Sunoba
Renewable Energy Systems

Annual Output of a New Solar Heat Engine

Noel Barton

Sunoba Pty Ltd
PO Box 1295,
Macquarie Centre, NSW 2113 Australia

Noel.Barton@sunoba.com.au

Summary

- This work involves a heat engine with a new thermodynamic cycle.
- We simulate the annual output of the engine, as powered by passive solar heat collection. Site is Wellington NSW; data from Bureau of Meteorology.
- Heat collection takes place under a transparent insulated canopy.
- The seminar describes a canopy heat transfer model coupled to a thermodynamic model of the engine. This is the basis for detailed simulations.
- Counting all losses (canopy plus engine), current estimates are:
  - peak power — 65 W/m^2 (carefully estimated)
  - annual output — 74 kWhr/m^2 (carefully estimated)
  - cost per peak Watt — AUD1.38/W_p (preliminary estimate)
  - Levelised Energy Cost — AUD163/MWhr (preliminary estimate)

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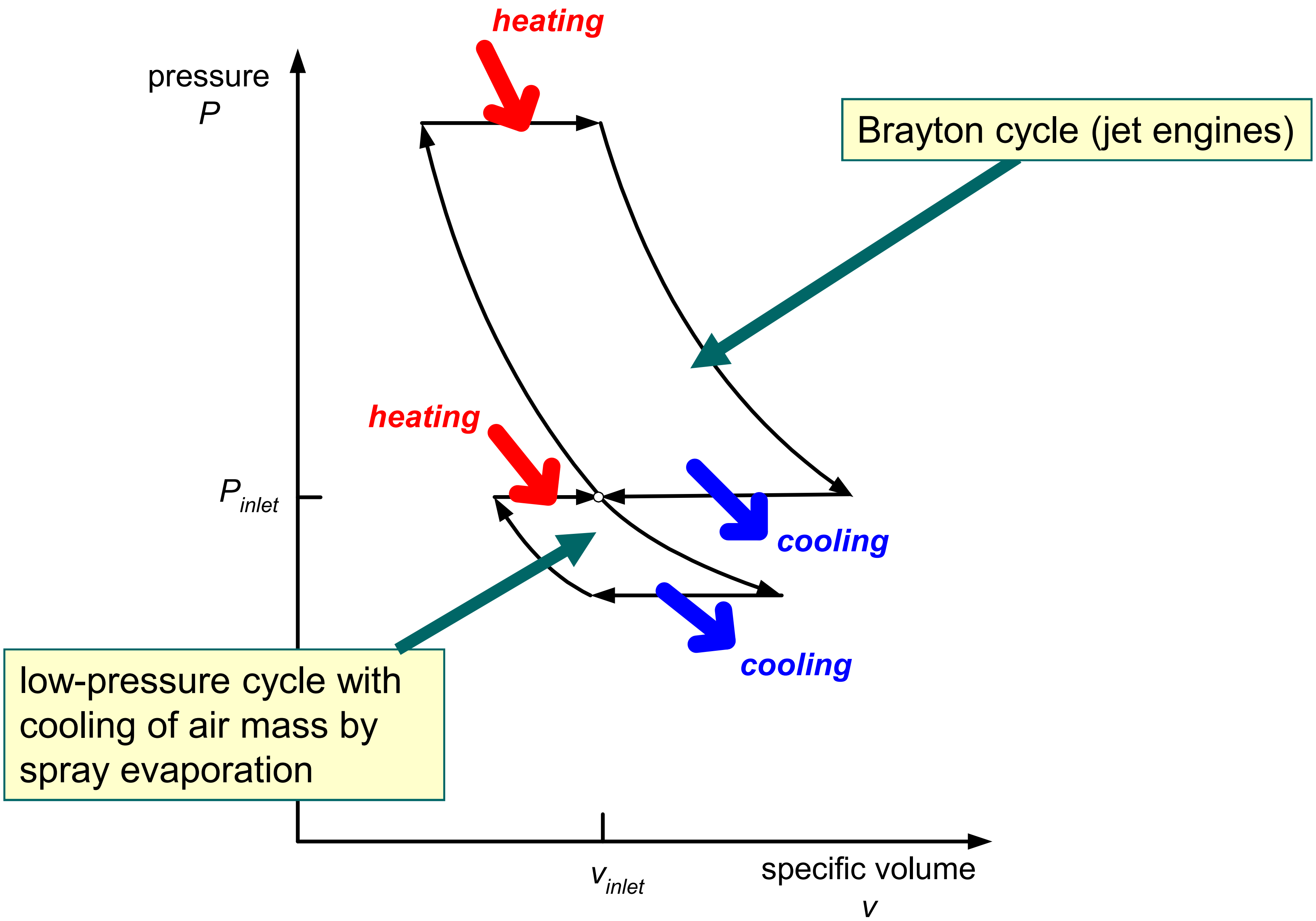
Thermodynamic cycle (continuous-flow version)



Mechanical principle

- inlet to receive hot dry air
- expand so that pressure is reduced (but <u>not</u> as far as saturation by water vapour in the air)
- spray water into low-pressure section; evaporation causes a decrease in temperature AND { pressure OR specific volume }
- re-compress allowing further evaporation; there will be surplus work that can be captured by a turbine or piston
- exhaust air is cooled and moistened

water + hot dry air → power + cool moist air

evaporative coolers can also produce power!

Pressure/volume plot (evaporative cooler)

