- In 1908, Willis Carrier developed his Psychrometric chart & formula.

**History: Pre 1945 – Cooling Load Calculation**

In 1908, Willis Carrier developed his Psychrometric chart & formula.

- In 1928, the first high-rise air-conditioned office building in U.S. was built in San Antonio “The Milam Building.”

The Milam Building

Original Carrier Centrifugal Refrigeration Unit

**History: Pre 1945 – Cooling Load Calculation**

In 1928, the first high-rise air-conditioned office building in U.S. was built in San Antonio “The Milam Building.”

- In 1905 – Stuart Reinforced-Concrete High-Rise Office Building: 210,851 ft²
- Air-Conditioning System was designed by Carrier Engineering Corporation.
- Two Chillers with a Maximum 375-ton Capacity provided Chilled Water, 562 ft²/ton.
- Radiant Heat was absorbed by the heavy construction.
- Venetian Blinds, Cloth Window Shades, Duct dampers were added to solve morning/afternoon overheating.
- Design methods never published.
- In 1930, Carrier designed / installed cooling system in the U.S. Oval Office.

**History: Pre 1945 – Cooling Load Calculation**

In 1938, TRANE Company published its first design manual called “TRANE Air-Conditioning Design Manual” and provided a load estimate sheet for engineers to use.

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TRANE Air-Conditioning Manual

**History: Pre 1945 – Cooling Load Calculation**

- Design Data
- Conduction Heat Gains
- Equipment Heat Gains
- Infiltration Heat Gains
- No direct treatment of thermal mass
- Summary of Heat Gains
- Solar Temperature Difference Method
- Duct Heat Gains
- Heat Load of Ventilation Air
- Total Cooling Load on Coils

**History: Pre 1945 – Cooling Load Calculation**

In 1944, Mackey and Wright developed Sol-Air Temperature Method which was published by ASHVE.

- Thermal Conductance (k)
- Decrement Factor (ρ)
- kρ Curve
- \[ \sum_{n=0}^{\infty} \left( \frac{856.0}{15} \cos \left( \frac{606.0}{15} n \pi \right) \right) \]
- Inside Surface Temperature
- There is time lag for the peak and a reduction in amplitude.
- Phase angle

**History: Pre 1945 – Cooling Load Calculation**

Effect of thermal mass could be calculated!
There is time lag for the peak and a reduction in amplitude.

The equations in Mackey and Wright and ASHRAE original test data were then tabulated in the ASHRAE Guide and Data Book.

Basic heat gain equation for exterior surface:

\[ q = UA(T_{ETD}) \]

Thermal mass is in the TETD

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**History: Pre 1945 – Cooling Load Calculation**


Guide Books:
- 1955 TRANE Air Conditioning Design Manual
- 1960 Handbook of Air Conditioning System Design by Carrier
- ASHRAE Guide and Data Book
- ASHRAE Handbook of Fundamentals

**History: 1946 – 1969 Cooling Load Calculation**

Peak Cooling Load Calculation

- **TETD/TA Method:**
  - Total Equivalent Temperature Difference/Time Averaging Method
  - Original outlined by Stewart in 1948 based on Mackey & Wright
  - TETD table added to ASHRAE Guide and Data Book in 1951

Basic heat gain equation for exterior surface:

\[ q = UA(T_{ETD}) \]

Thermal mass is in the TETD

**History: 1970 – 1989 Cooling Load Calculation**

CLTD/CLF permitted hourly estimations of heat gain for each surface/orientation, opaque/fenestrations = Totalized by zone.

