Energy Savings by Treating Buildings as Systems

L.D. Danny Harvey
Department of Geography
University of Toronto

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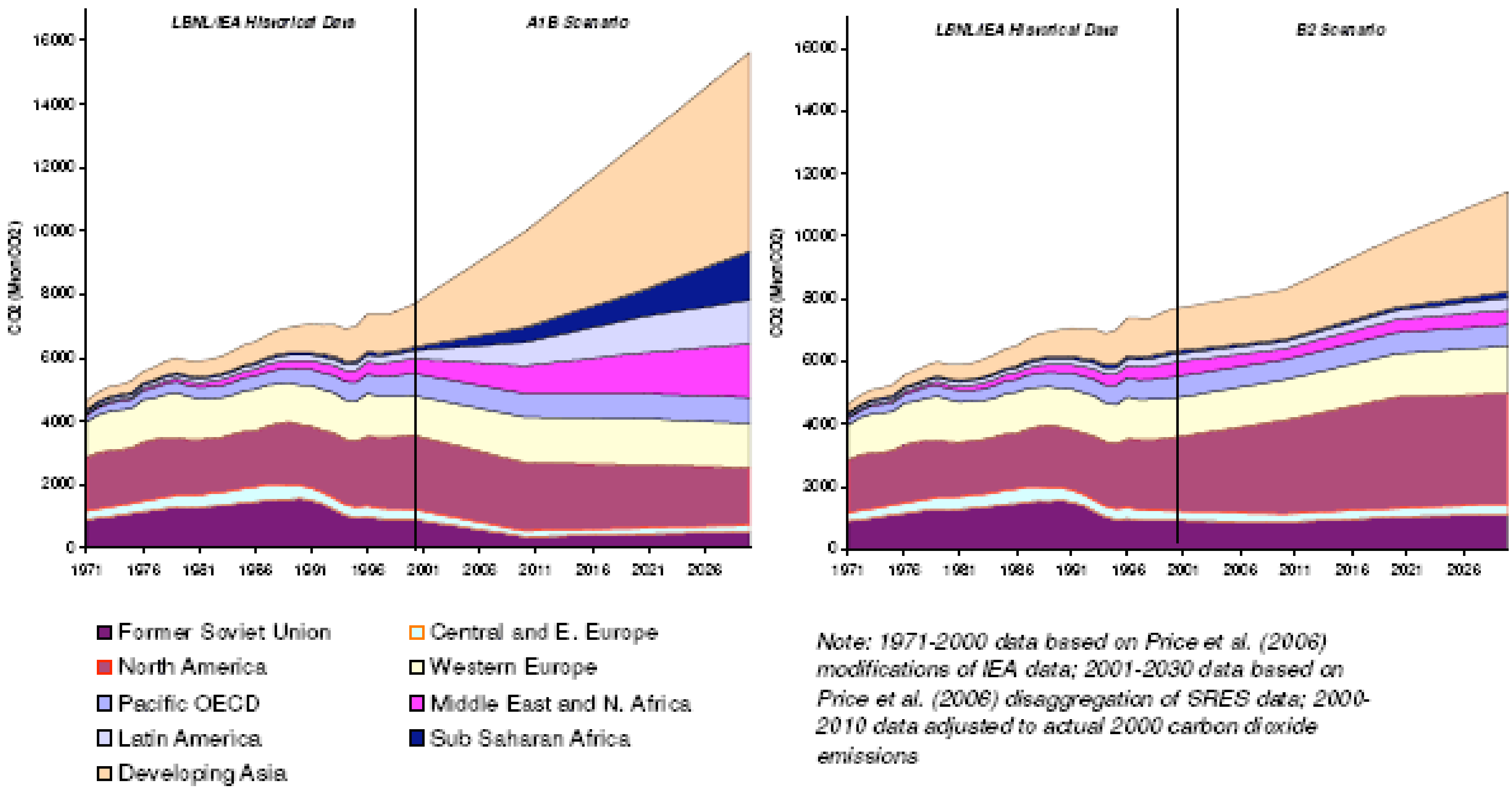
Human-Induced Climatic Change Poses a Grave Threat to the Well-being of the Human Race, and the Greatest Threat to Life on Planet Earth since the last major extinction event 60 million years ago

- Extinction of 1/3 to 2/3 of species of life, with unpredictable consequences
- Acidification of the oceans due to absorption of CO_2, with unpredictable but surely highly negative consequences
- An eventual sea level rise of 12 m or more
- Loss of agricultural productivity in many regions
- Loss of water resources in areas where water is already scarce or that depend on disappearing glaciers or winter snow accumulation (1/4 of China’s population, for example)

Buildings account for about 1/3 of OECD energy-related GHG emissions, and their emissions are growing in absolute terms

Trends in Building-related CO_2 Emissions



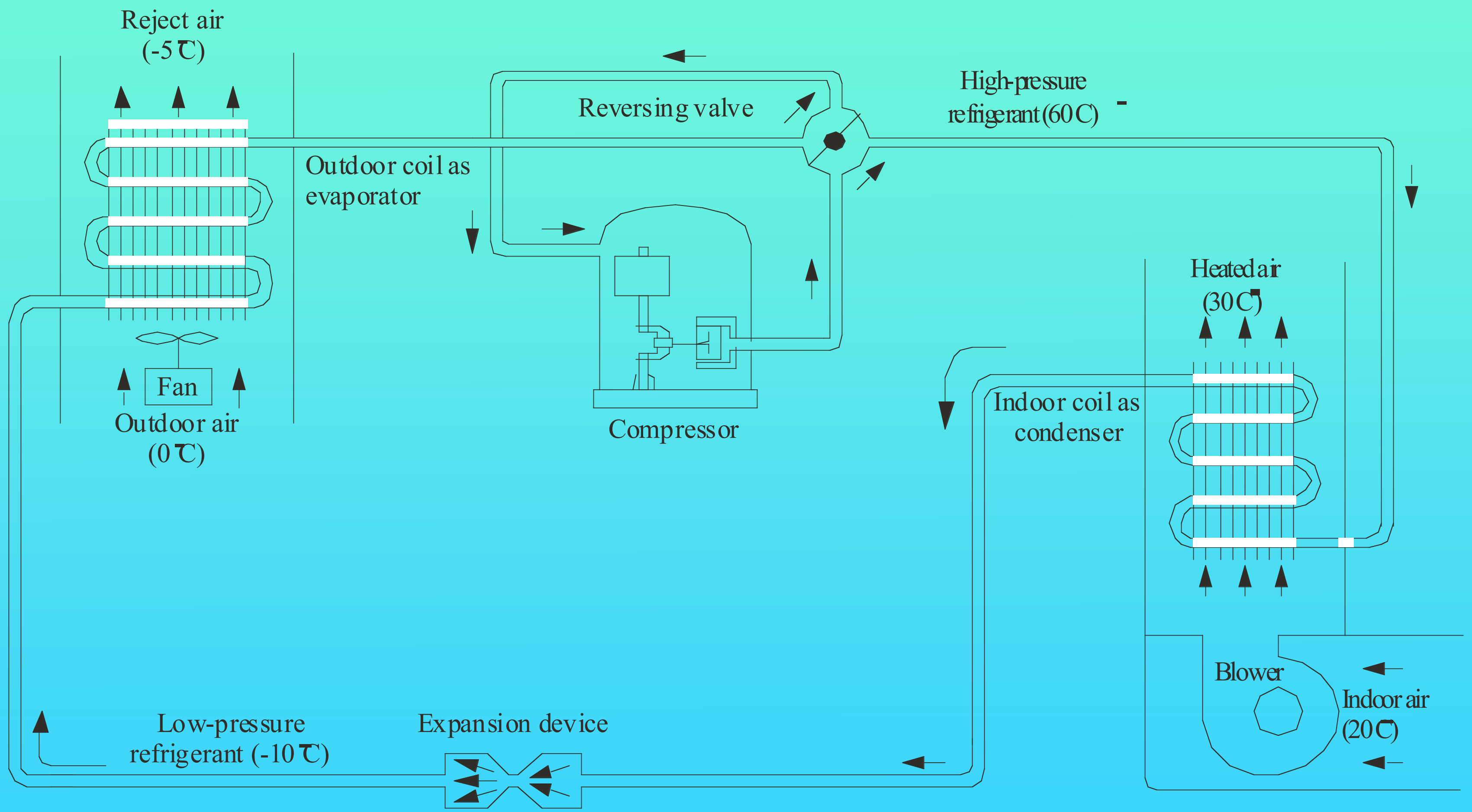
Note: 1971-2000 data based on Price et al. (2006) modifications of IEA data; 2001-2030 data based on Price et al. (2006) disaggregation of SRES data; 2000-2010 data adjusted to actual 2000 carbon dioxide emissions