expansion ratio r = 1.2

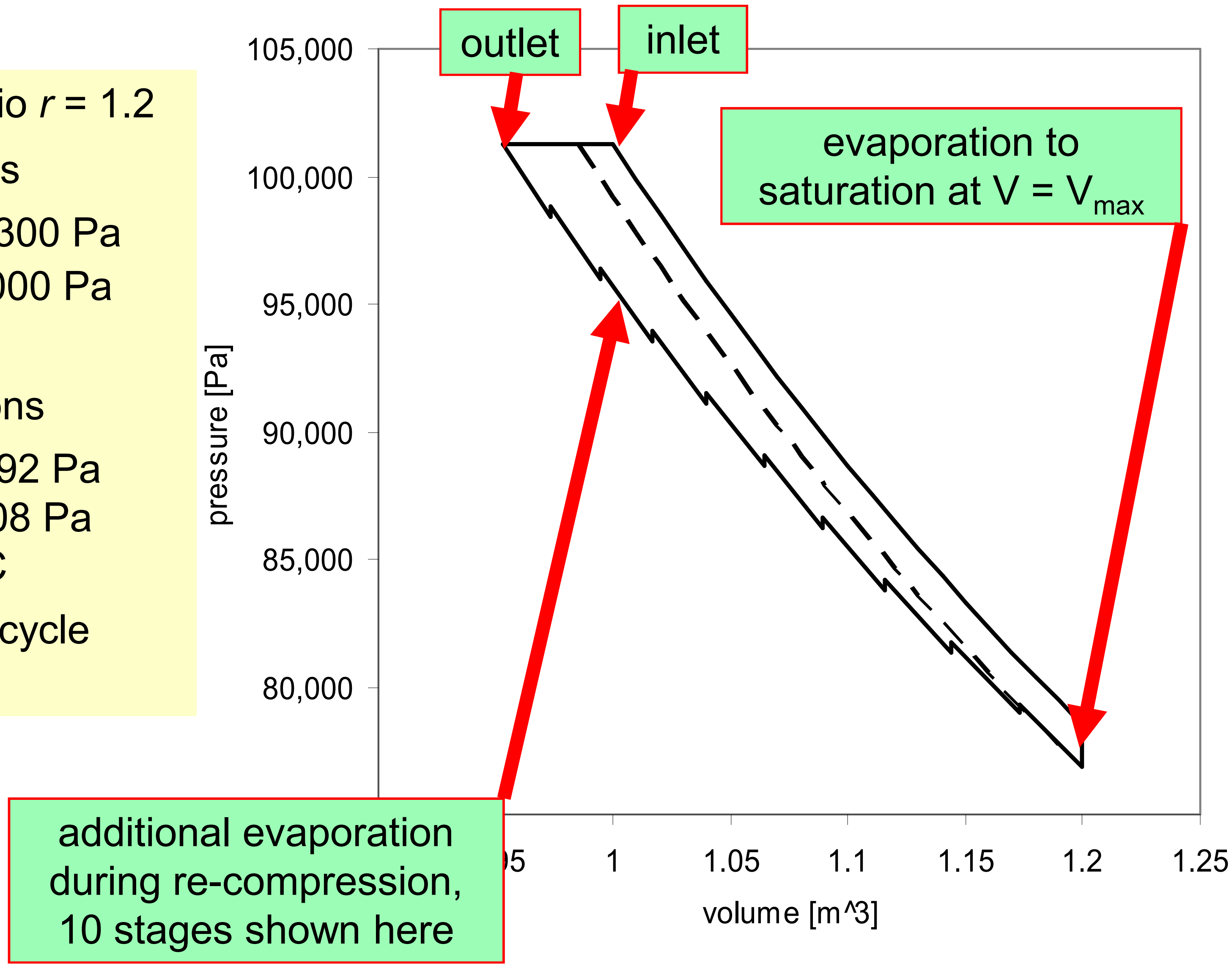
inlet conditions

P_{air} = 99,300 Pa
P_{vap} = 2,000 Pa
T = 45°C

outlet conditions

P_{air} = 98,092 Pa
P_{vap} = 3,208 Pa
T = 25.5°C

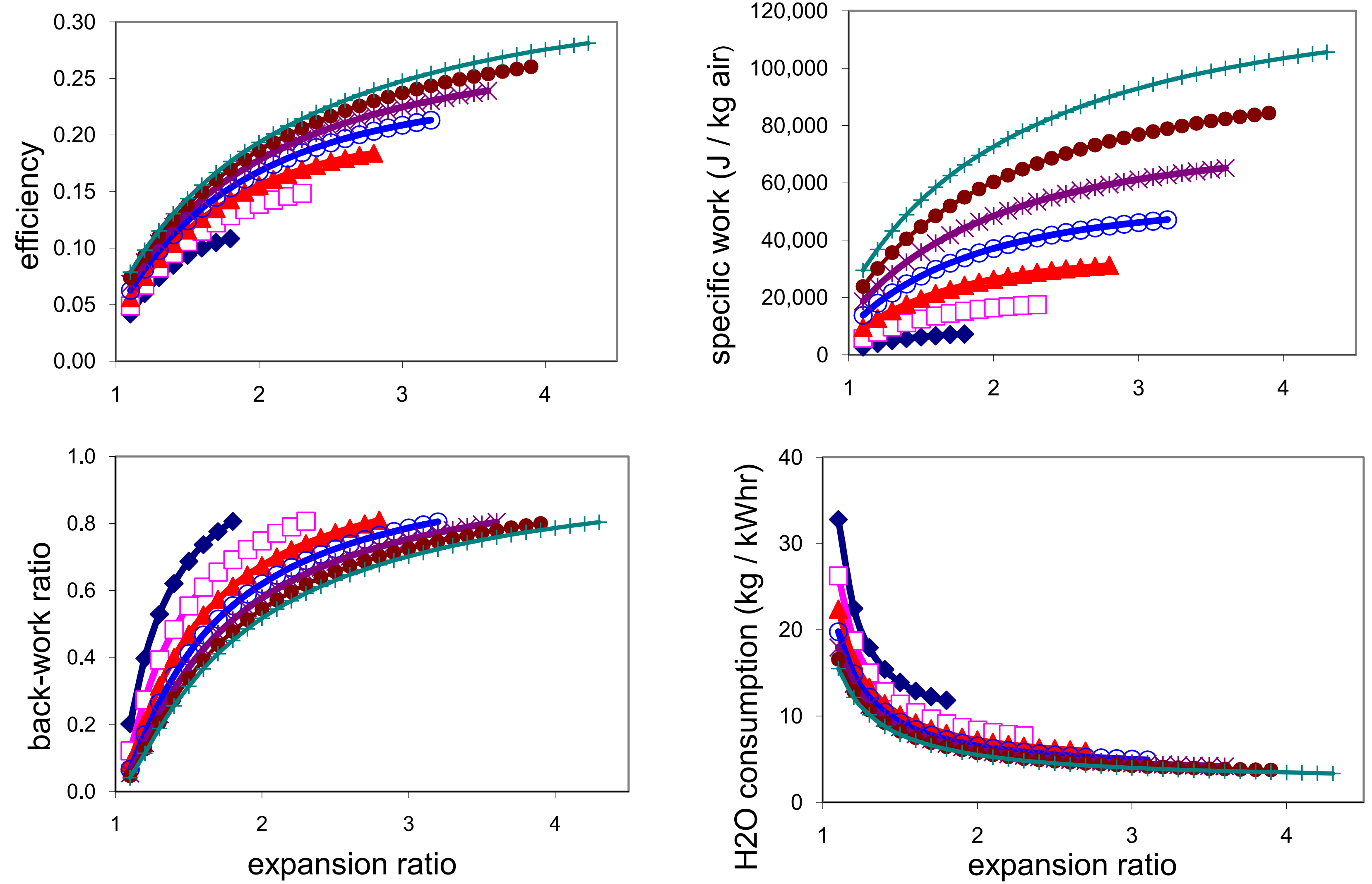
nett work per cycle
+ 788 J/kg



Theoretical analysis (piston-in-cylinder version)

- air and vapour – ideal gases with constant specific heat capacities
- isentropic expansion of air-vapour mixture
- evaporation to saturation at reduced pressure and constant volume
- re-compression of air-vapour-droplet mixture with further evaporation
- saturation given by Clausius-Clapeyron equation
- coupled algebraic equations for V, T, P_{air}, P_{vapour}, ρ_{air}, ρ_{vapour}
- Reference: N.G. Barton, “An Evaporation Heat Engine and Condensation Heat Pump”, *ANZIAM Journal*, vol 49 (2008), 503-524