In 1977 TETD/TA replaced with CLTD/CLF Method:
- First developed by Rudoy and Duran in 1974 and published in ASHRAE Transactions
- Later appeared in 1977 ASHRAE handbook

**History: 1970 – 1989 Cooling Load Calculation**

Other Developments:
- **Finite Difference /Finite Element Method:**
  - FDM/FEM available, used as a basis for early computer algorithms, very time consuming
- **Chartered institution of Building Services Engineers (CIBSE) Admittance Method:**
  - Original developed by Loudon in 1968
  - Standard method in UK
  - The concept of thermal admittance was first introduced by Institution of Heating and Ventilating Engineers (IHVE) Guide in 1970
  - Later selected by CIBSE Guide A
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**History: 1946 – 1969 Annual Energy Use**

**Annual Building Energy Use Calculation:**

- Heating Degree-Day Method:
  - Used to predict heating oil deliveries, crops & snow melt.
  - Manual method was adopted by ASHVE
  - Later appeared in *ASHRAE Handbooks*

- Equivalent Full Load Hours Method:
  - Manual method was adopted by ASHVE
  - Later appeared in *ASHRAE Handbooks*

- Classic Heating Degree-Day Method:
  \[
  E = \sum_{i=1}^{n} \frac{H_i \cdot D_i}{\Delta t}
  \]
  - Where:\n    - \( E \): fuel or energy consumption for the estimate period, Btu
    - \( HL \): design heat loss, including infiltration and ventilation, Btu/h.
    - \( D_i \): number of 65\(^\circ\)F degree days in the estimation period
    - \( \Delta t \): design temperature difference, \( ^\circ\)F
    - \( k \): a correction factor that includes the effects of rated full load efficiency, part load performance, oversizing and energy conservation devices
    - \( V \): heating value of fuel, units consistent with \( HL \) and \( E \)
    - \( CD \): empirical correction factor for heating effect versus 65\(^\circ\)F degree-days

- Cooling Season Power:
  \[
  P_c = \frac{\text{BTU}}{\text{W}} \times \frac{746}{24} \times \frac{E}{24}
  \]
  - Where:\n    - \( P_c \): cooling season power (kWh)
    - \( (\text{bhp})t \): brake horsepower per ton
    - \( T \): maximum refrigeration design load (tons)
    - \( H \): equivalent full-load refrigeration operating time (h)
    - \( E \): motor efficiency at average load (decimal)
  - Manual method adopted in the mid-1960s
  - Used for heating and/or cooling calculations
  - Later appeared in 1981 *ASHRAE Handbook*

- Bin Method:
  - Manual method adopted in the mid-1960s
  - Later appeared in *ASHRAE Handbooks*

**History: 1946 – 1969 Computer Developments**

- In 1957, FORTRAN I compiler was developed by John Backus and colleagues at IBM
- In 1960, PDP-1, the first commercial mini computer was available
- In 1964, BASIC programming was available

Today, most whole building simulation programs are still using FORTRAN


**History: 1946 – 1969 Cooling Load Calculation**

- Heat Balance Method:
  - Earliest use for general thermal modeling in aerospace and other industries
  - Used in detailed calculation procedures by Buchberg in 1958
  - Later appeared in *ASHRAE Handbooks*

- 1950s RC Networks:
  - Layered walls, roofs.
  - Nodal temperatures to be determined
  - Solved by analog computers (i.e., equiv. electrical circuits).
  - Results viewed on oscilloscope

Source: Building 11, 2009 Cooling load from Thermal Network Solutions, ASHVE Transactions, Vol. 64, pp. 145-148
Thermal Response Factor Method:
- First developed by Stephenson and Mitalas in 1967, based on 1950s work by Brisken & Reque (1956), Hill (1957).
- Appeared as part of the Weighting Factor Methods in ASHRAE Handbook.
- Used for CLTD/CLF tables.
- Heat Gain Weighting Factors:
  \[ w_1, w_2, \ldots, w_n \]
- Air Temperature Weighting Factors:
  \[ w_1, w_2, \ldots, p_1, p_2, \ldots \]

For each type of heat gain \( q \), cooling load for \( Q \):
\[
Q = \sum_{i=1}^{n} w_i q_i + \sum_{j=1}^{m} p_j \left( Q_w^j - Q_{w}^{j-1} \right)
\]

Transfer function coefficients:

History: 1946 – 1969 Annual Energy Use
Computer Algorithms:
Thermal Response Factor Method:
- First introduced in the 1972 ASHRAE Handbook of Fundamentals.

