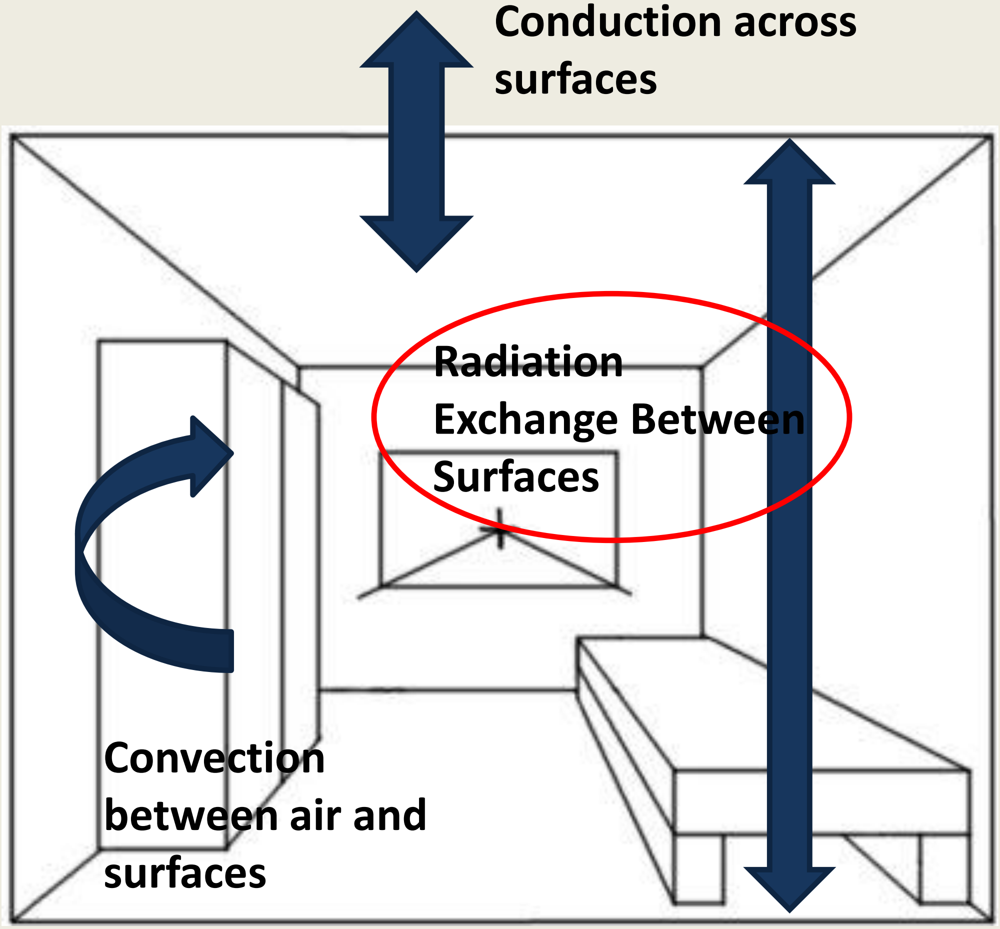
Module 1: Introduction to Radiant Cooling

BEEP
BUILDING ENERGY EFFICIENCY PROJECT

Module 1: Introduction to Radiant Cooling

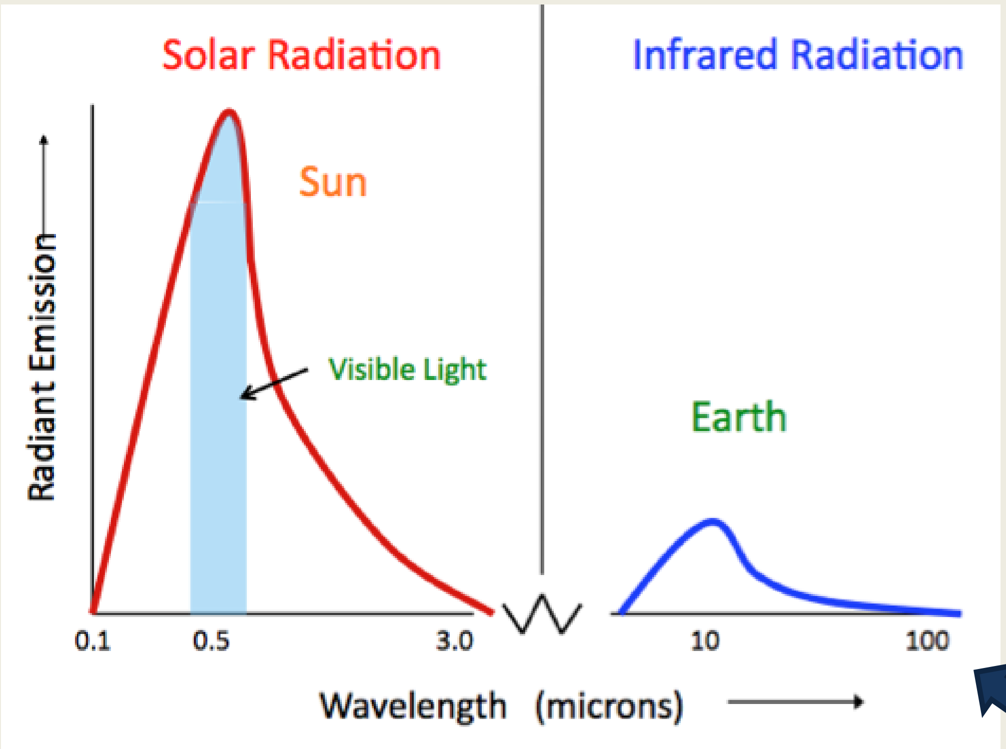
Heat Transfer Basics
Human Body Heat Exchange
Radiant Cooling – Basics
Radiant Cooling – Suitability ?
Radiant Cooling - Benefits
Conclusions

Modes of Heat Transfer



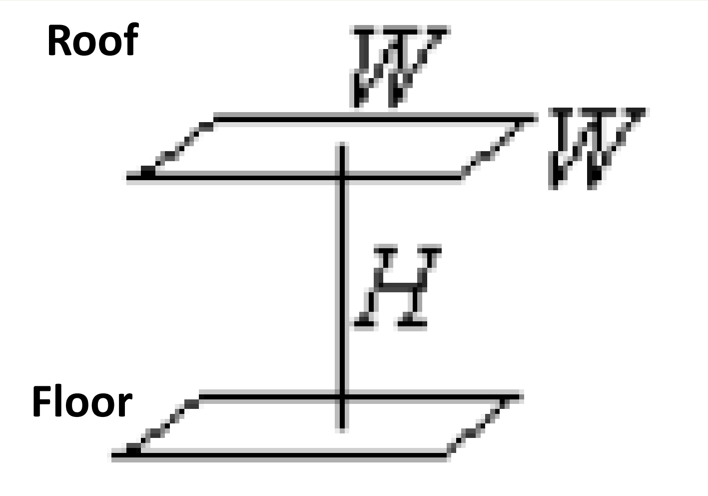
Thermal radiation, process by which energy, in the form of electromagnetic radiation, is emitted by a heated surface in all directions and travels directly to its point of absorption at the speed of light.