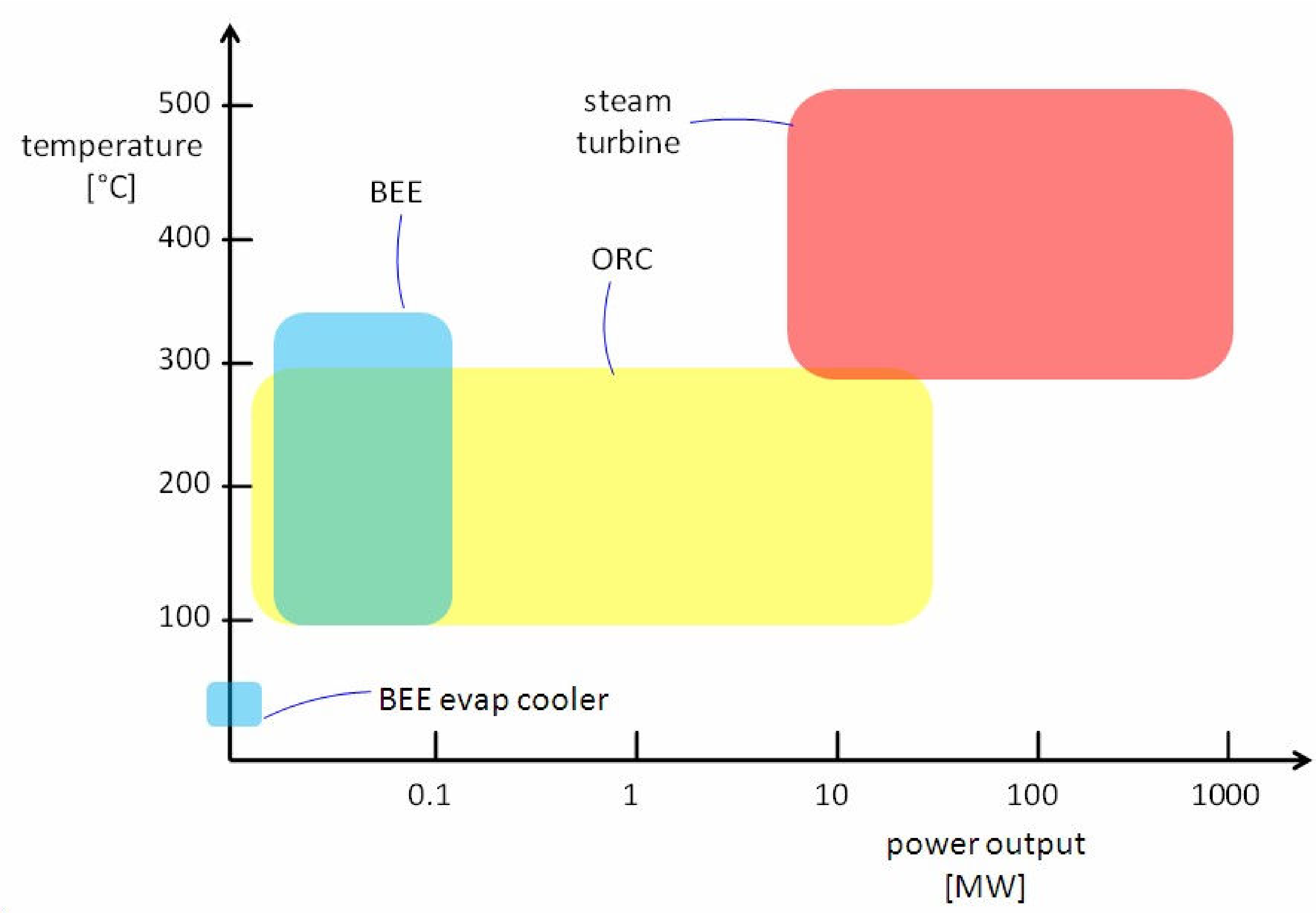
Efficiency, specific work, back-work ratio, water consumption



Ambient conditions: P_a = 99,300 Pa, P_v = 2,000 Pa, T = 30°C, T_{water} = 20°C.

Inlet temperatures: 100, 150, 200, 250, 300, 350, 400°C

Applications as an evaporative cooler and heat engine



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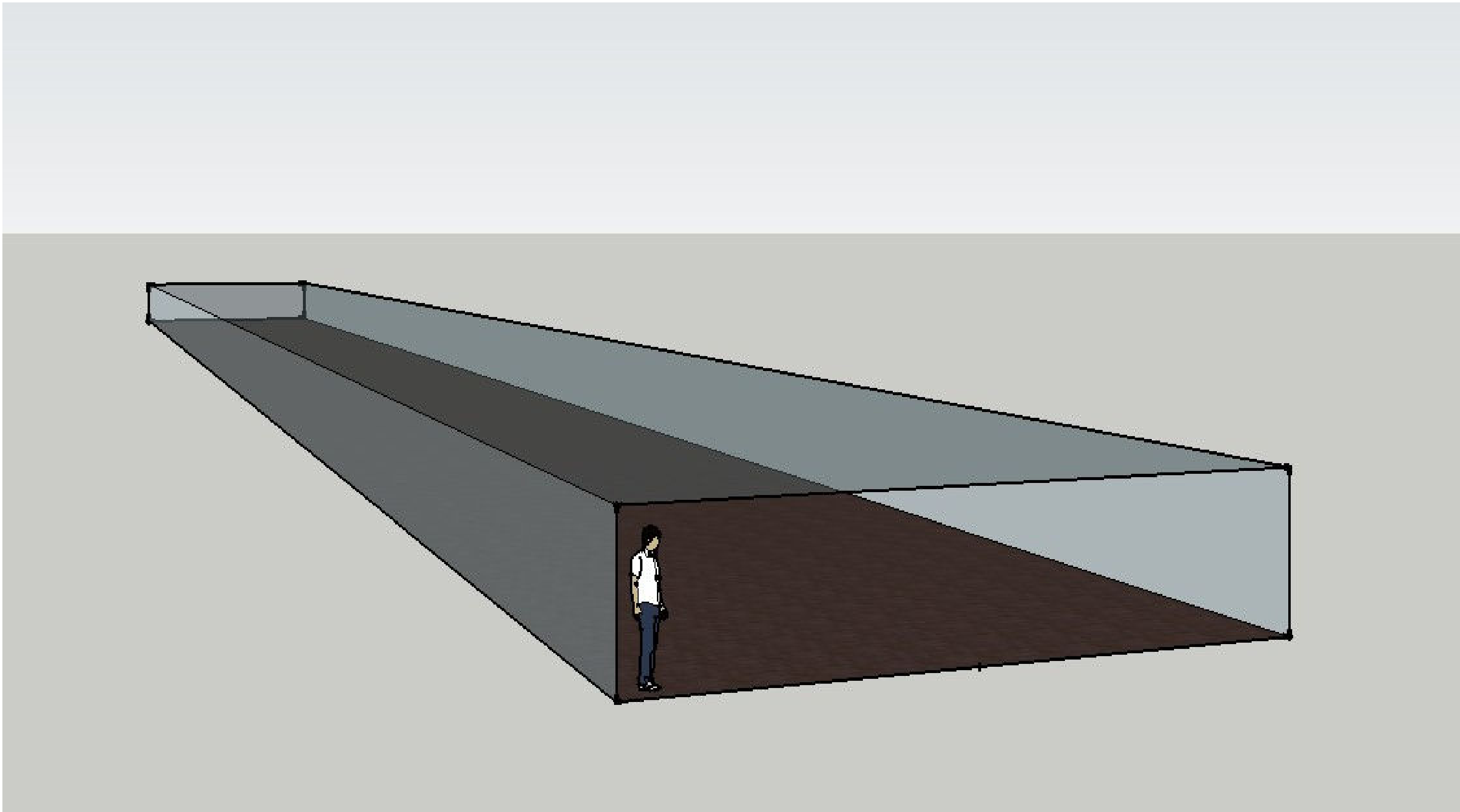
Passive solar collectors (1)

