Validation of an Unsteady 2.5D Thermal Convection-Radiation Finite Element Algorithm

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International Test and Evaluation Association

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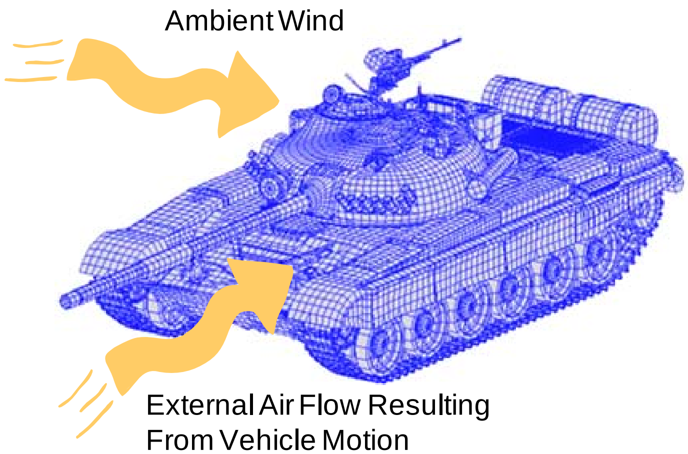
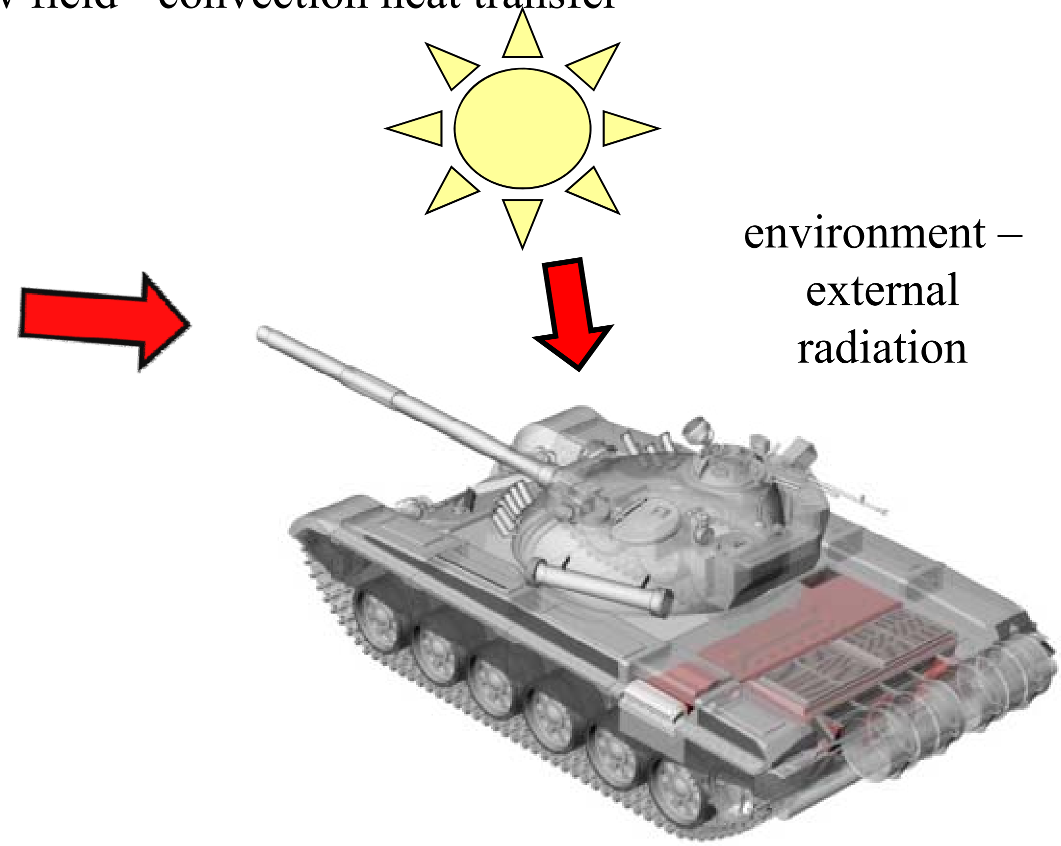
MP Code: Thermal