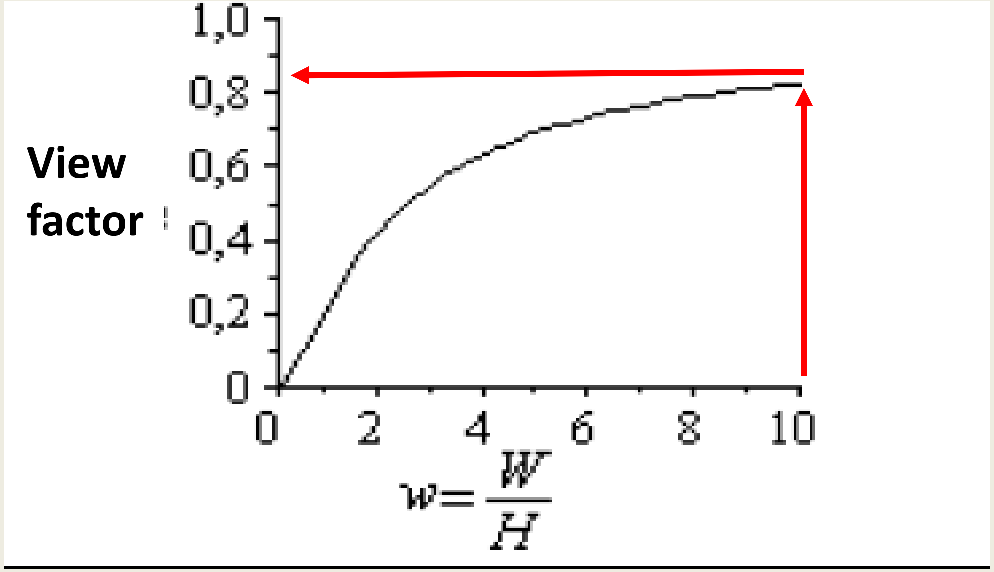
Thermal Radiation Spectrum



Thermal radiation exchange in buildings are in long wavelength infrared rays.

View Factor between roof and the floor





Large room of 35m x35 m (W=35 m)
Height of the room is 3.5 m
w= 35/3.5 = 10

For large rooms, the view factor between the roof and the floor is ~ 1

Radiative heat exchange between two surfaces (e.g. roof and floor) with a view factor of 1

- Black body radiation constant (Boltzmann)
- Infrared thermal emissivity
  - (generally inside buildings = 0.9)
- Surface temperature of surface 1
- Surface temperature of surface 2

$$\sigma := 5.67 \cdot 10^{-8} \cdot \frac{\text{watt}}{\text{m}^2 \cdot \text{K}^4}$$

$$\varepsilon := 0.9$$

$$T_1 := 293 \cdot \text{K}$$

$$T_2 := 294 \cdot \text{K}$$

$$q := \sigma \cdot \varepsilon \cdot \left(T_1{}^4 - T_2{}^4\right)$$

$Q_{rad} = 5.16 * 10^{-8} * (T_1^4 - T_2^4)$ W/m²

$$q = -5.161 \frac{\text{watt}}{\text{m}^2}$$

Radiant heat transfer coefficient linearized for buildings

- The pure radiative heat exchange equation
  - Not very handy
  - Simplify, linearize
- Use algebraic simplification

$$q := \sigma \cdot \varepsilon \cdot \left(T_1^{\,4} - T_2^{\,4}\right)$$

$$\left(T_1^{\,4} - T_2^{\,4}\right) = \left(T_1^{\,2} + T_2^{\,2}\right) \cdot \left(T_1^{\,2} - T_2^{\,2}\right)$$

$$\left(T_1^{\,4} - T_2^{\,4}\right) = \left(T_1^{\,2} + T_2^{\,2}\right) \cdot \left(T_1 + T_2\right) \cdot \left(T_1 - T_2\right)$$

Let us admit that T1 and T2 are almost equal (295 K and 275K), then (T1+T2)/2 = Tavg

$$T_{avg} := \frac{\left(T_1 + T_2\right)}{2}$$

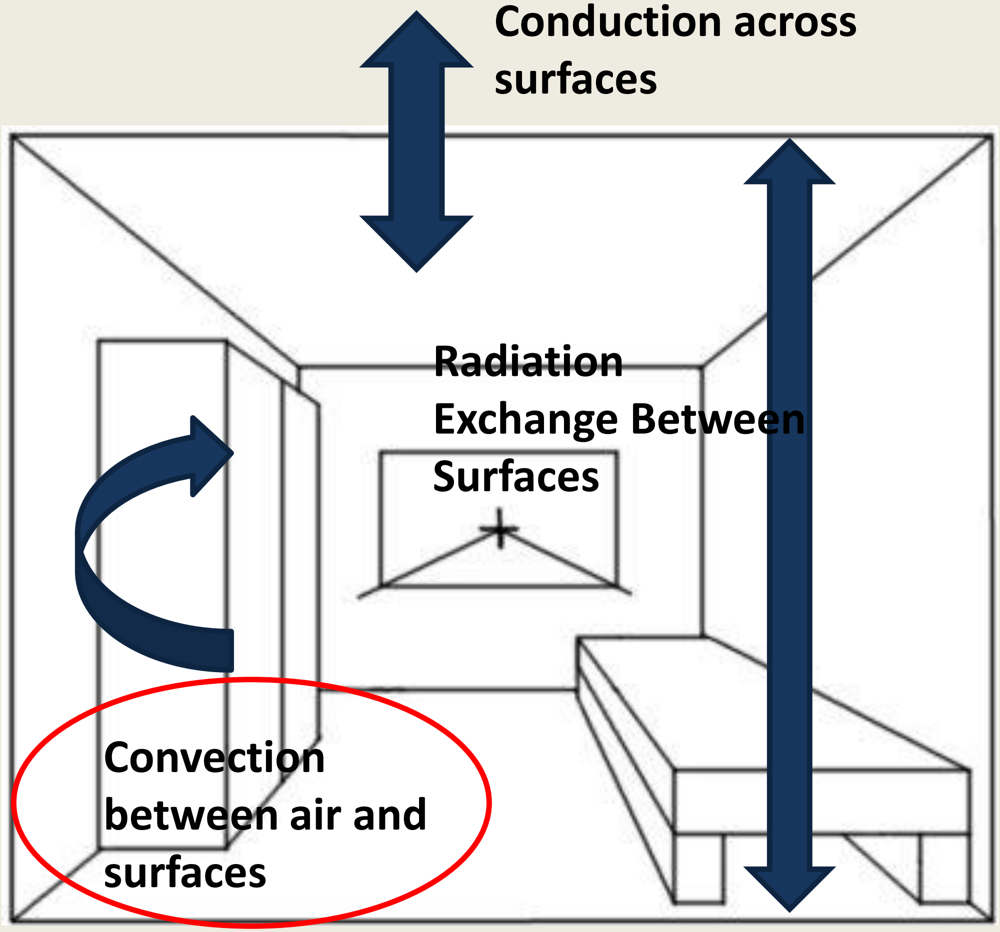
$$\left(T_1^{\,4} - T_2^{\,4}\right) = \left(T_{avg}^{\,2} + T_{avg}^{\,2}\right) \cdot \left(T_{avg} + T_{avg}\right) \cdot \left(T_1 - T_2\right)$$

$$q_{lin} := 4 \cdot \left(\sigma \cdot \varepsilon \cdot T_{avg}^{\,3}\right) \cdot \left(T_1 - T_2\right)$$