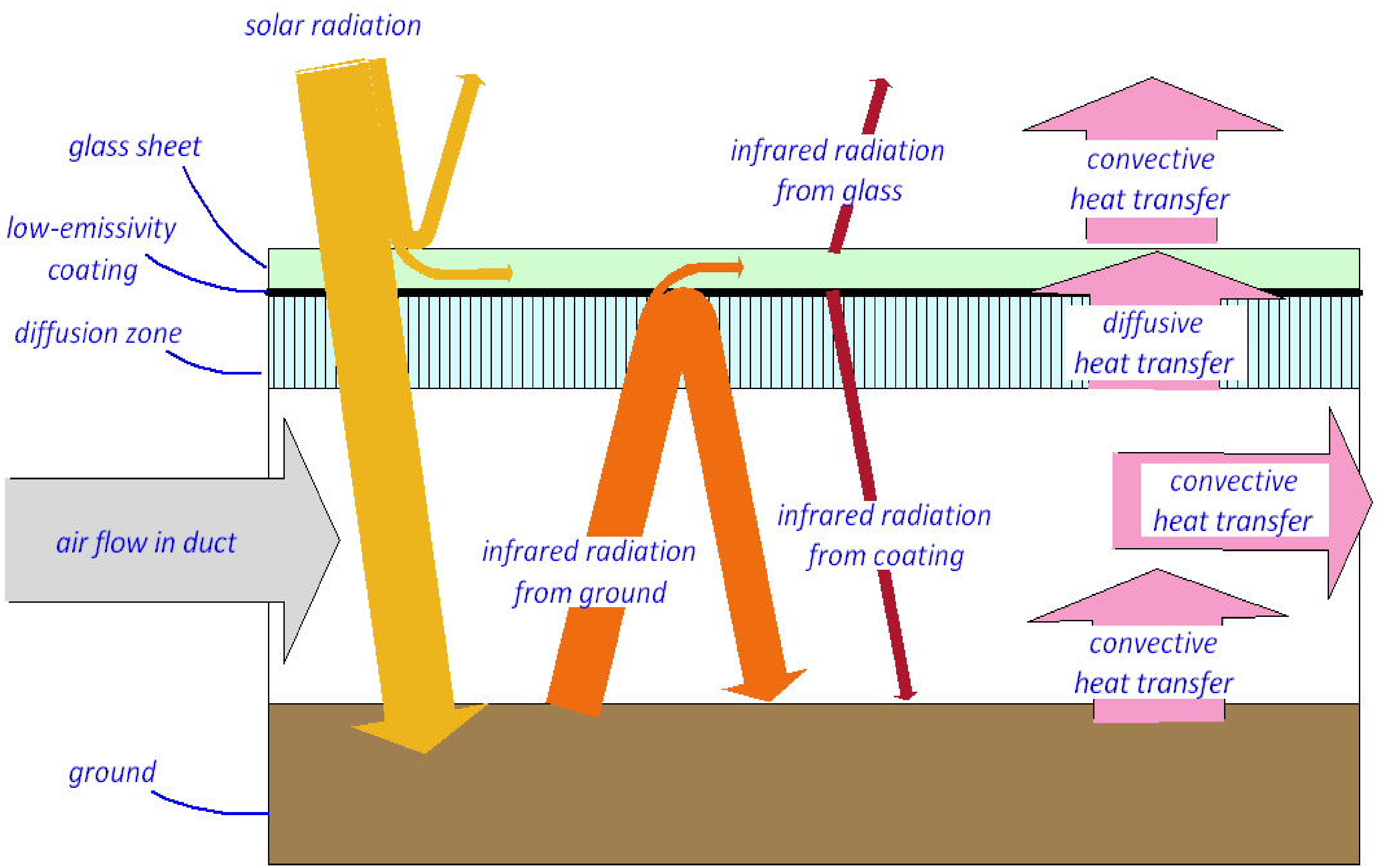
- typical commercial model shown (water-glycol coolant)
- stagnation temperature 209°C
- at 1 kW direct insolation, peak power is 827 W_{th}/m^2 (when storage temperature = ambient)
- used for hot water, space heating, process heat

Passive solar collectors (2)



- air is drawn by the engine through a ‘glasshouse’
- canopy has low-emissivity coating and is insulated
- simulations based on 1,000 m^2 canopy (100 m × 10 m × 2 m)

Elements of the heat transfer model



Equations (1)

1D steady-state heat transfer in the duct under the canopy:

$$\Phi C_{aP} \frac{dT_a}{dx} = F_s + F_{ir,c2} + F_{ir,g} + F_c$$

$T_a(0) = T_0$ inlet condition

$\Phi = HWU\rho_a$ mass flux

$F_s = W.\tau_{s,c}(\theta)\, I_s \sin\theta$ gain (incident solar radiation)

$F_{ir,c2} = W.I_{ir,c2}$ gain (infrared from cover)

$F_{ir,g} = -W.(1-\beta_{ir,c2})I_{ir,g}$ loss (infrared from ground)

$F_c = -(Wk_a/d).(T_a - T_{c2})$ loss (diffusion zone)

Equations (2)

Heat diffusion through the glass cover:

$$k_c \frac{d^2 T_c}{dz^2} = -\frac{1}{e}\left\{\alpha_{s,c}\, I_s \,.\sin\theta + \alpha_{ir,c}\, I_{ir,g}\right\}$$

$$-\left[k_c \frac{\partial T_c}{\partial z}\right]_{z=H} = \frac{k_a}{d}\left(T_a - T_{c2}\right) - I_{ir,c2}$$ bottom surface

$$-\left[k_c \frac{\partial T_c}{\partial z}\right]_{z=H+e} = h_{c/o}\left(T_{c1} - T_o\right) + I_{ir,c1}$$ top surface

Infrared radiation terms take the form:

$$I = \alpha\sigma T^4$$

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Numerical techniques

- calculate I_s,

  $$\int_{\text{dawn}}^{\text{dusk}} I_s \sin\theta(t)\ dt = I_s \cdot \int_{\text{dawn}}^{\text{dusk}} \sin\theta(t)\ dt$$ = daily insolation