The main purpose of this presentation is to show how the energy use of buildings depends to a significant extent on how the various energy-using devices (pumps, motors, fans, heaters, chillers, and so on) are put together as systems, rather than depending on the efficiencies of the individual devices. In particular, the savings opportunities at the system level are generally many times what can be achieved at the device level (and these system-level savings can often be achieved at a net investment- cost savings)

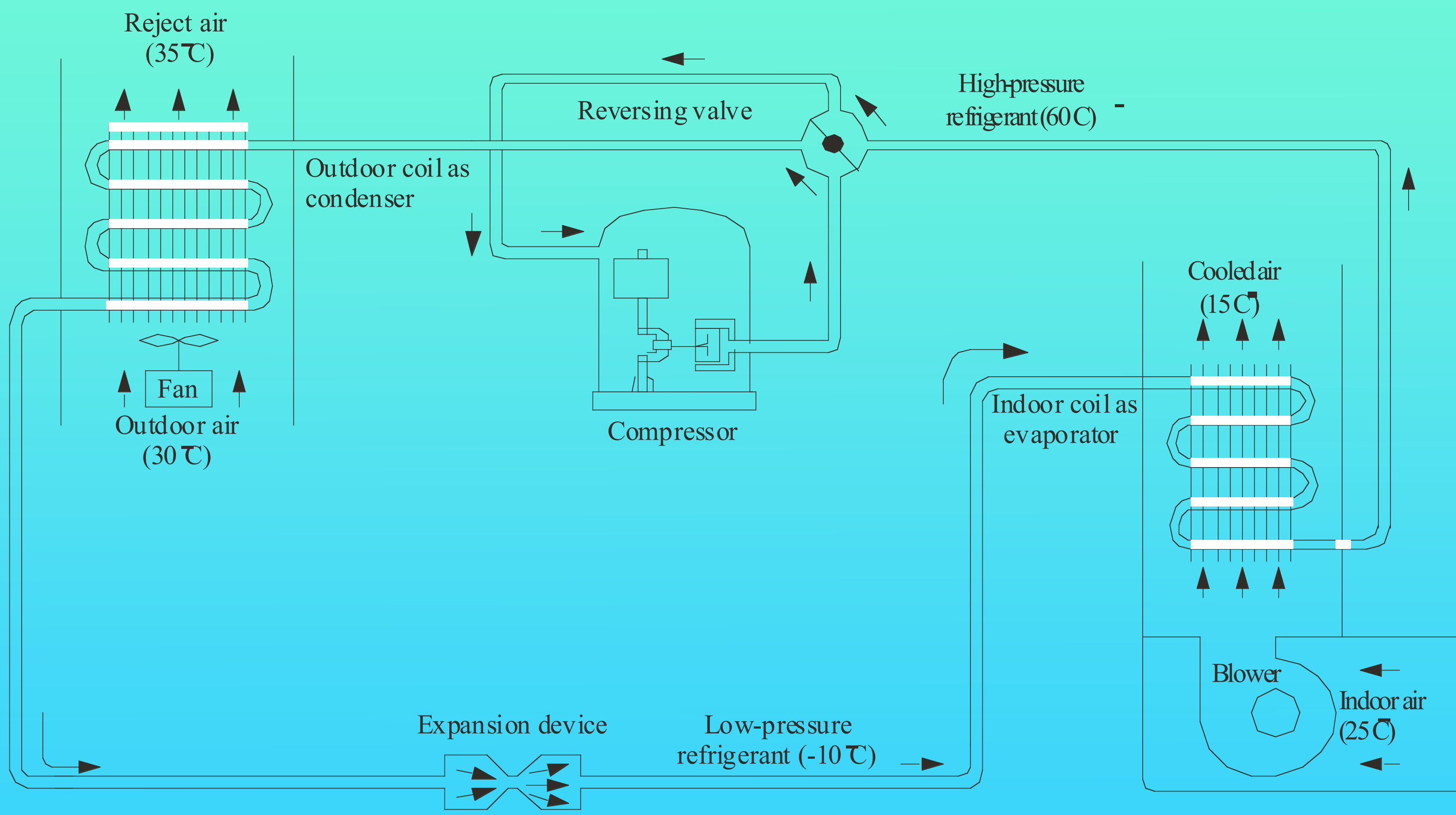
Heat Pump, Operating Principles

- Overall transfer of heat from *cold to warm* (against the macro temperature gradient)
- At each point in the system, heat flow is from warm to cold
- Relies on the fact that a gas cools when it expands, and is heated when it is compressed, to create local temperature gradients contrary to the macro-gradient

(a) Heating Mode



(b) Cooling Mode



Heat Pump, Efficiency Principles

- The ratio of heat delivered to energy input is called the *coefficient of performance (COP)*
- The *maximum possible* COP (called the *Carnot cycle COP*) is related to the temperature lift, T_H-T_L, T_H=condenser T and T_L=evaporator T