$Q_{rad\ lin} = 5.16 * (T_1 - T_2)$ W/m²

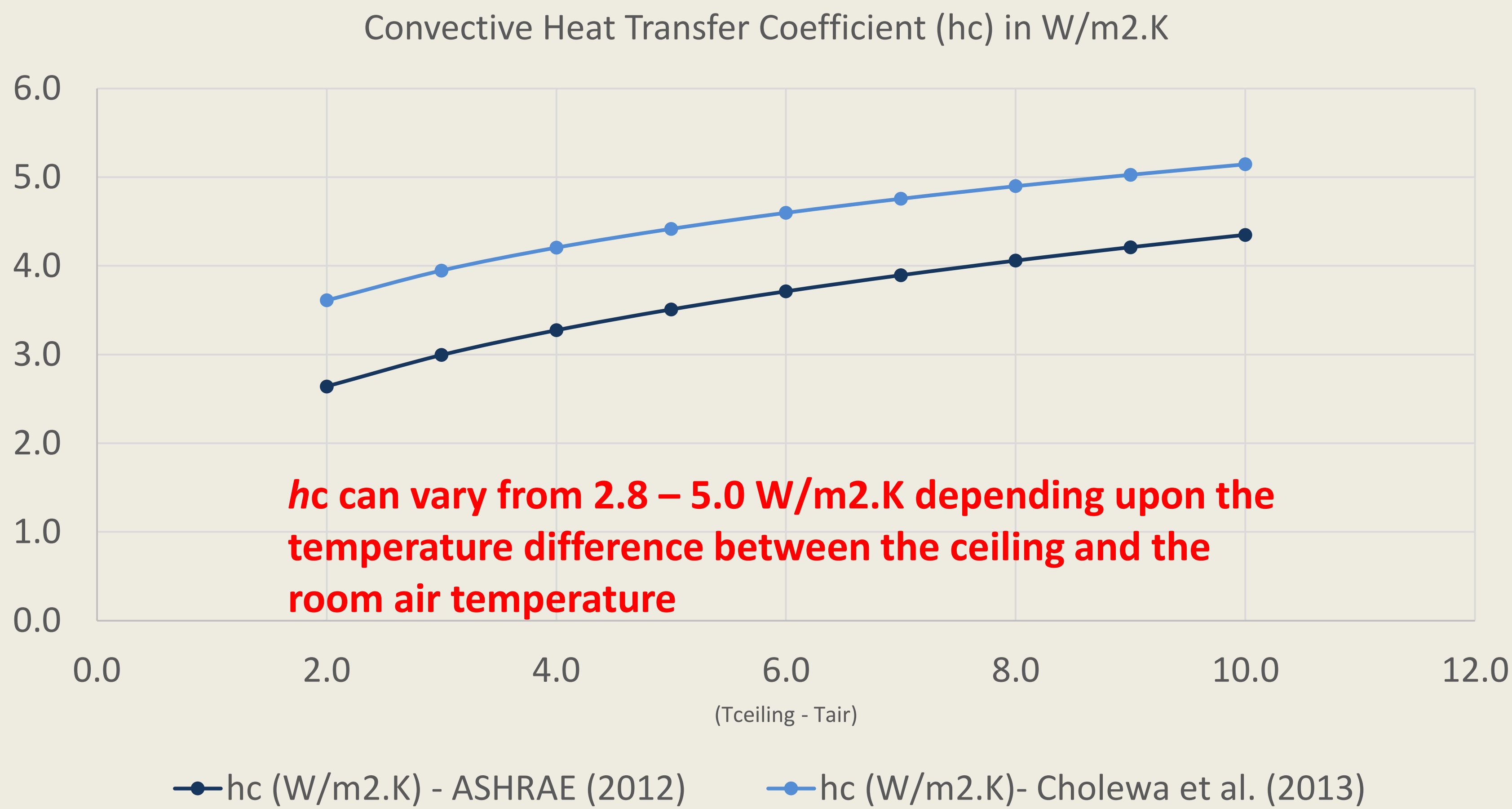
$h_r \sim 5.16$ W/m².K

Modes of Heat Transfer



Convection is heat transfer by mass motion of a fluid such as air or water when the heated fluid is caused to move away from the source of heat, carrying energy with it.

Natural convective heat transfer coefficient for cold ceiling (without air movement)



hc **can vary from 2.8 – 5.0 W/m2.K depending upon the temperature difference between the ceiling and the room air temperature**

Increase of the heat transfer at the ceiling by air movement (ceiling fans)

- Increased heat transfer coefficient by air movement
  - Ceiling
  - ~1.0 m/sec at ceiling level → h_c increased from 2.8 to ~5.8 W/m_2-K

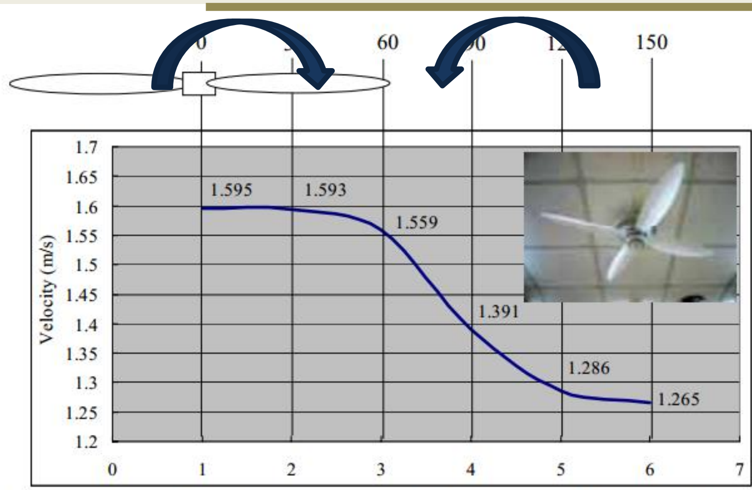


Figure 2. Profile of mean air velocity generated by the studied ceiling fan at height 150cm (fan was set at medium rotation speed)

Watmuff et al. (1977) report that this equation should be

$$h = 2.8 + 3.0V$$

SOLAR ENGINEERING OF THERMAL PROCESSES

Second Edition

JOHN A. DUFFIE
Emeritus Professor of Chemical Engineering

WILLIAM A. BECKMAN
Professor of Mechanical Engineering
Solar Energy Laboratory
University of Wisconsin-Madison

Conclusions – Heat Transfer Coefficients for radiant cooling systems

- Typical radiative heat transfer coefficient h_r ~ 5.1 W/m^2.K
- Typical natural convection heat transfer coefficient h_c ~ 2.8 -5.8 W/m^2.K.
- Combined heat transfer coefficient (h_r +h_c) ranges from ~ 8-11 W/m^2.K.

Heat Transfer Basics

Human Body Heat Exchange

Radiant Cooling – Basics

Radiant Cooling – Suitability ?

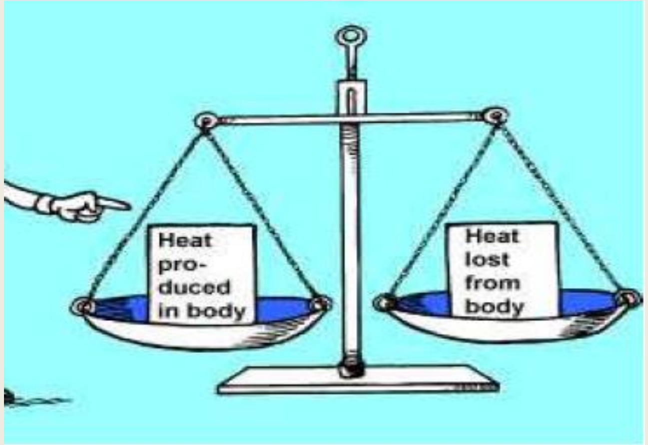
Radiant Cooling - Benefits

Conclusions

HUMAN BODY - HEAT GENERATION

- Humans are exothermic heat generators
- Degree of heat generation depends on activities we do like sitting, standing, walking etc.
- If Heat generated > heat loss , then we feel heating of body, sweat formation starts
- If Heat generated < heat loss , then we feel cooling of the body, starts shivering

If **HEAT GENERATED** = **HEAT LOSS**, known as thermal neutrality. It is also called as THERMAL COMFORT when the conditions are stable and agreable