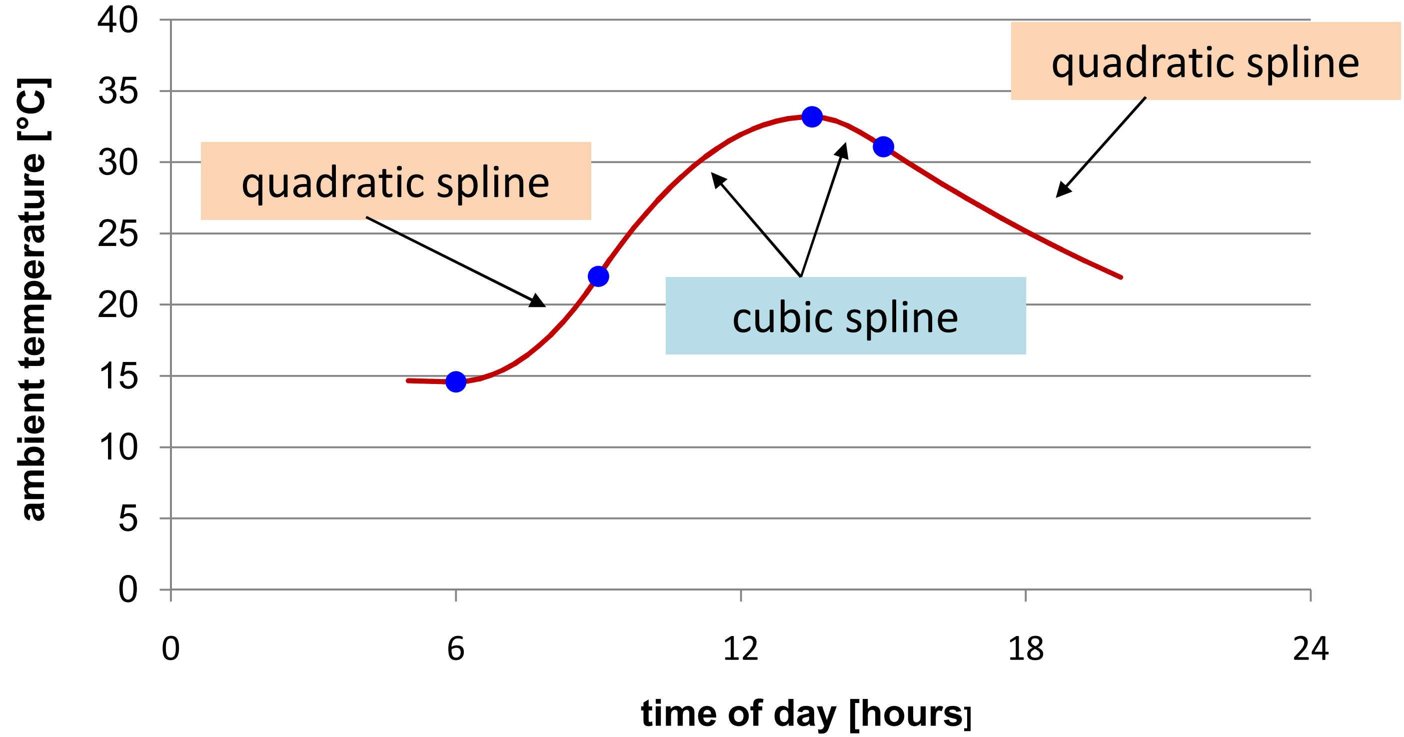
- sun angle from www.sunposition.info; assign other parameters
- heat transfer models for air and glass need to be solved jointly
- predictor-corrector method used; involves analytical solution in glass cover
- key factor is air mass flow-rate $\Phi = HWU\rho_a$
- flow-rate increases, then

  → temperature decreases

  → efficiency decreases but losses also decrease

- optimum flow-rate during each time interval found by simple root-finding procedure

Ambient temperature on a typical day (1 November 2009)



- BoM data for 0900 and 1500 hours, maximum and minimum
- min/max assigned to 0500/1230 (with daylight saving adjustment)

Pilkington data on transmission and reflection

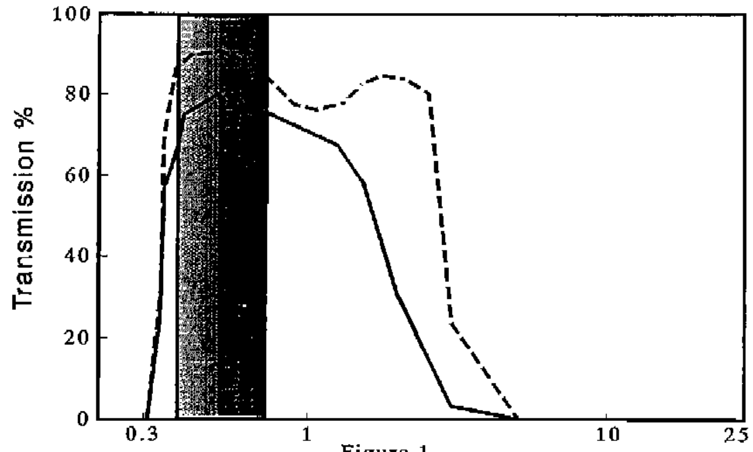


Figure 1
Wavelength (micrometre)
1/8" Clear Float Transmission ····· LOF Low-E Transmission ——
Visible Spectrum