Target heat transfer $\Rightarrow$ due to operation + environment

Immersion flow field - convection heat transfer





environment –
external
radiation

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Unsteady energy conservation principle + BCs

$$\mathrm{L}(T) = \rho c_p \frac{\partial T}{\partial t} - \nabla \bullet \left[k(x) \nabla T \right] - s\left(\mathbf{x}, t\right) = 0$$

$$\ell(T) = k \nabla T \bullet \hat{\mathbf{n}} + h(T - T_{con}) + \varepsilon\sigma(T^4 - T_{rad}^4) + f(t) = 0$$

BCs: convection + radiation + solar flux

Approximation => $$T(x, y, z, t) \approx T^N(\mathbf{x}, t) \equiv \sum_{\alpha=1}^{M} \Psi_\alpha(\mathbf{x}) Q_\alpha(t)$$

Galerkin 2.5D weak form algorithm:

$$\mathrm{GWS}^N \equiv \int_\Omega \Psi_\beta(\mathbf{x}) \left[\rho c_p \frac{\partial T^N}{\partial t} - \nabla \bullet \left[k \nabla T^N \right] - s\left(\mathbf{x}, t\right) \right] \mathrm{dxdydz} \equiv 0 \ \forall\ \beta$$

$$= \int_\Omega \Psi_\beta \Delta z(\sigma) \left(\frac{\partial T^N}{\partial t} \right) \mathrm{d}\sigma + \int_\Omega \nabla \Psi_\beta \bullet \kappa \nabla T^N \Delta z(\sigma) \mathrm{d}\sigma$$

$$+ \frac{1}{\rho c_p} \left[\int_{\partial\Omega_{\mathrm{BCs}} \cap \partial\Omega} \Psi_\beta \left[h(T^N - T_{conv}) + \sigma\varepsilon \left[(T^N)^4 - T_{rad}^4 \right] + f(t) \right] \mathrm{d}\sigma \right]$$

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Target simulation data requirements

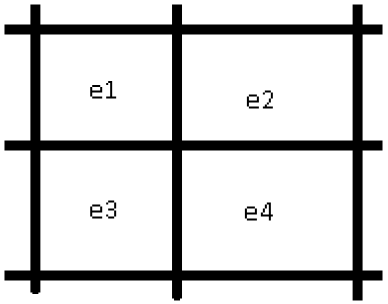
GWS^h + θTS template organizes data requirements

target material properties: ( )( ){THK}(0;1)[b3000]{Q – Qold}
( )(KAPA) {THK} (11+22;-1) [b3011] {Q}
( )(HCON/RCP) { } (0;1) [b200] {Q}

convection heat transfer: ( )(HCON/RCP) { } (0;1)[b200] {Q}

radiation heat transfer: (SIG)(EPS/RCP,VUF) { } (0;1)[b200]{Q exp4}

solar dome radiation: ( )(1/RCP) { } (0;1) [b200] {FLX}



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Convection heat transfer ⇔ target flow field immersion

( )(HCON/RCP) { } (0;1) [b200] {Q}

forced convection - $U > 0$

$HCON = (C1\ k\ Pr^{1/3}\ Re^{1/2})/x$

$Pr = \mu cp/k \sim 0.7$	- Prandtl number for air
$k = 0.0257$ (W/mK)	- air thermal conductivity
x	- distance from flow onset
$Re = \rho Ux/\mu$	- local Reynolds number
$C1 = 0.664$	- from experiment

natural convection - $U \approx 0$

$HCON = k\ C2\ (Gr * Pr)^n$

$Gr = (\rho\ \beta\ \Delta T\ x^3)/\mu^2$	- Grashoff number f(T and DT)
$Pr = \mu cp/k \sim 0.7$	- Prandtl number for air
n = exponent	- depends on flux direction
= 1/4	- target cooled by DT ($\Delta T < 0$)
= 1/3	- target heated by DT ($\Delta T > 0$)
C2 = 0.540; 0.27; 0.14	- from experiment