HUMAN BODY – ENERGY BALANCE

- Heat generated = M – W

    Where **M = metabolic rate**

    W = rate of mechanical work accomplished

- Heat loss = $Q_{sk} + Q_{res}$

    Where Q_{sk} **= rate of heat loss through skin**

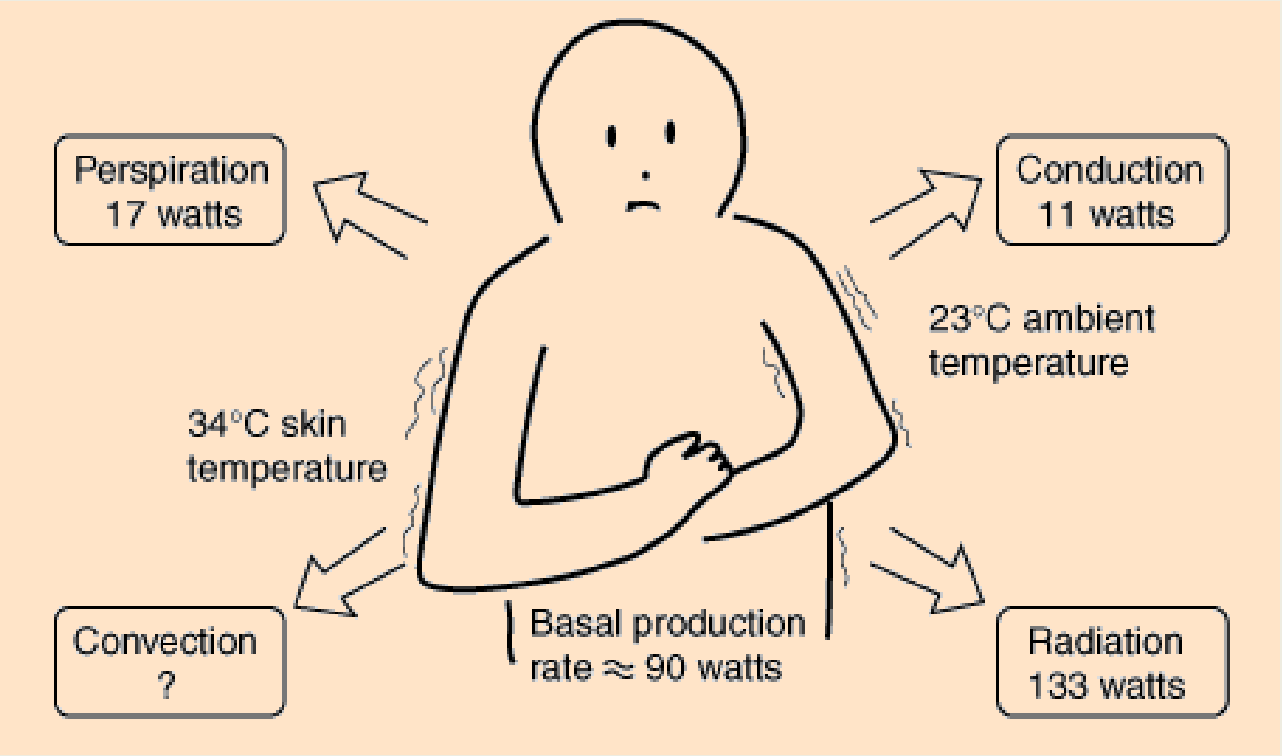
    Q_{res} **= rate of heat loss through respiration**

$$M - W = Q_{sk} + Q_{res}$$ (neglecting body heat storage)

- **Heat loss from skin (Q_{sk}) = Radiation + Convection + Evaporation + Conduction**

Source: ASHRAE Handbook _2009

Cooling of the Human Body – Radiation Heat Transfer Dominated



An adult male (naked), losses most of the heat through radiation (133 W) > Base metabolic rate (90 W) and hence the person will feel cold.

http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/coobod.html#c1

HEAT LOSSES OF THE HUMAN BODY – HAND CALCULATIONS

T_{skin} [°C] = 34

$T_{ambient}$ [°C] = 23

velocity [m/sec] = 0.1

$Area_{skin}$ [m^2] = 1.7

emissivity = 0.97

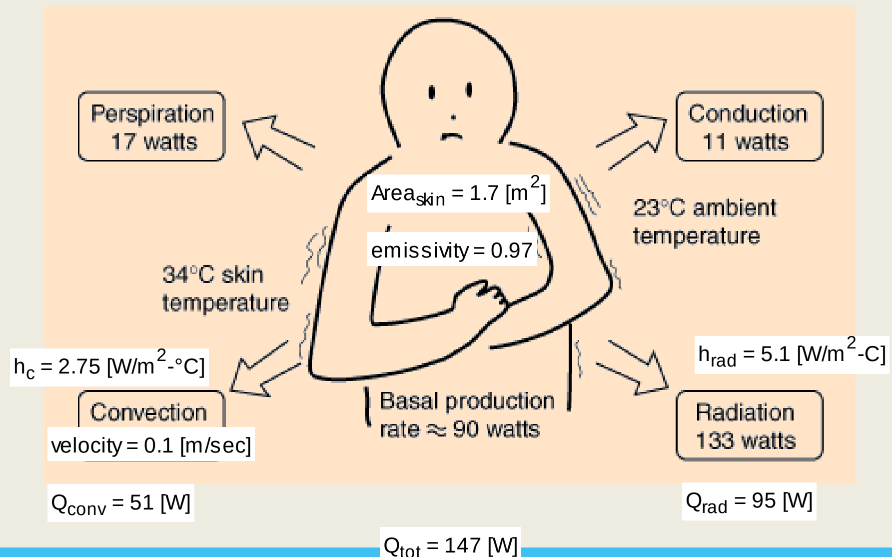
h_{rad} [W/m^2-C] = 5.1

h_c [W/m^2-°C] = 2.75

$$Q_{rad}\ [W] = h_{rad}\ [W/m^2\text{-}C] \cdot Area_{skin}\ [m^2] \cdot (T_{skin}\ [°C] - T_{ambient}\ [°C])$$

$$Q_{conv}\ [W] = h_c\ [W/m^2\text{-}°C] \cdot Area_{skin}\ [m^2] \cdot (T_{skin}\ [°C] - T_{ambient}\ [°C])$$

$$Q_{tot}\ [W] = Q_{rad}\ [W] + Q_{conv}\ [W]$$

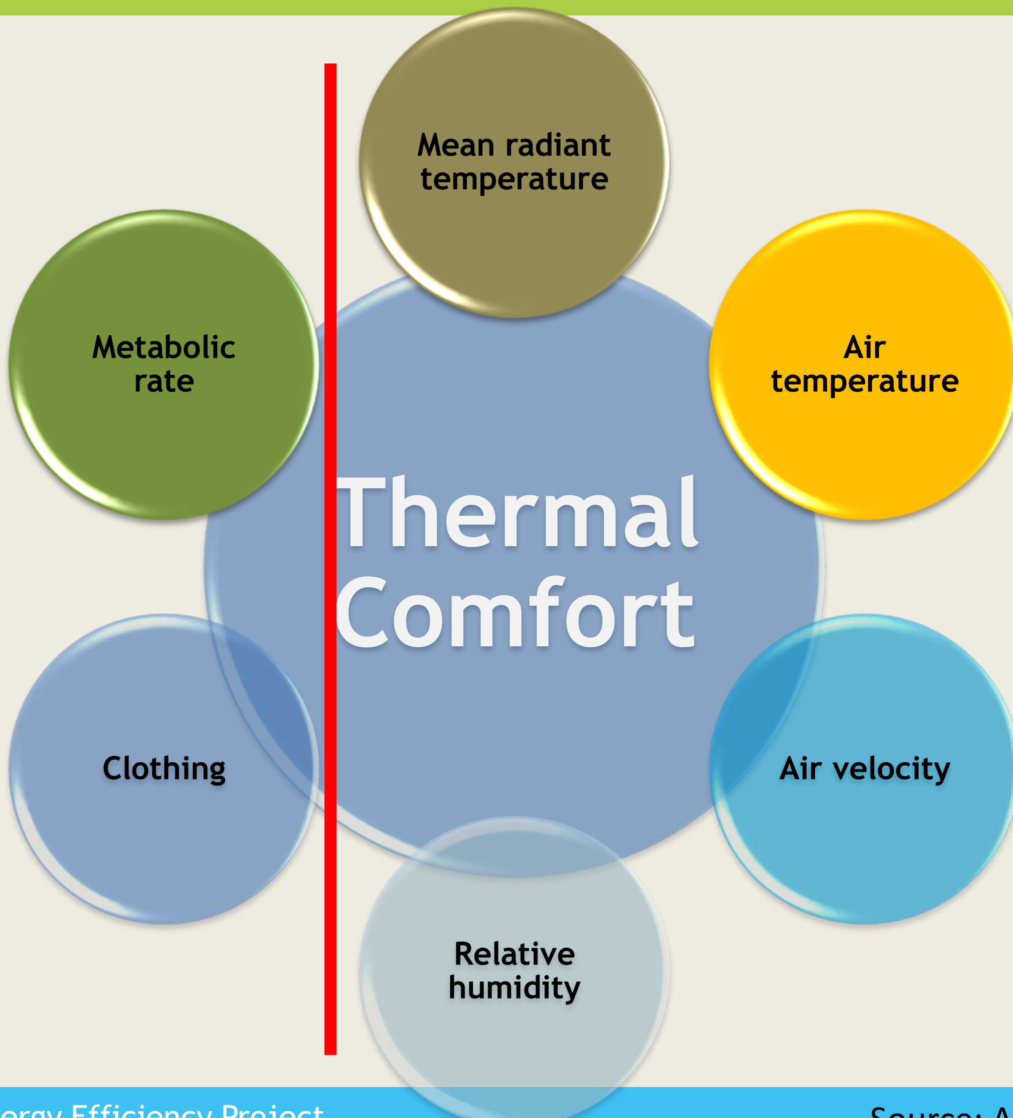


Heat loss from human body – Dominant heat transfer modes

- **Radiation**
- **Convection**
- Evaporation of sweat
  - Sweat forms when heat loss << heat generation.
  - Least probability of happening in conditioned spaces
- Conduction: Very less contribution