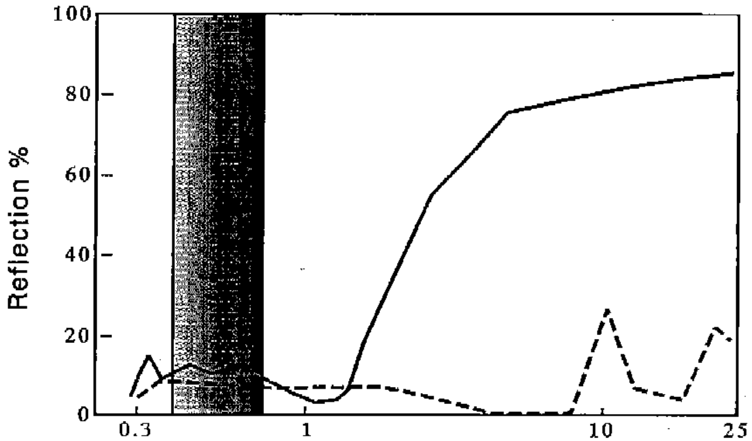
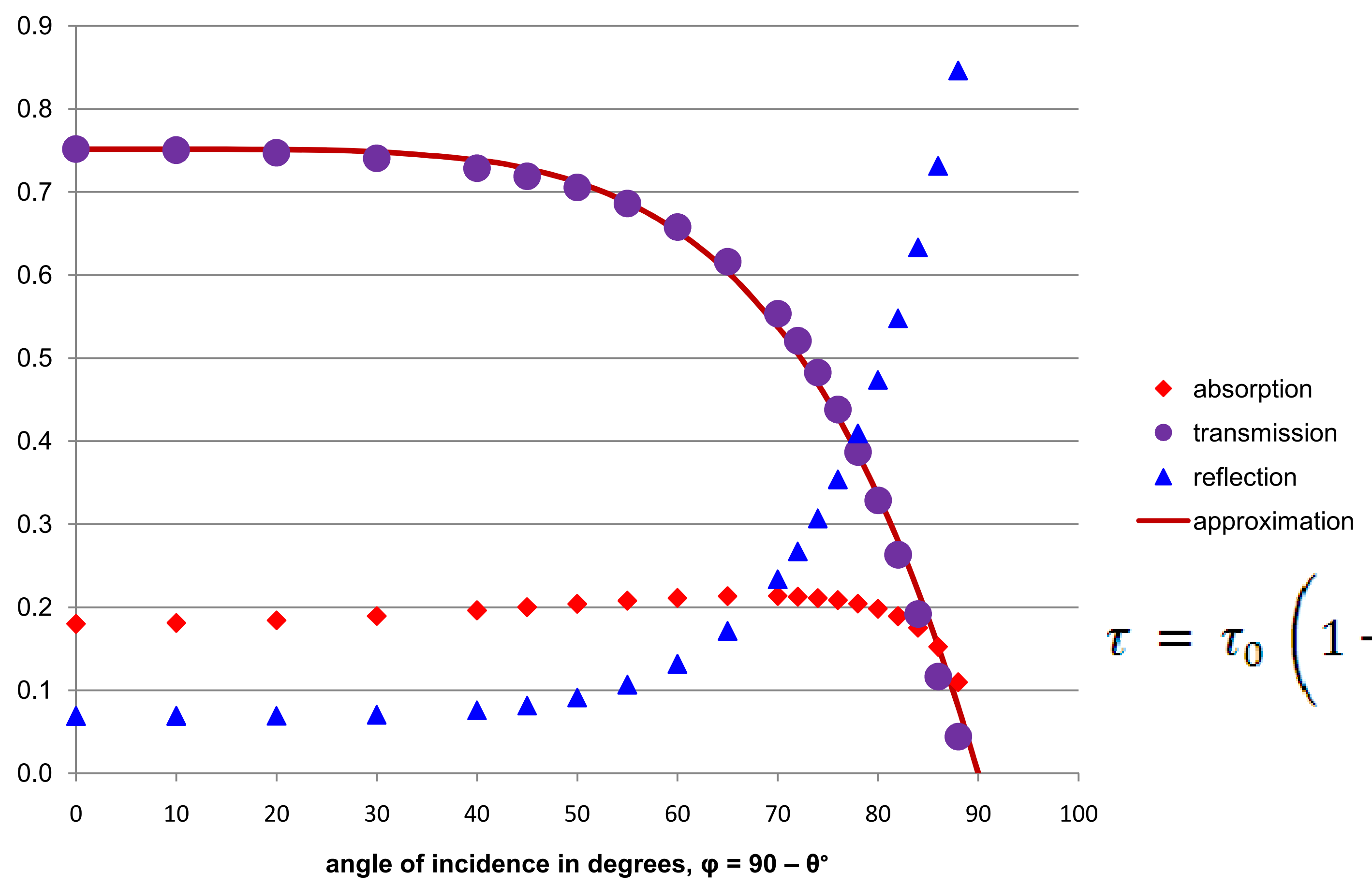


Figure 2
Wavelength (micrometre)
Clear Glass Reflection ····· LOF Low-E (film side) Reflection ——
Visible Spectrum

Incident angle modifier (from Mitalas & Stephenson, 1962)



$$\tau = \tau_0 \left(1 - \left[\frac{2\varphi}{\pi}\right]^5\right)$$

Other data

L	100 m	$\alpha_{s,c}$	0.18	C_{aP}	1,005 J.(kg.K)$^{-1}$
W	10 m	$\beta_{s,c}$	0.12 *	C_{aV}	718 J.(kg.K)$^{-1}$
H	2 m	$\alpha_{ir,c}$	0.15	C_{vP}	1,872 J.(kg.K)$^{-1}$
d	0.025 m	$\beta_{ir,c}$	0.85	C_{vV}	1,411 J.(kg.K)$^{-1}$
e	0.003 m	ρ_c	2,500 kg.m^{-3}	k_a	0.0261 J.(kg.K)$^{-1}$
δx	2 m	k_c	1.20 W.(m.K)$^{-1}$	$h_{c/o}$	50 W.(m^2.K)$^{-1}$
r	1.9	C_c	840 J.(kg.K)$^{-1}$	σ	5.67×10^{-8} W.(m^2.K^4)$^{-1}$

- vapour pressure average of 0900 and 1500 readings
- air pressure 97,630 Pa (Wellington is 305 m above sea level)
- canopy model assumes dry air; thermodynamic model includes water vapour
- air and vapour treated as ideal gases with constant specific heats