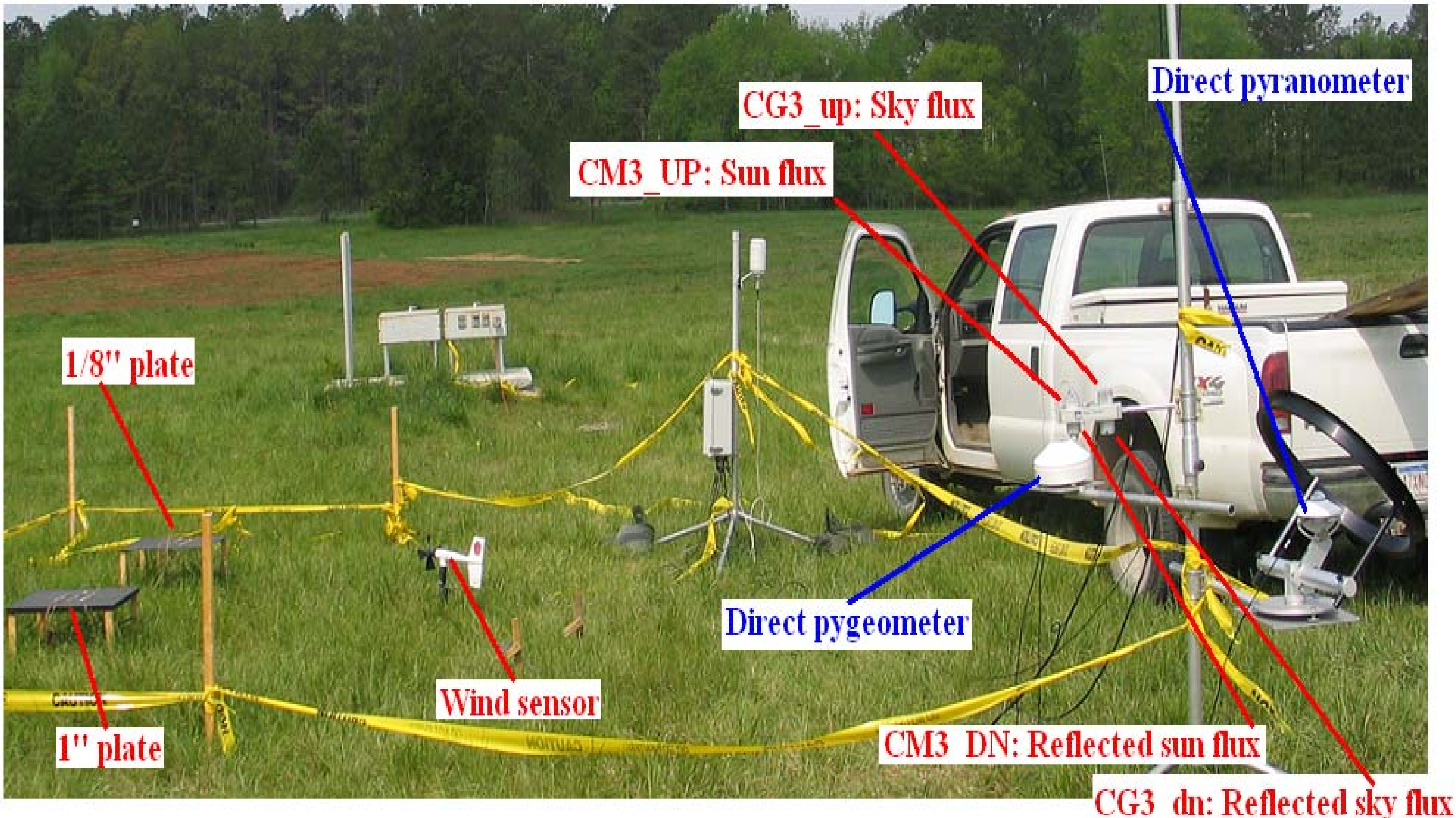
mixed convection - $U \geq 0+$

linear combinations

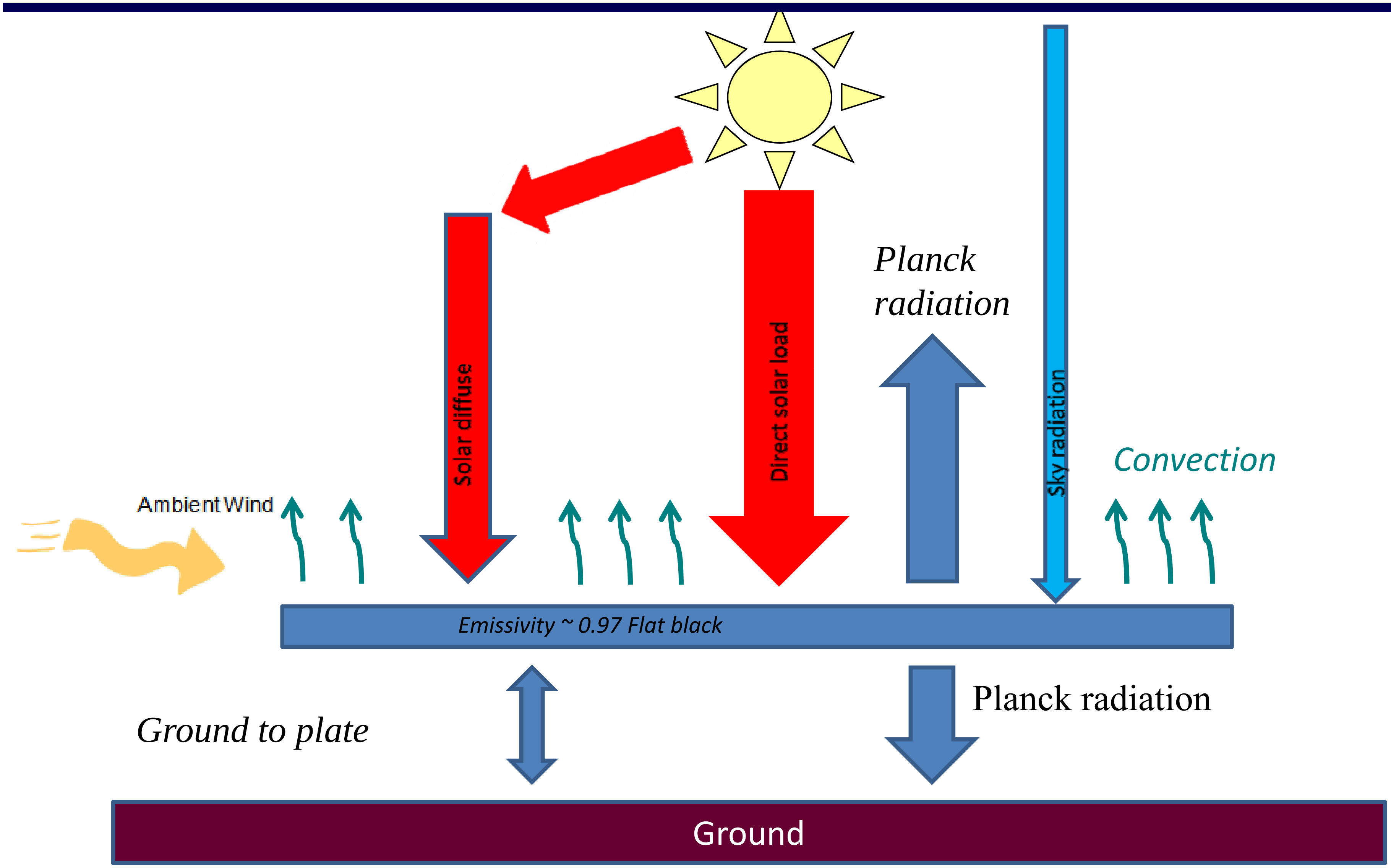
add buoyancy for vertical surfaces

Bobcat Salmon: flat plate diurnal experiments

- two surface flat black aluminum plates, 1/8, 1 inch thick
- convection, both surfaces, all types ⇔ unsteady onset wind
- radiation, non-participating, direct & reflected flux