Factors influencing Thermal Comfort

Personal Factors



Environmental Factors

Source: ASHRAE Handbook _2009

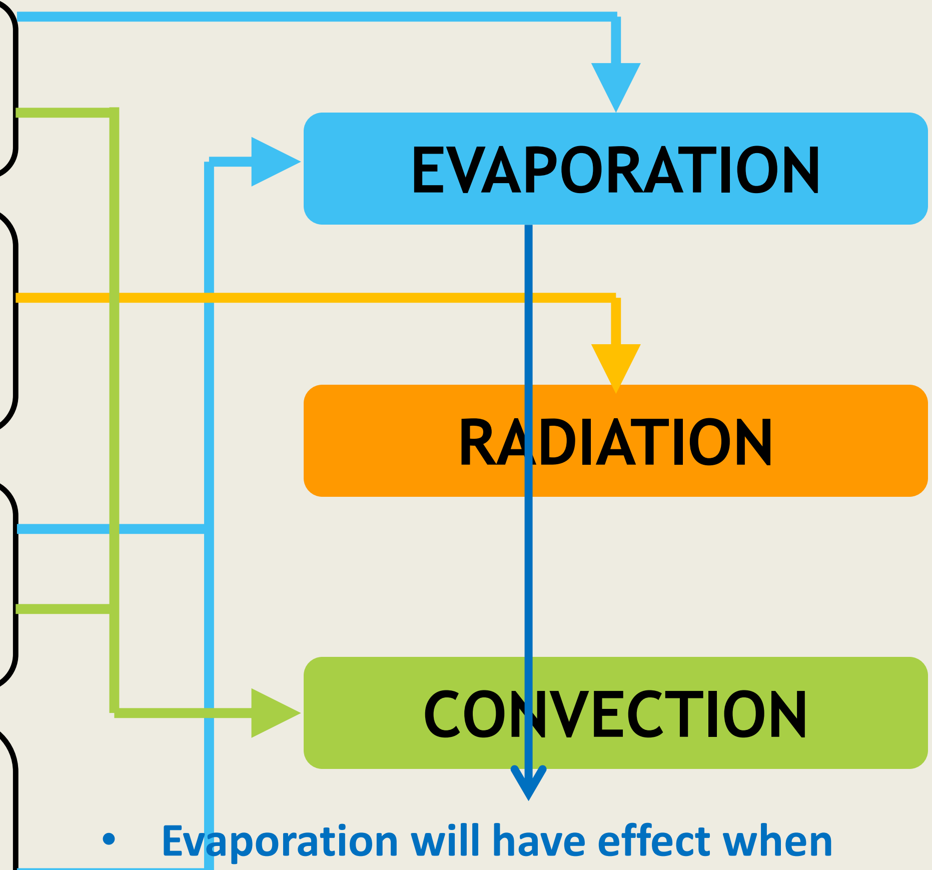
Factors influencing Thermal Comfort: Environmental Factors

Air Temperature:
Temperature of the air surrounding the body.

Mean Radiant Temperature:
Weighted average of the temperatures of all the surfaces in direct line of sight of the body.

Air Movement:
Average speed of the air to which the body is exposed.

Humidity:
Amount of water vapor in a given space. The amount of moisture that air can hold is a function of the temperature.



- **Evaporation will have effect when sweating happens**
- **Sweating happens if heat generated is not lost by radiation and convection**

Conclusions – Human body heat exchange

Maintaining lower indoor surface temperatures

↓

Enhance radiant heat exchange between human body and indoor surfaces – The central idea of radiative cooling

Heat Transfer Basics

Human Body Heat Exchange

Radiant Cooling – Basics

Radiant Cooling – Suitability ?

Radiant Cooling - Benefits

Conclusions

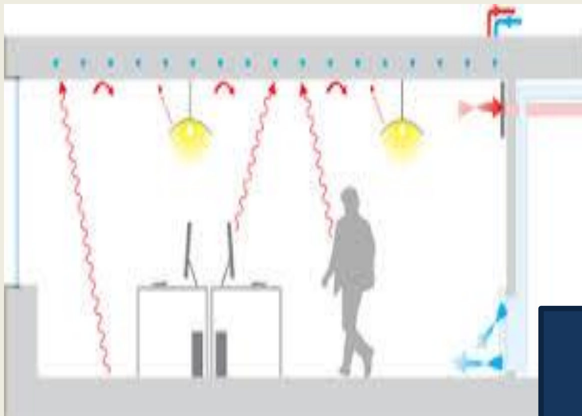
OLD PRACTICES: HIGH THERMAL MASS BUILDINGS