Heat gain through a wall or roof:
\[
q_n = \left( \sum_{i=1}^{n} w_i q_i \right) + \sum_{j=1}^{m} p_j \left( Q_w^j - Q_{w}^{j-1} \right)
\]

where,
\[ k, c, d \]
Transfer function coefficients.

History: 1970 – 1989 Annual Energy Use
Computer Algorithms:
DOE-2 (Weighting Factor Method).

Guide Books:
- 1972 ASHRAE Handbook of Fundamentals
- 1977 TRANE Air Conditioning Manual

History: 1990 – Present Guide Books:
Guide Books:
- 1993 - 2009 ASHRAE Handbook of Fundamentals

History: 1990 – Present Cooling Load Calculation
Computer Algorithms:
Radiant Time Series Method:
- First proposed by Spiller, Fisher and Pedersen in 1997 to replace RF, TETD, CLTD/CLF.
- Requires software.
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**Residential Heat Balance (RHB) and Residential Load Factor (RLF) Methods:**
- First introduced by Barnaby, Spiller and Xiao in 2004
- Both methods used for residential calculations
- Later appeared in *2005 ASHRAE Handbook of Fundamentals*

**Modeling Radiant HVAC Systems Using a Heat Balance Simulation:**
- Required the development of new type of transfer functions.
- Now a module in the EnergyPLUS program

**History: 1990 – Present Cooling Load Calculation**

**Building Energy Modeling Programs:**

**History: 1960 – Present Annual Energy Use**

**History: 1990 – Present Summary**

**Summary:**
- Important to consider age of building stock in the U.S. 1900 to present
- History of building load calculation methods tied to:
  - The development of ASHVE, ASRE, ASHAE, ASHRAE.
  - The development of computers, FORTRAN programming language, graphics, etc.
  - Previous developments: thermo, H.T., materials, etc.
- 1904 – 1938 no direct consideration of thermal mass in building heat load calculation.
Summary

• Other considerations:
  • 1848 - Invention of refrigeration
  • Late 1800s – resolution of A.C. vs D.C. for electric motors
  • 1911 – Psychrometric chart (Willis Carrier)
  • 1903 – 1928 air conditioning (NYSE, St. Louis World’s Fair, Milam Building, San Antonio, TX)

• 1944 – First use of thermal mass: Mackey and Wright developed sol-air temperature with decrement factor, phase angle.

• 1951 – Total Equivalent Temperature Difference/Time Average (TETD/TA) method developed based on Mackey & Wright

• 1977 – TETD/TA replaced with Cooling Load Temperature Difference/Cooling Load Factor (CLTD/CLF) Method, later modified to CLTD/SCL/CLF

• Annual Calculation Methods: 1950s - heating degree days, equivalent full load hours, 1970s - bin method, 1980s modified bin method.

• 1944 - 1958 – thermal network models created, based on electrical RC circuits. Solved with analog computers.

Summary

• Computer Algorithms (1960 – present):
  • thermal response factors,
  • transfer functions,
  • weighting factors/ heat balance method,
  • radiant time series,
  • residential heat balance, residential load factors
  • new transfer functions for radiant heating HVAC systems

• Examples of Thermal Mass Studies: thermal mass structural factors, thermal mass factors, radiant floor systems, etc.

Summary

• 1977 – TETD/TA replaced with Cooling Load Temperature Difference/Cooling Load Factor (CLTD/CLF) Method, later modified to CLTD/SCL/CLF

• Annual Calculation Methods: 1950s - heating degree days, equivalent full load hours, 1970s - bin method, 1980s modified bin method.

• 1944 - 1958 – thermal network models created, based on electrical RC circuits. Solved with analog computers.

Questions?