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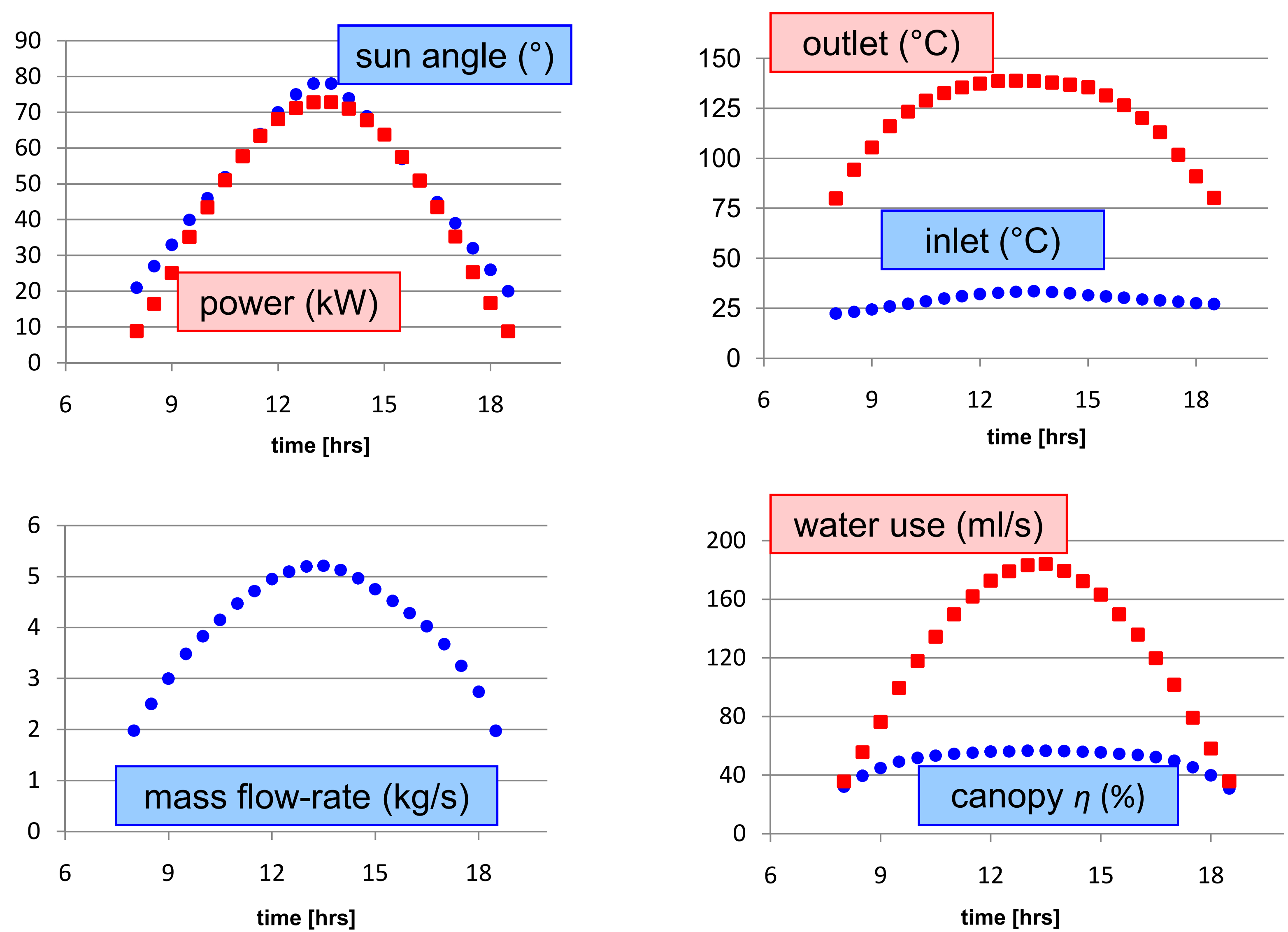
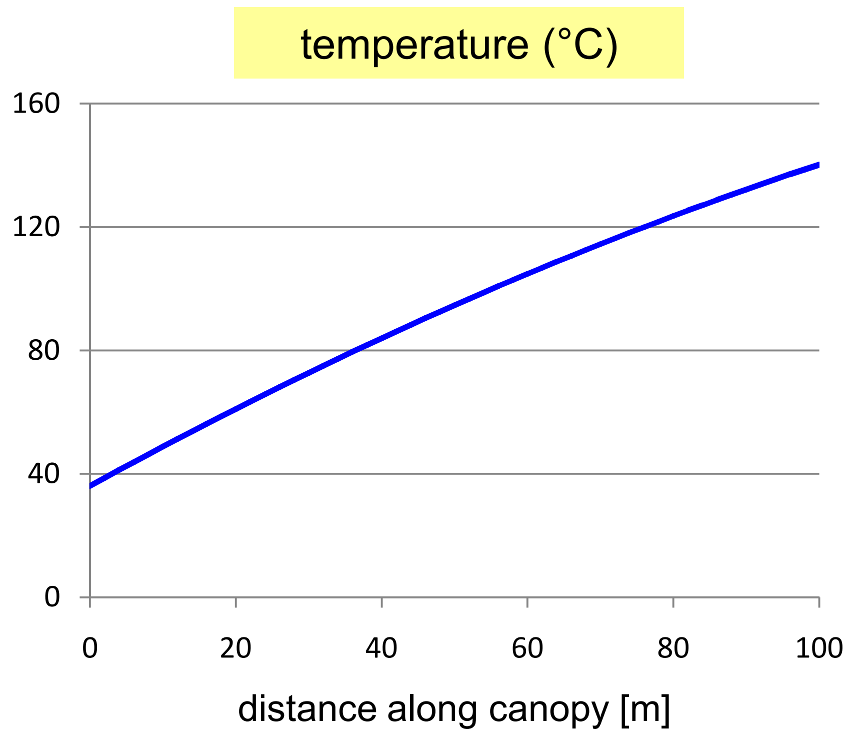
<u>Results for a typical summer day (15 January 2010)</u>

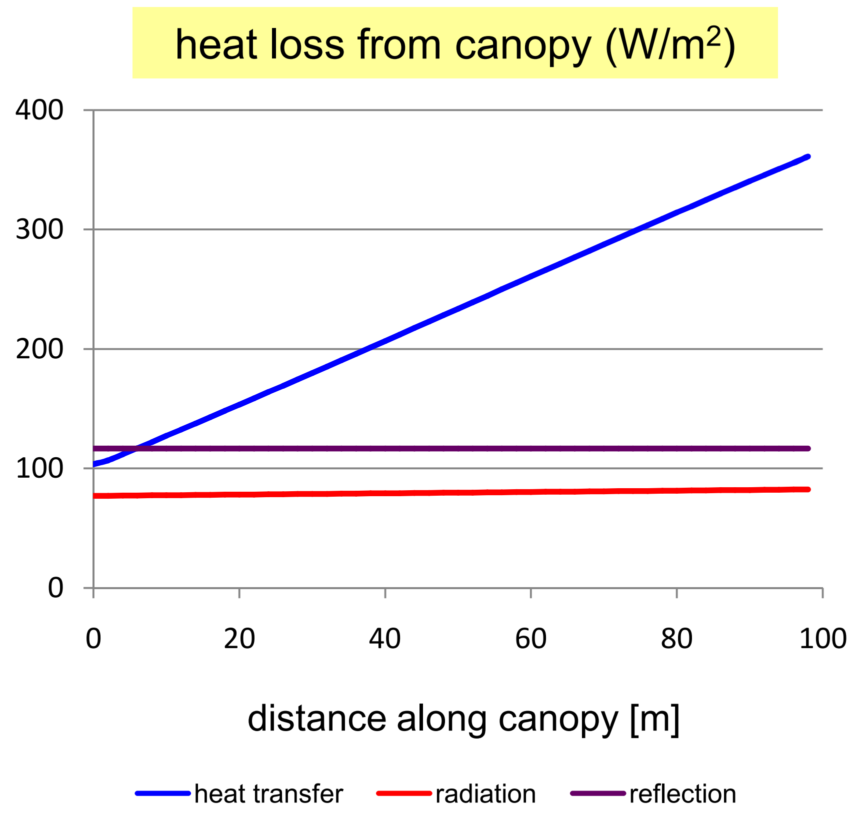
- lovely day for solar energy, although humid for Wellington in summer
- 30.5 MJ/m^2 insolation; 11 hours of sunshine; I_s = 995 W/m^2
- temperatures:
  - 0900 24.5°C
  - maximum 33.5°C
  - 1500 31.6°C
- average vapour pressure 1,920 Pa (63% RH at 0900, 41% at 1500)

Results for 15 January 2010 (for 1,000 m^2 canopy, no engine losses)