- Uses thermal mass to keep the indoor surface temperatures at lower level



New practices: Radiant cooling structures

- Structure integrated cooling systems



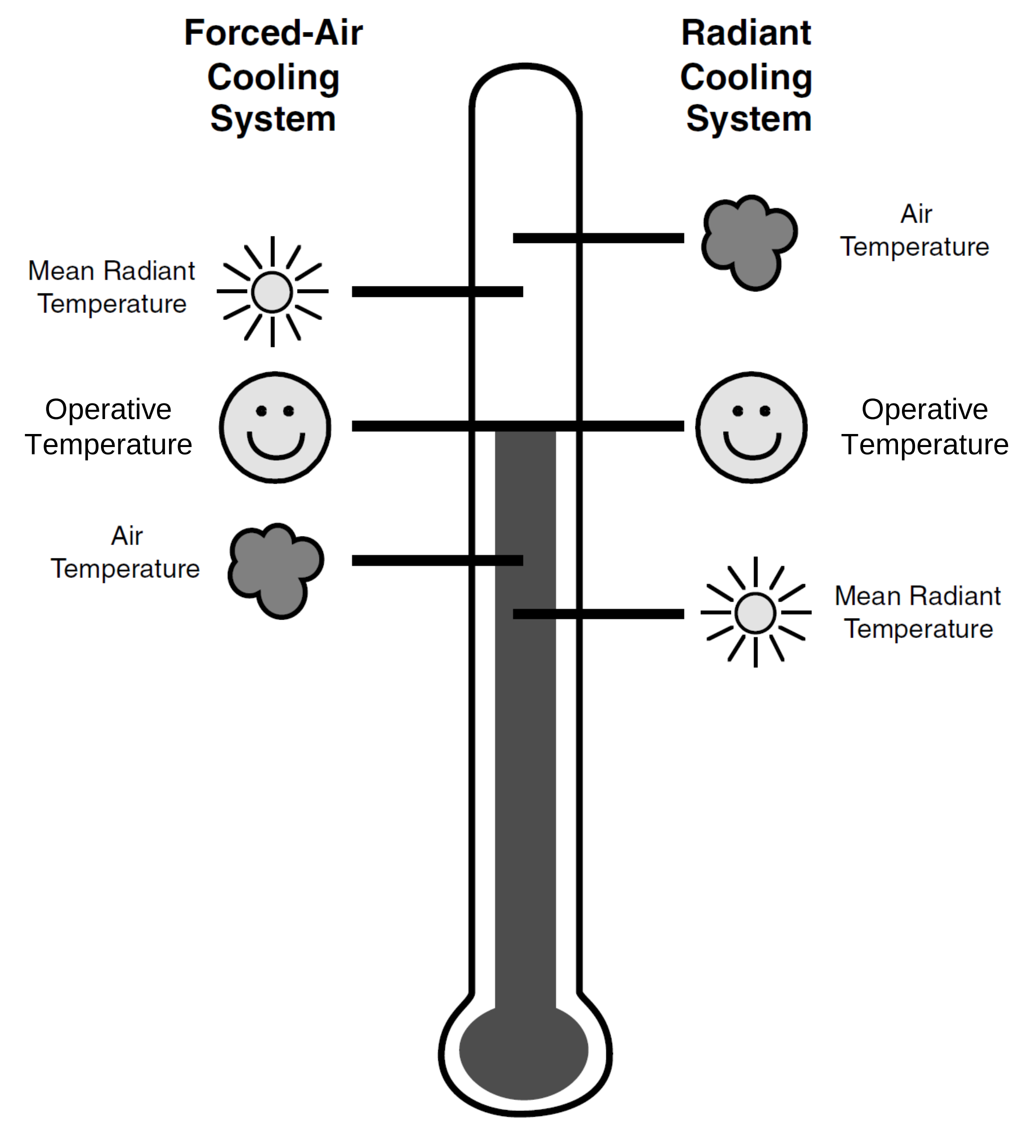
Supply of chilled water

- Panel cooling systems

Radiant cooling – Basics

- An actively controlled surface is considered a "radiant system" if <u>at least 50% of the design heat transfer</u> is by thermal radiation (2004 ASHRAE Handbook)
- Radiant cooling is <u>often part of a hybrid system</u> that includes conditioning of ventilation air to address internal latent loads (humidity) from occupants and infiltration, plus sensible and latent loads associated with outside ventilation air.

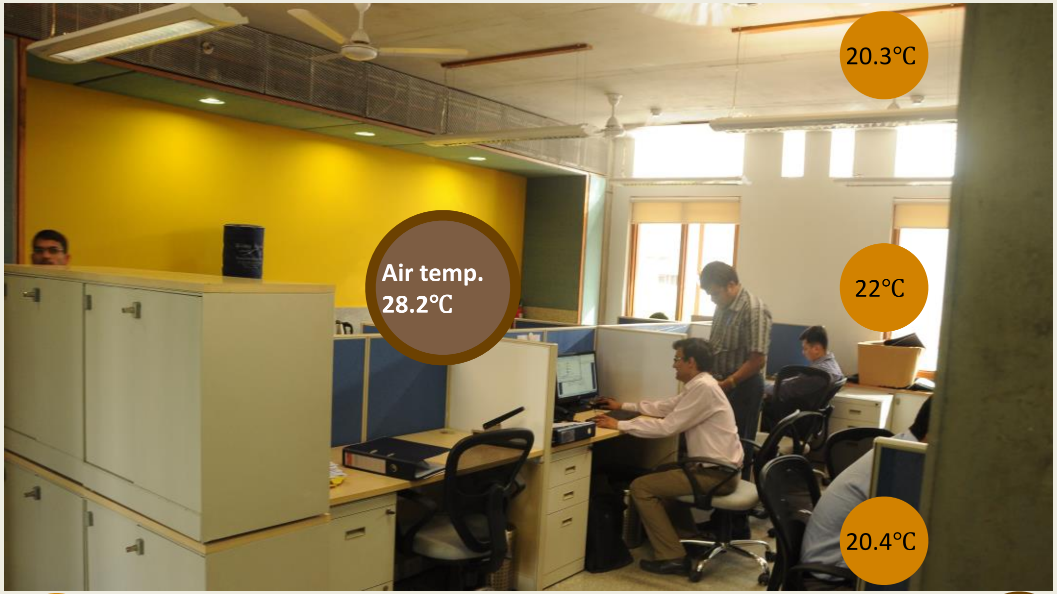
RADIANT COOLING – BASICS



With Radiant cooling, comfort conditions can be maintained with higher air temperature as compared to forced air cooling system.

Source: Radiant Cooling and Heating Handbook (Richard D Watson, Kirby S Chapman)

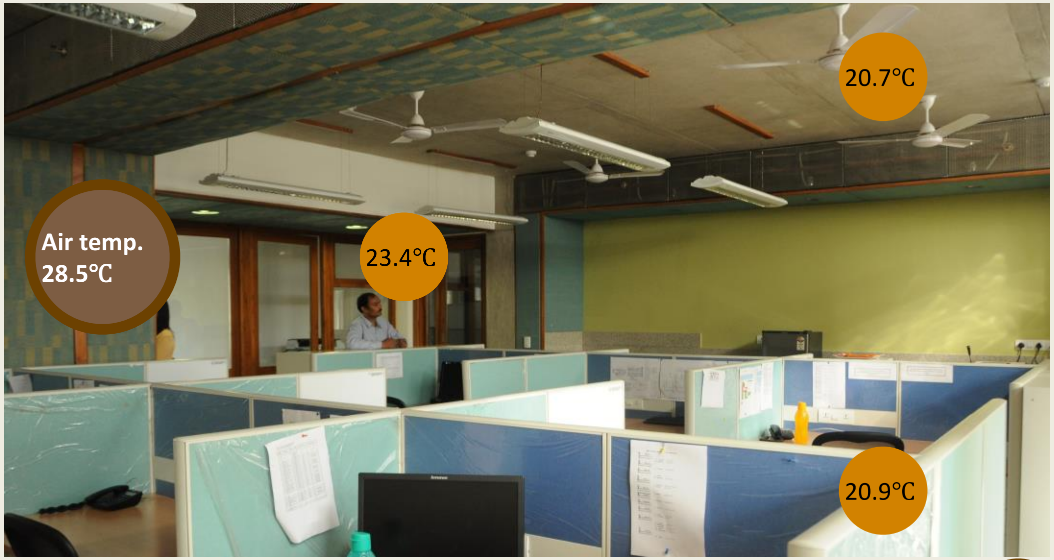
INTERIORS AND TEMPERATURE ANALYSIS : FIRST FLOOR



Surface temperature of Wall, Floor and Ceiling

Air temperature

INTERIORS AND TEMPERATURE ANALYSIS : SECOND FLOOR



Surface temperature of Wall, Floor and Ceiling

Air temperature

Heat Transfer Basics

Human Body Heat Exchange

Radiative Cooling – Basics

Radiant Cooling – Suitability ?