$$COP_{cooling,Carnot} = T_L/(T_H-T_L)$$

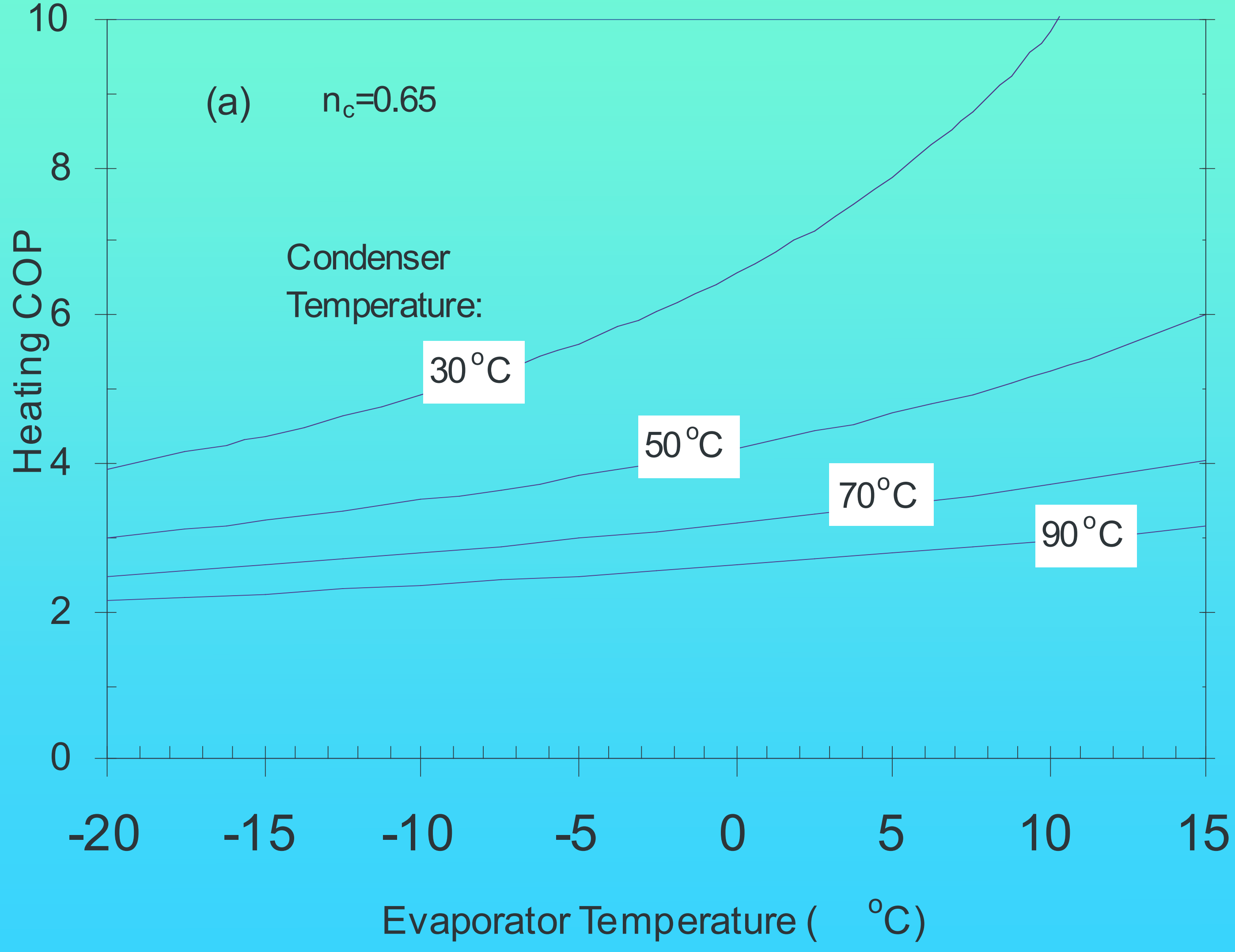
$$COP_{heating,Carnot} = T_L/(T_H-T_L)+1.0$$

- The actual COP is given by

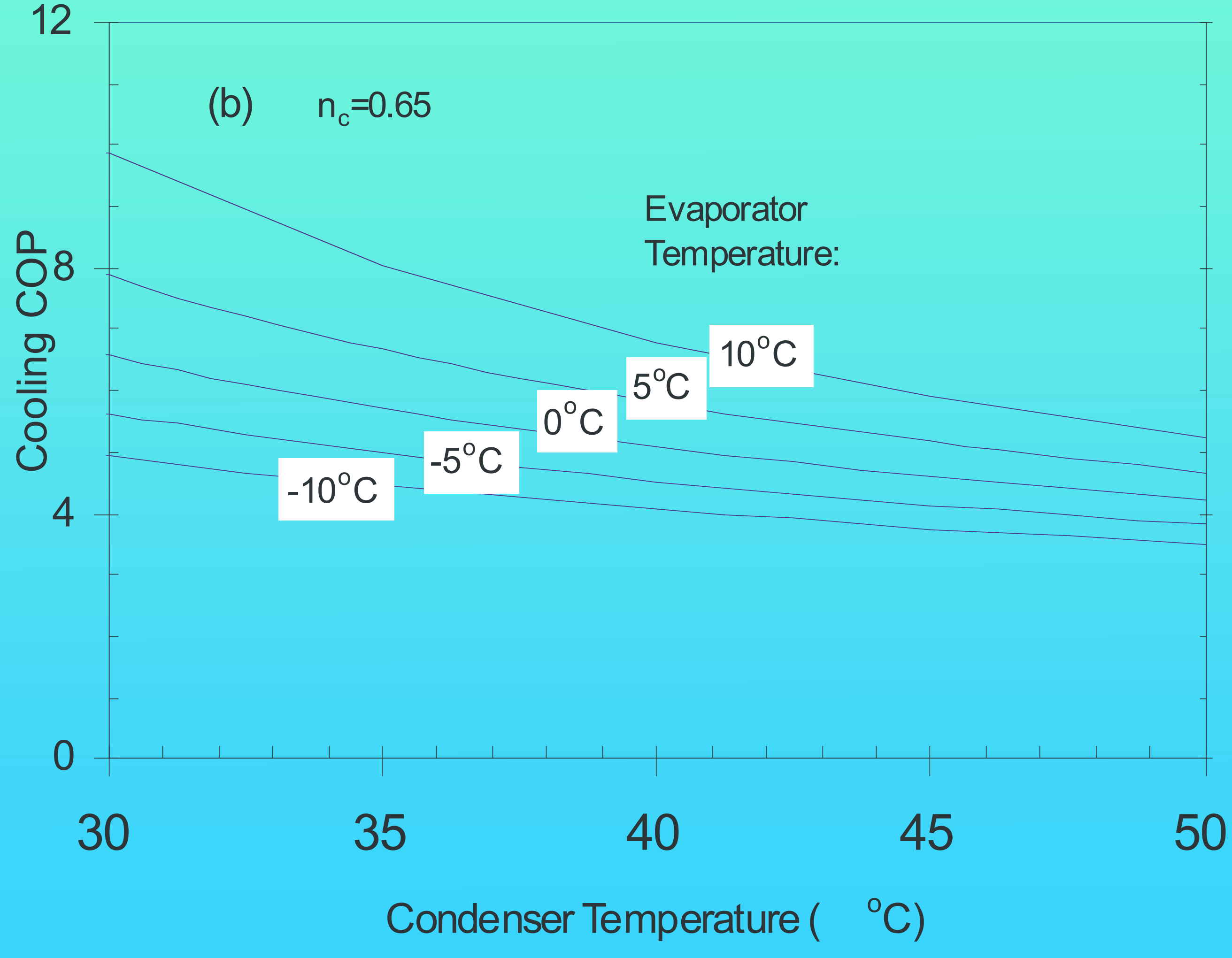
$$COP_{cooling,\ real} = \eta_c\,(T_L/(T_H-T_L))$$