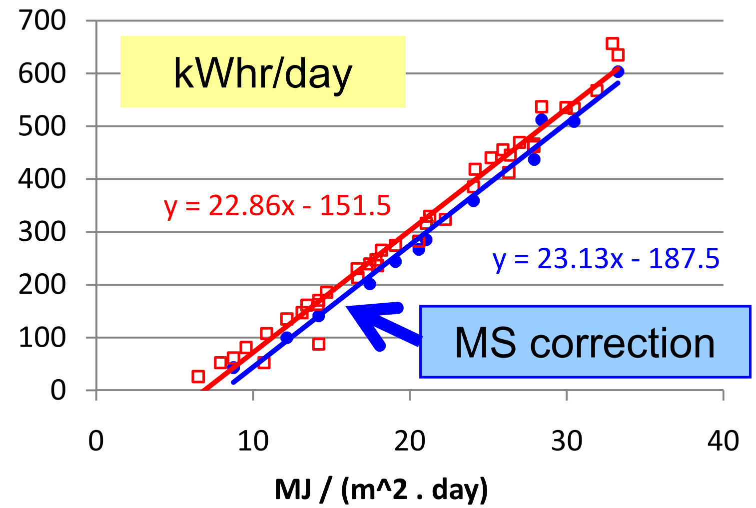


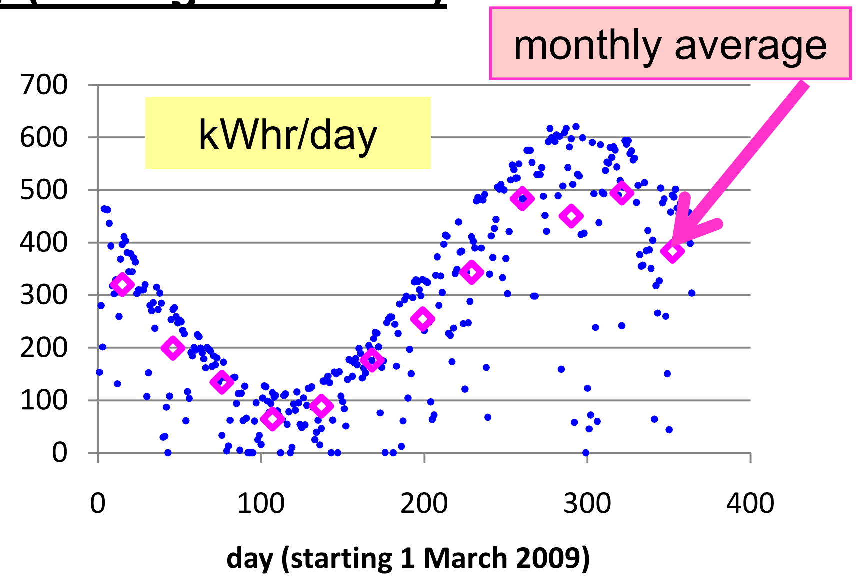
15 January 2010 at 1330 hours

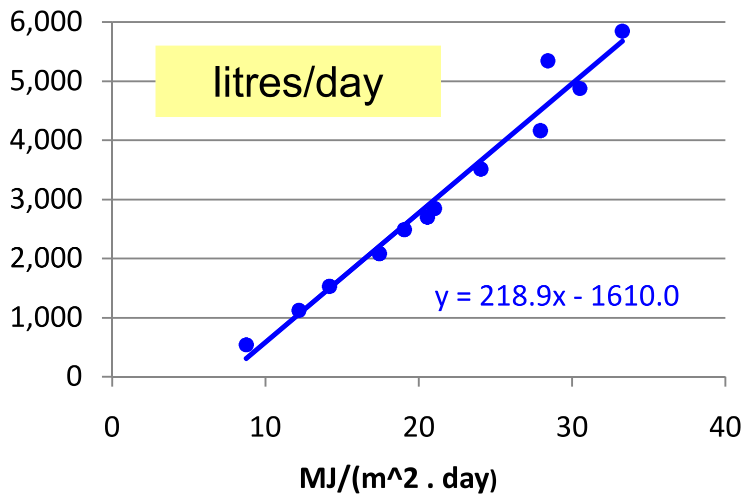


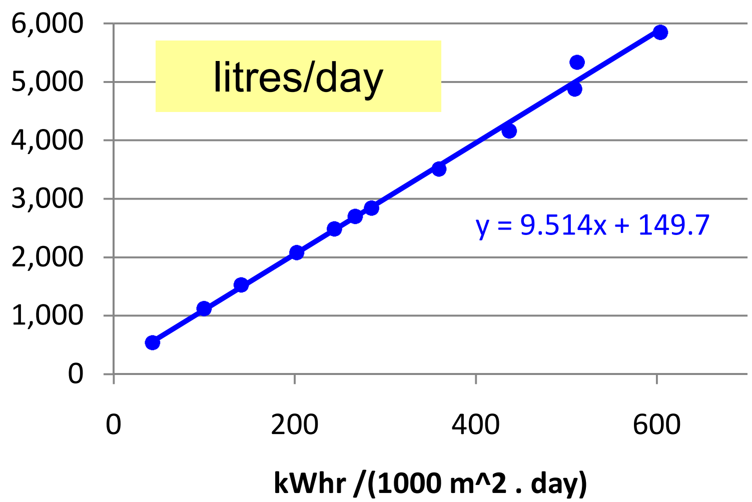


Annual results for 1,000 m^2 canopy (no engine losses)









Annual results from Wellington simulations

Power output: 104 MWhr / (1,000 m^2.yr)

Water consumption: 1,038 m^3 / (1,000 m^2.yr)

(considering canopy losses but not engine losses)

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Engine losses

- transient heat transfer 7%
- leakage around valves and seals 1%
- dead zones 1%

- incomplete evaporation during re-compression 4%
- aerodynamic valve losses 1%
- mechanical friction 4%

- RO water purification 0.004 $MWhr/m^3$
- water injection 0.0028 $MWhr/m^3$

- mechanical/electrical conversion 3%

Estimates

- engine losses lead to 25-30% reduction in simulated power output
- water consumption 14% higher than theoretical estimate

Contents

Estimates of costs for a 1,000 m^2 canopy, 65 kW engine, 74 MWhr/year

Basis for estimates: mass-produced components, operated as part of a big system at location like Wellington

Caution: estimates are preliminary, taxation not considered

Cost of land, earthworks, frame and glass	\$25/m^2, so \$25,000 per canopy
Cost of engine and balance of plant	\$1,000/kW, so \$65,000 for a 65 kW engine
Capital cost	\$90,000
Interest rate	8%
Rate of capital return (based on 8% interest and 25 year pay-back)	9.368%
Capital expenditure per year	0.09368 × 90,000 = \$8,431
Operating expenditure per year	4% of capital cost, hence \$3,600
Expenditure per year	\$8,431 + \$3,600 = \$12,031
Metric 1: cost per peak Watt	**\$90,000/65,000W = \$1.38/W_p**
Metric 2: Levelised Energy Cost	**\$12,031/74 = \$163/MWhr**

Final remarks

- Simulations provide a basis to estimate performance.
- Maximum temperature ≈ 140°C; some engine components can be plastic.
- Engine will be large, multi-cylinder, lightly stressed, slow-revving.
- Heat exchangers and condensers not required.
- Engine does not require sophisticated manufacturing techniques (*cf* PV).
- Canopy run-off in Wellington would meet 58% of water need.
- Further studies: sloping canopy, true desert location, variable *r*.
- Construction of a prototype would greatly increase the knowledge base.
- Investors are needed for further progress.