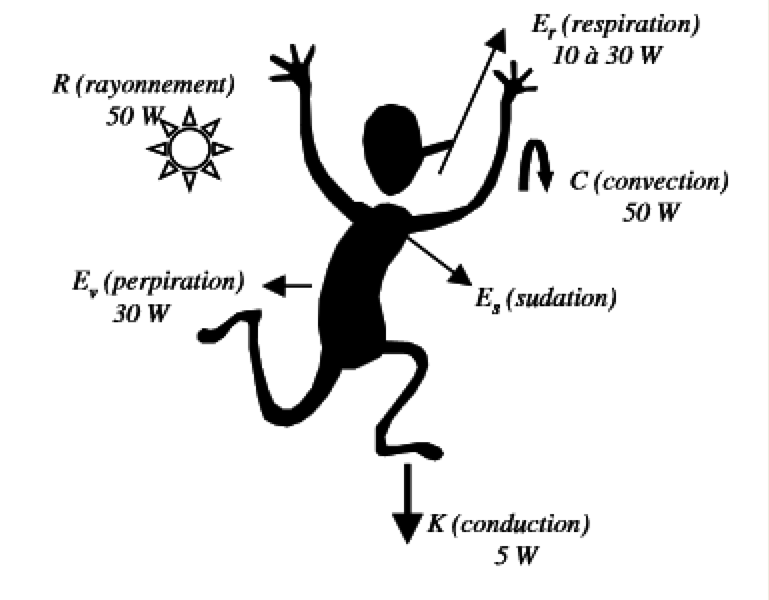
Radiant Cooling - Benefits

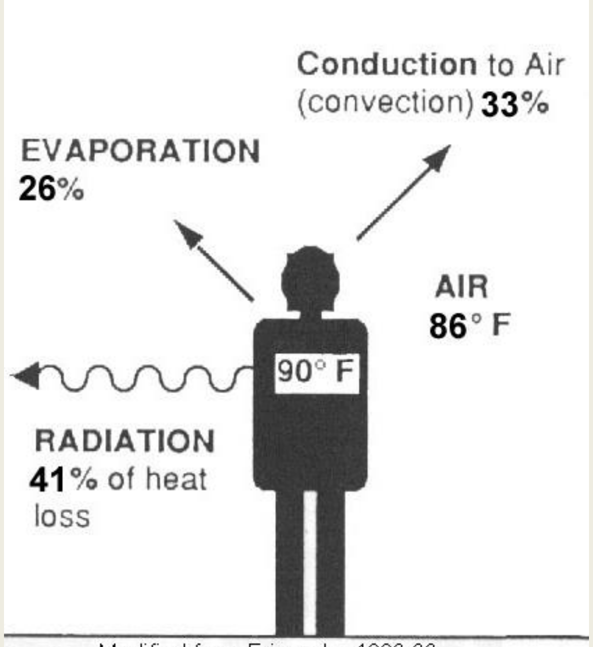
Conclusions

Nature of office thermal loads – humans and equipment

HUMANS – THERMAL LOAD

- ~ 50 % radiative /50 % convective





Modified from Frisancho 1993:33

Equipment Thermal Loads

- About 75% convective
- ~25% radiative

SE-99-1-4 (RP-1055)

Experimental Results for Heat Gain and Radiant/Convective Split from Equipment in Buildings

Mohammad H. Hosni, Ph.D.
Member ASHRAE

Byron W. Jones, Ph.D.
Member ASHRAE

Hanming Xu
Student Member ASHRAE

TABLE 1
Office Equipment

Equipment	Description	Name-plate*** (W)	Idle Mode - Power Consumption (W)				Operational Mode - Power Consumption (W)				Fan	Usage
			Peak	Average	Radiant	Convective	Peak	Average	Radiant	Convective		
Computer and Monitor	Gateway 2000, Pentium-200 Monitor: Gateway 17"	N/A 220	110	51	12 (24%)	39 (76%)	108	98	27 (27%)	71 (73%)	Y N	Continuous
Computer and Monitor**	Pentium-200 17" monitor	575						133	30 (22%)	103 (78%)	Y N	Continuous
Computer and Monitor**	486DX33 15"monitor	420						125	36 (29%)	89 (71%)	Y N	Continuous
Computer and Monitor	Dell Pentium-333 Monitor: Dell 19"	N/A 207	111	110	22 (20%)	88 (80%)	132	130	31 (24%)	99 (76%)	Y N	Continuous

ACTUAL OFFICE EQUIPMENT HEAT GAINS

- Usually power consumption in office eqpts much less than the name plate
- Real measured values to be used for large projects
- If not then oversizing and wrong ratio radiative/convective

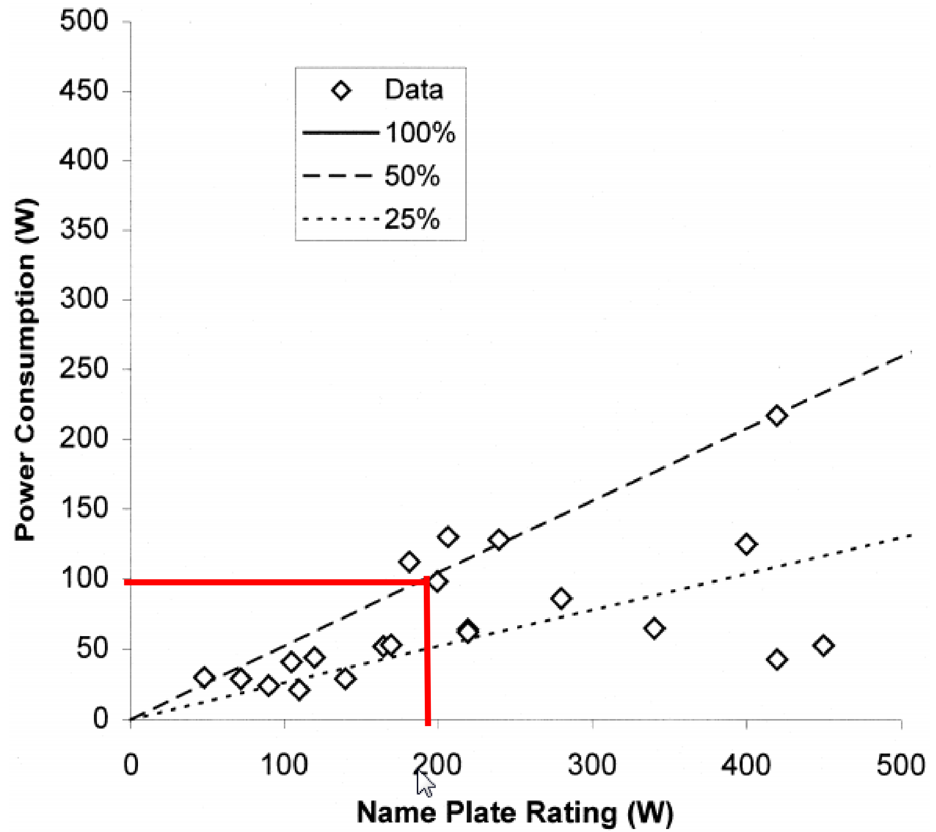
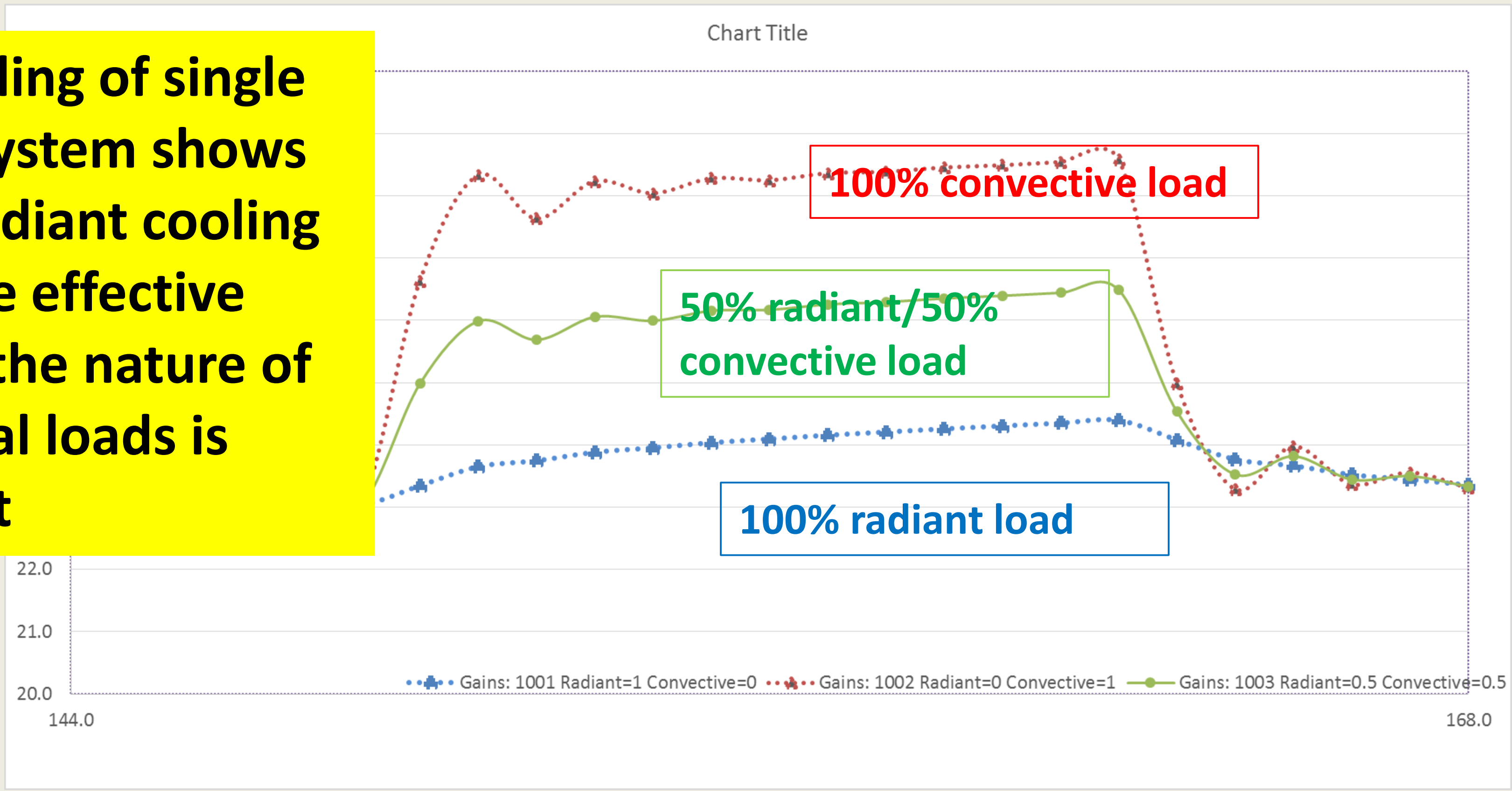