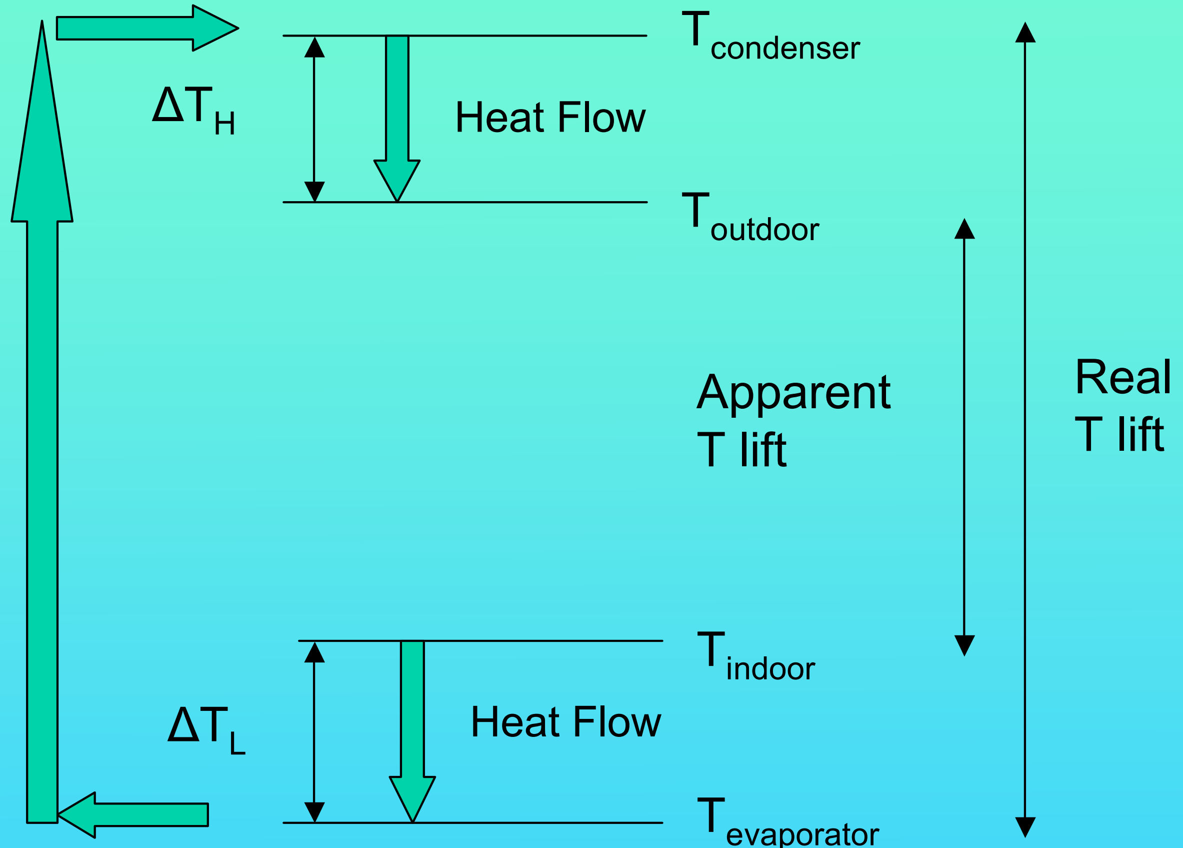
where η_c is the Carnot efficiency

Heat Pump COP in heating mode



Heat Pump COP in Cooling Mode (or chiller COP)





If $T_{condenser}$= 40°C
$T_{outdoor}$= 30°C
T_{indoor}= 16°C
$T_{evaporator}$ =6°C,

then

Apparent Carnot
COP = **20.6**

Real Carnot
COP= **8.5**

Actual COP= **5.53**
if Carnot efficiency
= 0.65

Thus, to reduce heat pump energy use,

- Distribute heat at the lowest possible temperature (e.g., at 30°C instead of 60°C – using radiant floor heating or radiant ceiling)
- Distribute coldness at the warmest possible temperature (e.g., at 20°C instead of 6°C – using chilled ceiling or chilled floor slab)
- Minimize ΔT_H and ΔT_L by

  - minimizing the required heat flows (which must balance heat loss or heat gain)

  - using as large a radiator surface as possible

Because heat pump heat flows must balance the building heat loss or gain, minimizing the heat flows and thus maximizing the heat pump COP requires

- A high performance thermal envelope (windows, insulation level, air tightness) to minimize building heat loss or gain
- Minimizing internal heat gains
- (so, improving the thermal envelope both reduces the heating and cooling loads, and increases the efficiency in supplying the reduced loads – a double dividend (also applicable to boilers for heating)

Radiant ceiling cooling

Energy Required to Move Air or Water through Ducts or Pipes

- Power imparted to fluid

  $P_{fluid} = \Delta P \times Q$

- Electric power required

  $P_{electric} = (\Delta P \times Q)/(\eta_m \eta_p)$

  but $\Delta P \; \alpha \; Q^2$ for turbulent flow, so

  $P_{fluid} \; \alpha \; Q^3$

- Cutting the required flow in *half* reduces the electrical energy requirement by a *factor of 6-7* (not by a factor of 8, because motor and pump or fan efficiencies drop slightly with lower flow)

As it turns out, ventilation air flow requirements can be reduced by a factor of two by using *displacement ventilation* rather than ceiling-based mixing ventilation, while improving air quality and reducing total heating loads on the chillers

Energy required to deliver heat by circulating warm water vs warm air

- Rate of heat supply to a room is equal to the rate of heat loss from the circulating air or water, which is given by

  $$Q_H = \rho c_p Q\ (T_{supply} - T_{return}) = \rho c_p Q\ \Delta T$$

- The ratio of energy supplied to move the fluid to heat delivered is given by

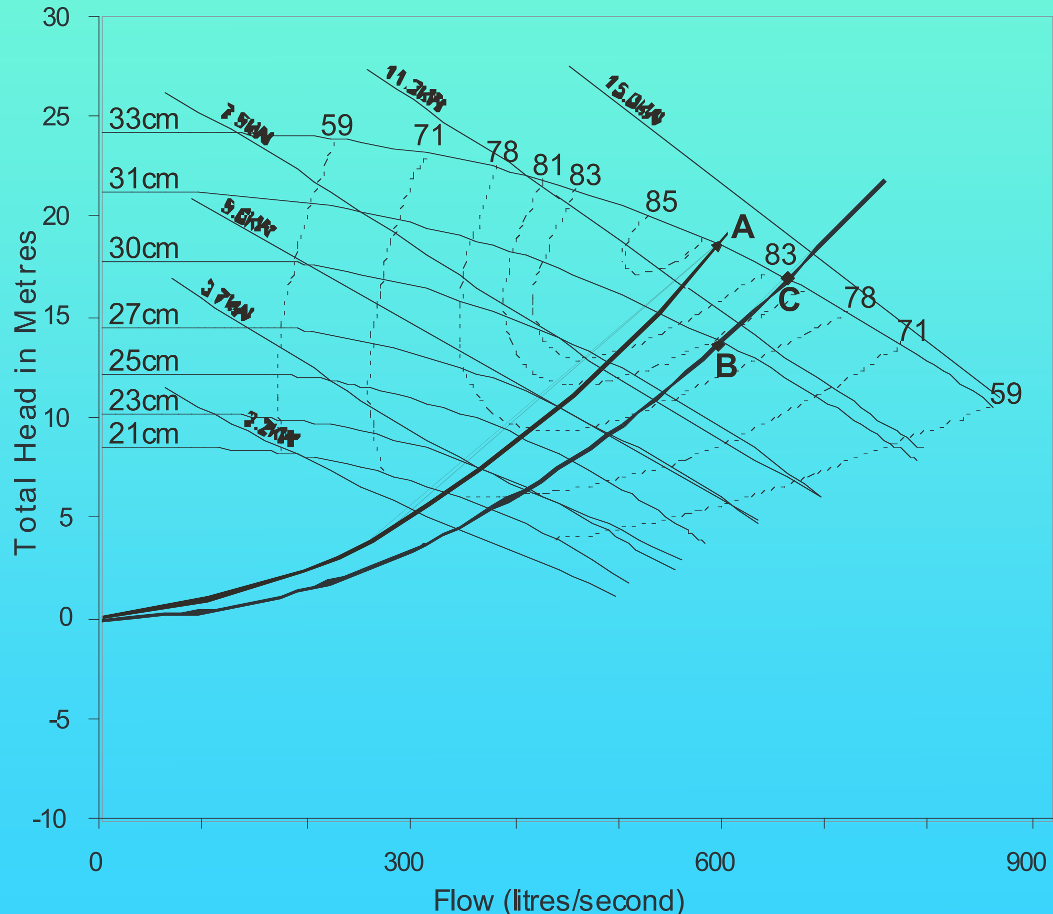
  $$\Delta P / \rho c_p\ \Delta T$$

- Given the large ρ and c_p for water compared to air, and given typical ΔPs and ΔTs, it takes about 25 times energy to *deliver* heat by moving water than by moving air