Energy Budget

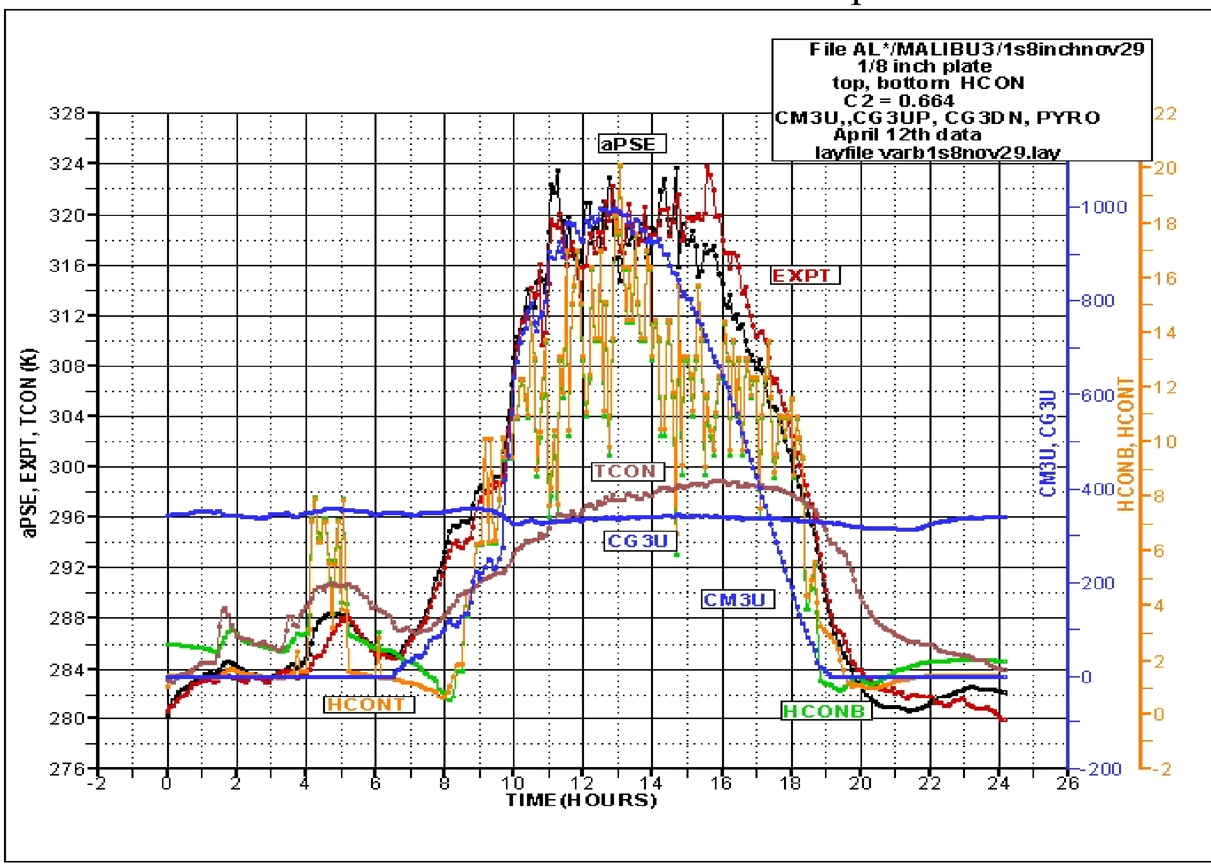


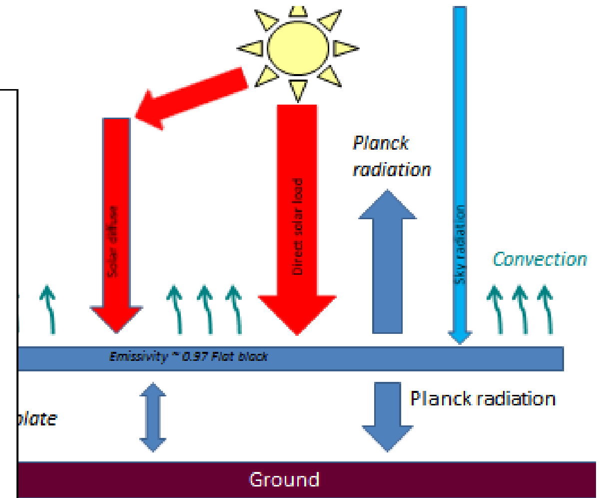
MP Code: Thermal

Validating heat transfer: flat plate diurnal experiments

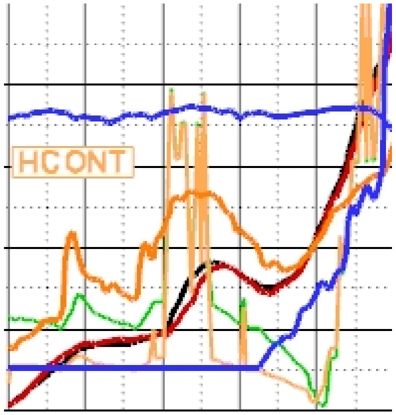
- two surface flat black aluminum plates, 1/8, 1 inch thick
- convection, both surfaces, all types ⇔ unsteady onset wind
- radiation, *non-participating*, direct & reflected flux
- Maximum deviation of just 2-3 Kelvin

*a*PSE GWS^h + ϴTS predictions

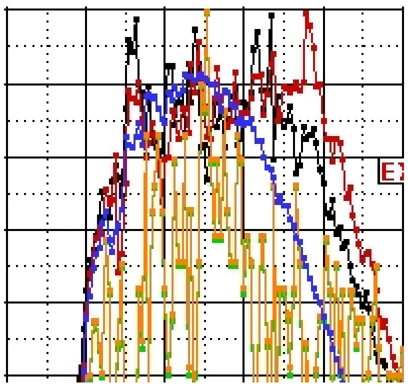




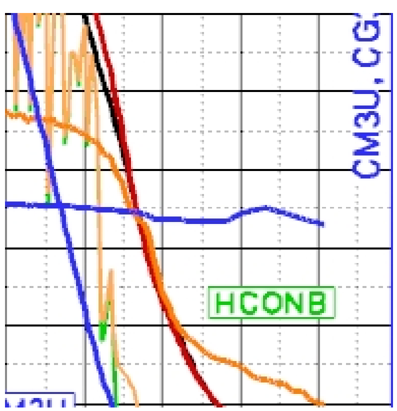
Summary and Conclusions:



- Atmospheric turnover.
- Atmospheric turnover requirement: linear combination of natural and forced convection.
- Excellent agreement



- Temperature profiles dominated by radiation.
- Unsteady onset wind field generates oscillations.
- Agreement excellent ~ 2-3 Kelvin.



- Wind field unsteadiness diminishes, convection goes to zero.
- Temperature profiles track smoothly – excellent agreement.
- Excellent agreement