Figure 2b *Power consumption with continuous operation, office equipment.*

Is radiant cooling the universal solution for cooling ? Load typology and air temperature control

Influence of the radiative/convective distribution on the temperature profile with time over 24 hr

Modelling of single zone system shows that radiant cooling is more effective when the nature of thermal loads is radiant



Suitability & Applications

Applicable:

- Anywhere sensible loads are more dominant than latent loads
- where indoor humidity control is possible
  - Laboratories
  - Office buildings
  - Educational facilities
  - Healthcare facilities
  - Government facilities

Not applicable:

- Where space sensible loads are not dominant
- Where indoor humidity control is not possible
  - Kitchens
  - Bathrooms
  - Toilets

Precaution to be taken to avoid condensation

- Building air tightness (no infiltration) – positive air operation

Heat Transfer Basics

Human Body Heat Exchange

Radiative Cooling – Basics

Radiative Cooling – Suitability ?

Radiative Cooling - Benefits

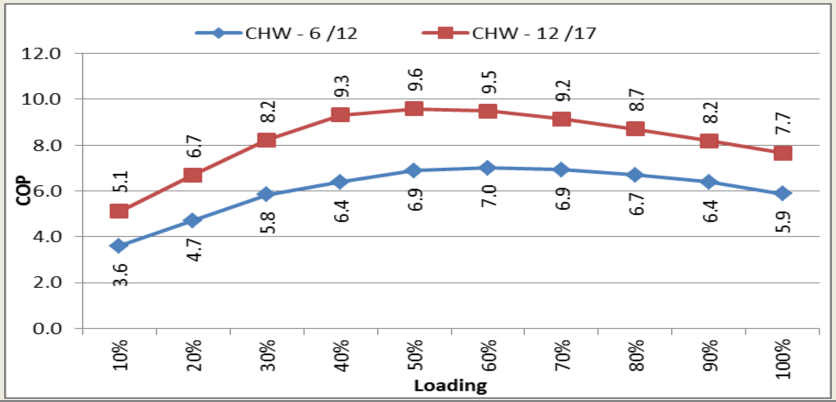
Conclusions

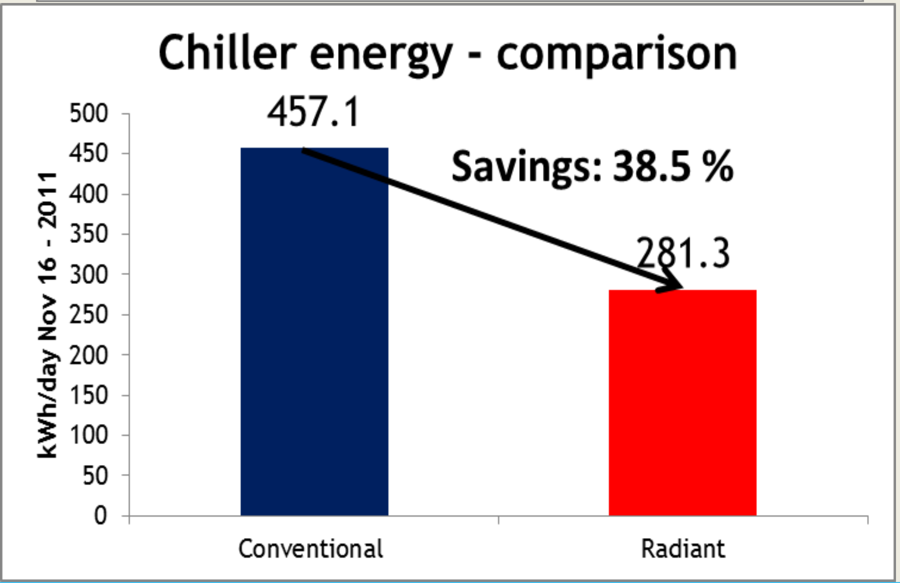
Conventional vs Radiant systems

No	Parameter	Air systems	Radiant cooling
1	Space cooling medium	Air (Sensible + Latent load)	Radiant system (Sensible load) + D O A S (Latent load)
2	Chilled water supply temperature	**5 - 9 ^{0} C**	**Radiant system: 14 - 18 ^{0} C** **D O A S: 5 - 9 ^{0} C**
Operative temperature = 25 ^{0} C			
3	Space air temperature	22 – 24 ^{0} C	26 – 28 ^{0} C
4	Surface mean radiant temperature	26 – 28 ^{0} C	22 – 24 ^{0} C
5	Air quantity handled by fan	(Recirculated + Fresh) air	Only fresh air – D O A S

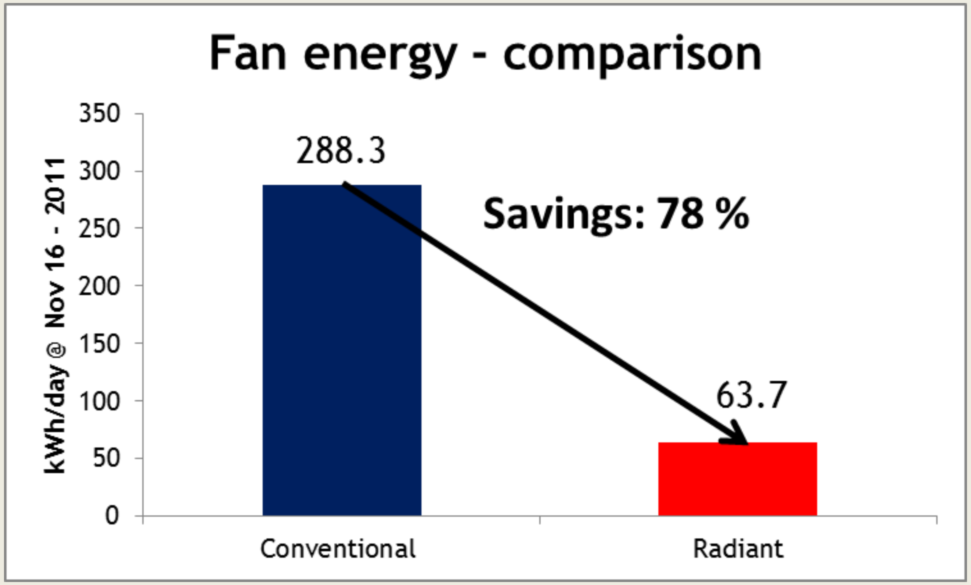
ENERGY BENEFITS

- Chiller energy savings





- Fan energy savings
  - No recirculation of indoor space air



Source: Infosys_Technicalpaper_Guruprakash sastry

Other benefits

- Better IEQ (Indoor Environment Quality)
  - Less noise due to less draft
  - Even temperature distribution
- Space savings per floor (reduction in mechanical rooms space)
- less floor to floor height (no change in ceiling to floor height), implies reduction in building wall material usage

Introduction of Radiant Cooling – Topics Covered

Heat Transfer Basics
Human Body Heat Exchange
Radiative Cooling – Basics
Radiative Cooling – Suitability ?
Radiative Cooling - Benefits

THANK YOU