Thus, to minimize the energy use in *supplying* and *delivering* heat/coldness and fresh air

- Separate heating/cooling and ventilation functions
- Used chilled water at the warmest possible T for cooling (best: 20ºC)
- Use hot water for heating at the coolest possible temperature (best: 30°C)
- Circulate only the amount of air required for ventilation purposes using displacement ventilation

Pressure-flow relationship for a pump with different impellor diameters (convex upward curves) and for a piping system as originally estimated (upper concave up curve) and in reality (lower concave up curve)



Point A: intended operating point

Point C: actual operating point without trimming the impellor – energy use is 6% larger

Pont B: operating point with impellor trim – energy use drops by 25%!

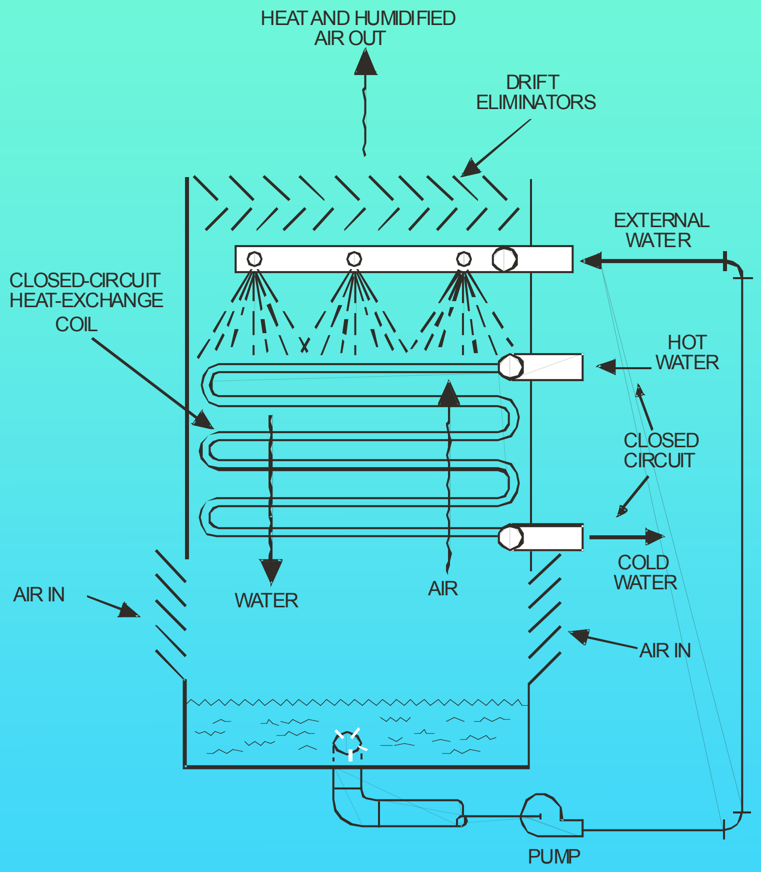
In many systems,

- Several times more air is circulated than is needed for ventilation alone, so as to provide adequate cooling through airflow alone
- In “efficient” systems, 80% of the air might be recirculated and mixed with 20% fresh outside air on each circuit, rather than replacing and having to cool and dehumidify 100% outside air
- However, 80% of the internal heat gains picked up by the air will have to be removed by the chillers

In a Dedicated Outdoor Air Supply system (100% outside airflow but only what is needed for ventilation) with displacement ventilation,

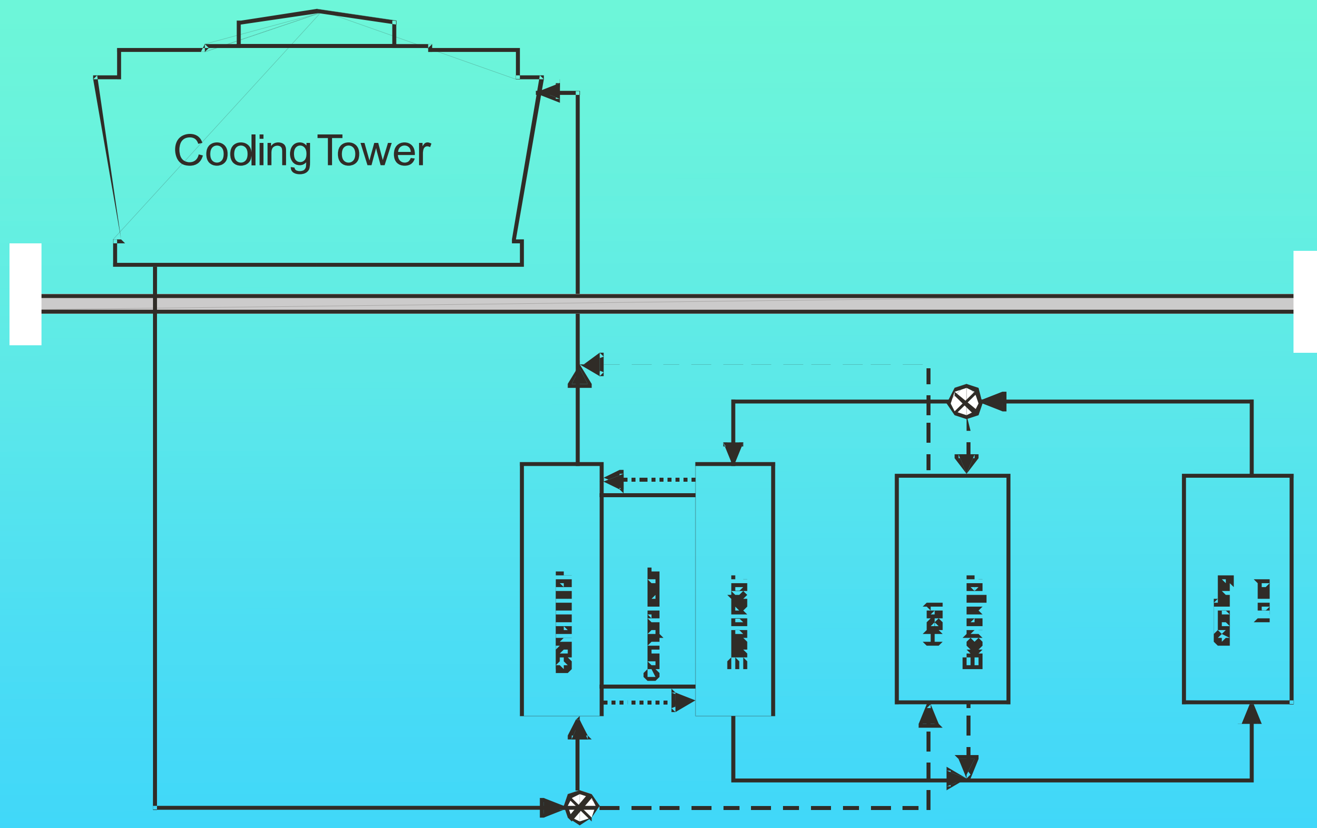
- Heat gains from the ceiling (from lighting) or heat rising to the ceiling is directly vented to the outside – reducing the cooling load on the chillers by up to one third
- Ventilation rates can be reduced to near zero when the building is not occupied (because ventilation is not used for temperature control) – can save 20-30% in total heating+cooling+ventilation energy use

Another advantage of using chilled ceilings for cooling is that the required chilled-water temperature (18-20°C) is cool enough that it can often be supplied through evaporative cooling using the chiller cooling tower

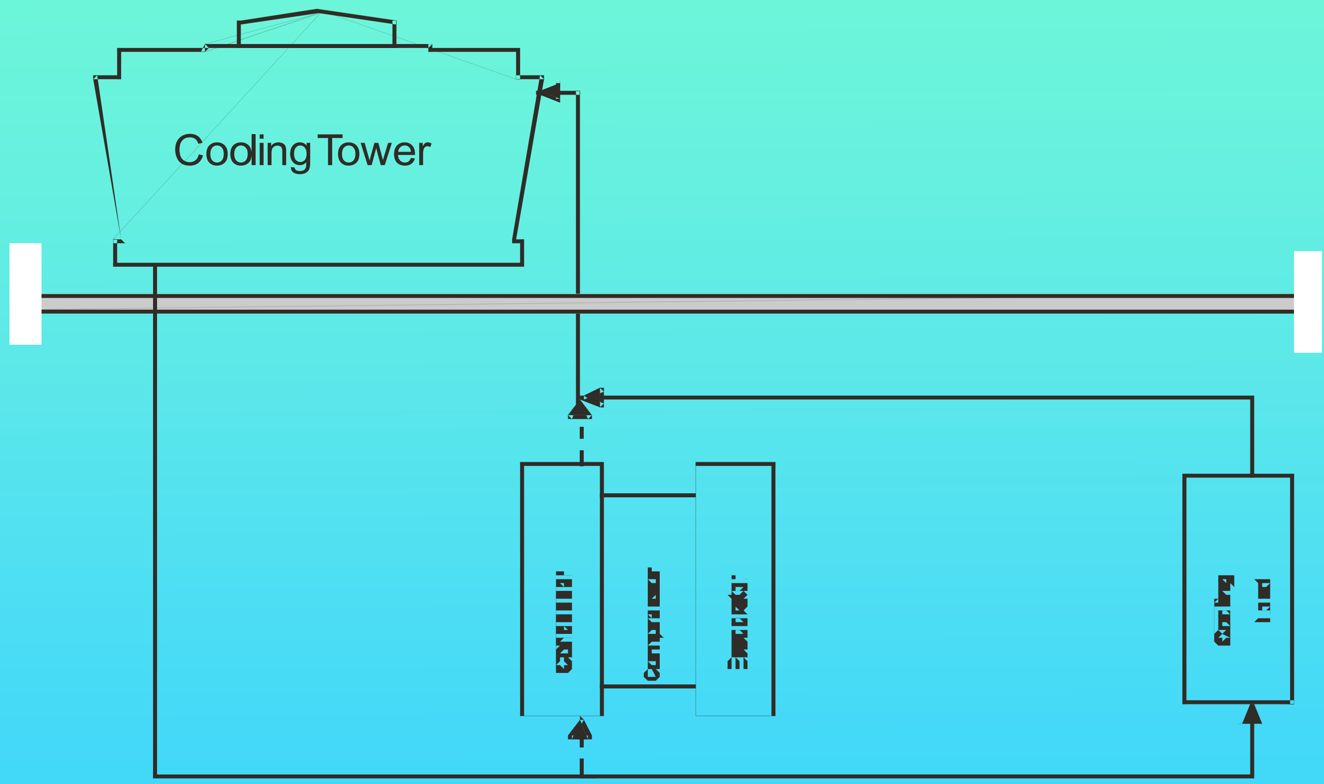


HEAT AND HUMIDIFIED
AIR OUT
DRIFT
ELIMINATORS
EXTERNAL
WATER
CLOSED-CIRCUIT
HEAT-EXCHANGE
COIL
HOT
WATER
CLOSED
CIRCUIT
COLD
WATER
AIR IN
WATER
AIR
AIR IN
PUMP

(a)

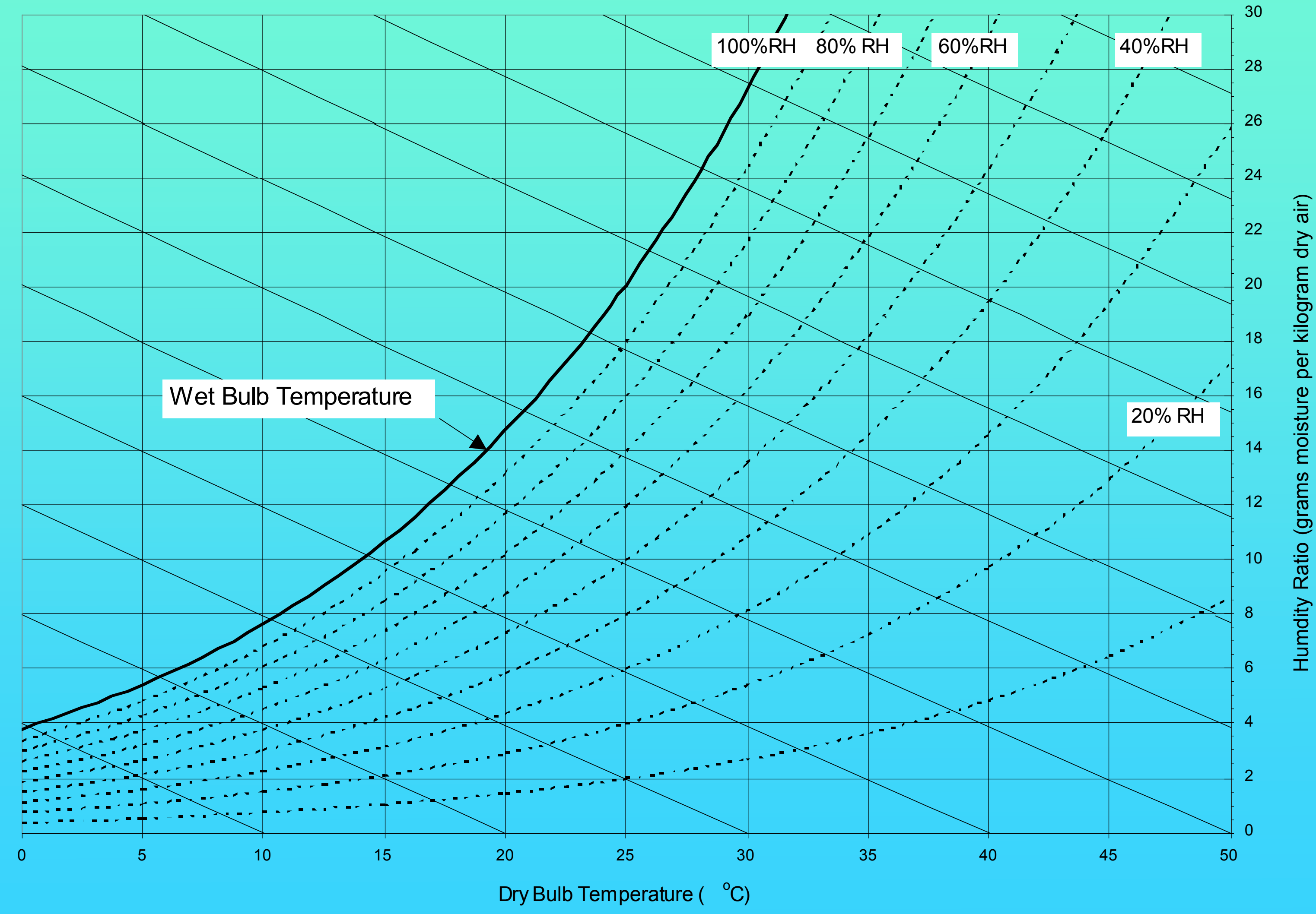


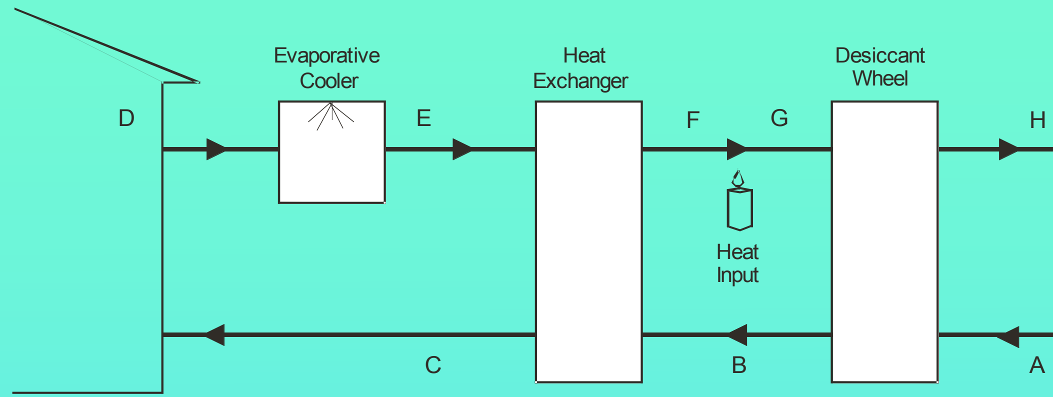
(b)

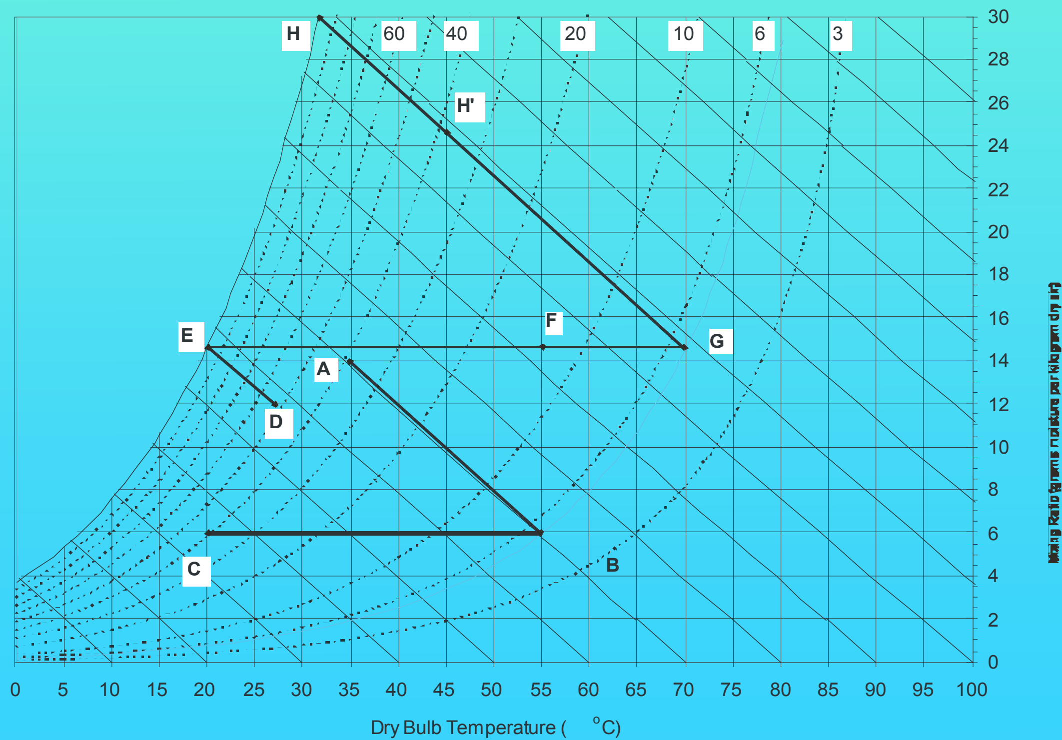


The lowest temperature that can be achieved through evaporation is called the *wetbulb temperature*

- In most of the world, most of the time, the wetbulb temperature is low enough to cause adequate cooling, especially if cooling loads are reduced through good design
- Where water is limiting, diurnal T variations are large – so a combination of external insulation, exposed internal thermal mass, and night time ventilation can provide adequate cooling
- Evaporative cooling techniques can be extended to hot-humid climates using solid or liquid dessicants that can be regenerated using low-T solar thermal energy


100%RH
80% RH
60%RH
40%RH
20% RH
Wet Bulb Temperature
0
5
10
15
20
25
30
35
40
45
50
Dry Bulb Temperature (°C)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Humdity Ratio (grams moisture per kilogram dry air)


Evaporative Cooler
Heat Exchanger
Desiccant Wheel
Heat Input
D
E
F
G
H
C
B
A


H
H'
E
F
G
A
D
C
B
60
40
20
10
6
3
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Dry Bulb Temperature (°C)

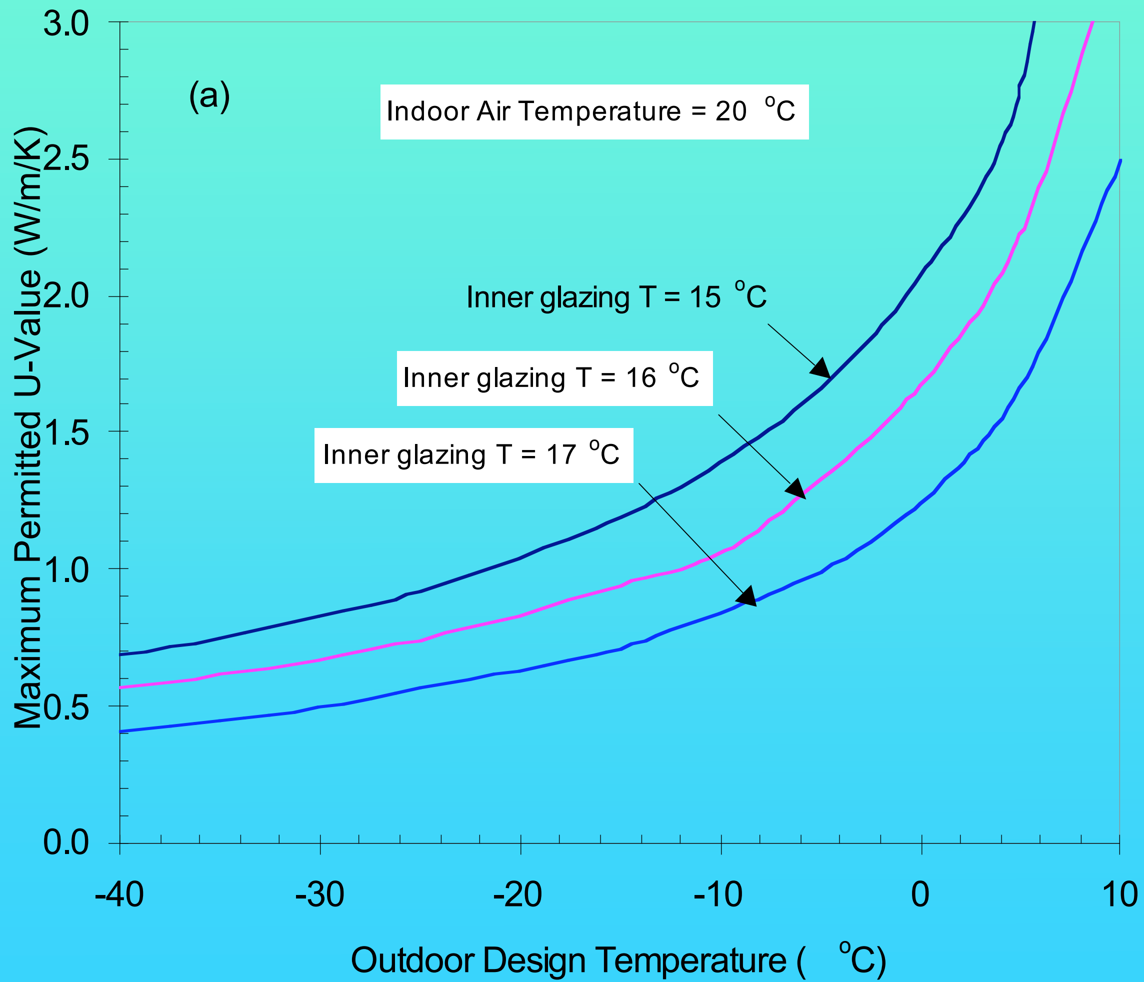
Solar Energy in Buildings

- Passive solar heating
- Passive ventilation
- Active solar thermal collectors, used for
  – domestic hot water
  - space heating
  -desiccant dehumidification systems
- PV panels

To maximize passive solar heating requires

- Attention to building form and orientation
- Use of high-performance windows
- Use of thermal mass to avoid overheating by day and to release stored heat by night
- High levels of insulation to retain heat that is released from thermal mass at night

Window-U value at which perimeter heating units can be eliminated as a function of the outdoor design temperature and the coldest permitted inner glazing surface temperature



Solar Chimney to induce ventilation, Building Research Establishment, Garston, UK

Integrated Design Process

- Consider *building orientation, form, thermal mass*
- Specify a *high-performance building envelope*
- Maximize *passive* heating, cooling, ventilation, and day-lighting
- Install efficient *systems* to meet remaining loads
- Ensure that individual energy-using *devices* are as efficient as possible, and properly sized
- Ensure the systems and devices are *properly commissioned*

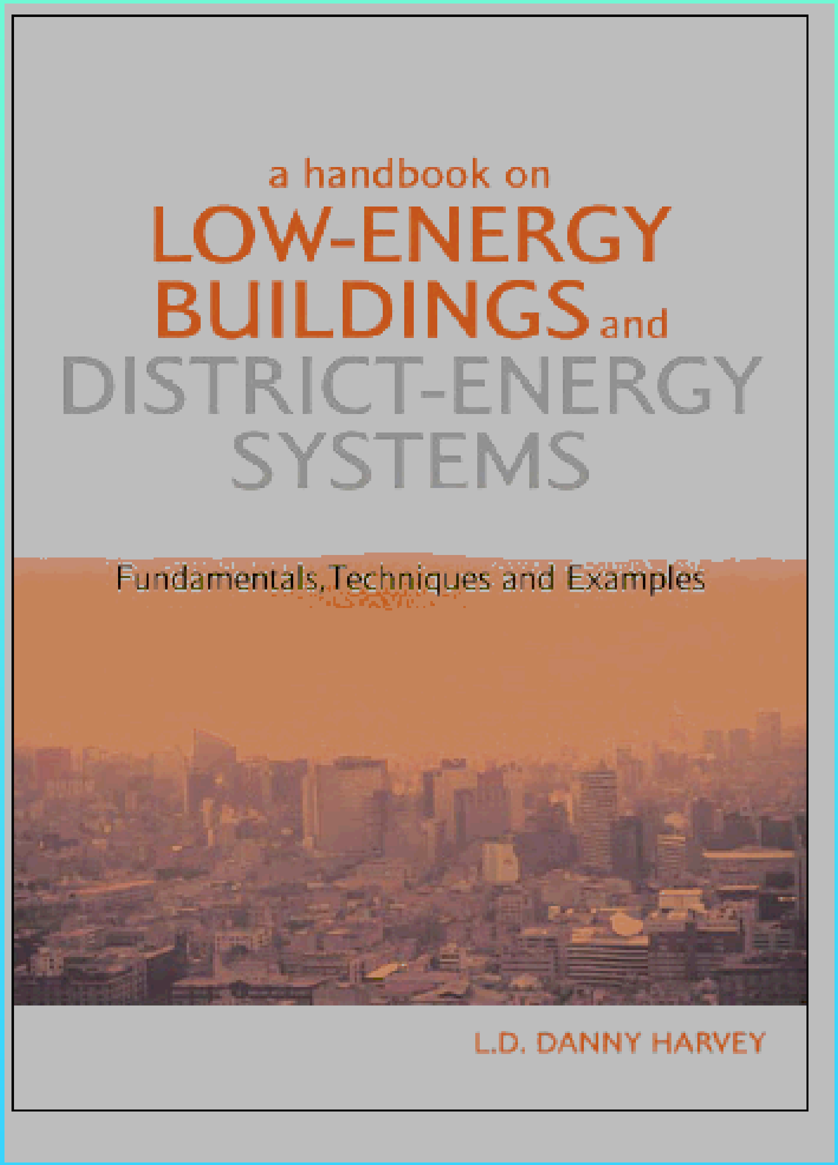
Savings and Costs

- With *nothing fancy* and without requiring detailed computer simulations, this approach will frequently give a 50% savings in annual energy use compared to current practice
- Use of *computer simulation models* run by simulation experts to fully optimize the design of the building and mechanical systems and use of more advanced designs can push the savings to 60-70%
- Savings can be pushed to 75-80% with *enlightened occupant behaviour*
- Buildings achieving such high energy savings sometimes cost no more than conventional buildings, due to the downsizing of mechanical equipment, and are superior in other respects
- Sometimes saving more energy costs less

Potential Area of Interest to Physicists Wanting to Move into the Building Energy Efficiency Area:

- Computational fluid dynamics (CFD) to simulate passive ventilation or hybrid passive-mechanical systems
- Optical properties of windows with regard to passive solar gain, minimization of cooling loads, maximization of daylighting opportunities
- Research pertaining to phase-change materials and thermal mass
- All elements of building energy simulation

Currently Available:



701 pages,
160 tables,
330 figures,
1600 references

Forthcoming (Spring 2009):

Energy and the New Reality: Facing Up to Climatic Change

Part I: Efficiency Potential

Fossil Fuel Electricity Generation
Buildings
Transportation
Industry
Agriculture and the food system

Part II: Carbon-Free Options

Solar
Wind
Biomass
Hydro
Geothermal
Oceanic
Nuclear
C sequestration
H Economy