Implementation and validation of conjugate heat transfer and surface heat transfer, using P_1 thermal radiation model

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The results and the main contents presented in this document, have been reported in the Ph.D. thesis:

- Carlo Cintolesi. *Large-eddy simulations of conjugate heat transfer with evaporation-condensation and thermal radiation*. University of Trieste, School of Environmental and Industrial Fluid Mechanics. Ph.D. thesis, 29 April 2016. NBN: to be assigned

And in the journal paper:

- Carlo Cintolesi, Håkan Nilsson, Andrea Petronio, Vincenzo Armenio. *Numerical simulation of conjugate heat transfer and surface radiative heat transfer using the P_1 thermal radiation model: parametric study in benchmark cases.* To be submitted.

Outline

Research motivations

Thermal radiation rules different environmental and industrial systems.

Environmental flow:

- ▷ atmospheric stratification; solar thermal radiation.

High-temperature applications:

- ▷ combustion processes (engines, rocket nozzles, furnaces);
- ▷ sun emission (greenhouses, solar collectors);
- ▷ nuclear reaction (nuclear power plants).

Low-temperature systems, when combined with convection-conduction:

- ▷ industrial devices (electric ovens, lamp bulb enclosures);
- ▷ building optimisation (room heating systems).

Questions to be faced

- ▷ Radiation is a overwhelming complex phenomenon:
  ⇒ only simplified mathematical models are available;
- ▷ Strong interaction among heat transfer modes in fluid medium:
  ⇒ effective thermal-radiation coupling strategy is required;
- ▷ Heat exchange between fluid-solid media is often crucial:
  ⇒ suitable heat transfer strategy needs to be adopted.

Outline

Radiative Heat Transfer in participating medium

The P_1-model reads:

$$\begin{cases} \nabla^2 G(\mathbf{r}) = \kappa(3\kappa + 3\sigma_s - \sigma_s A)\left[G(\mathbf{r}) - 4\sigma T^4(\mathbf{r})\right] & \text{(medium)} \\ \hat{\mathbf{n}} \cdot \nabla G(\mathbf{r}_w) = \dfrac{\epsilon}{2-\epsilon}\dfrac{3\kappa + 3\sigma_s - \sigma_s A}{2}\left[G(\mathbf{r}_w) - 4\sigma T^4(\mathbf{r}_w)\right] & \text{(Marshak b.c.)} \end{cases}$$

where we denote: $G(\mathbf{r})$ incident radiation, κ absorption/emission coeff., σ_s isotropic scattering coeff., A linear anisotropic scattering coeff., ϵ solid emissivity, σ Stefan-Boltzmann const.

Ref. Modest, *Radiative Heat Transfer*, Elsevier (2013).

Temperature equations for fluid and solid media

- **Fluid**, participating medium term:

$$\frac{\partial T_f}{\partial t} + u_j \frac{\partial T_f}{\partial x_j} = \alpha_f \frac{\partial^2 T_f}{\partial x_j \partial x_j} + \underbrace{\frac{\kappa}{\rho C_p}\left[G(\mathbf{r}) - 4\sigma T^4(\mathbf{r})\right]}_{\textit{medium radiative source}} .$$

- **Solid**, surface radiative heat transfer term:

$$\frac{\partial T_s}{\partial t} = \alpha_s \frac{\partial^2 T_s}{\partial x_j \partial x_j} - \underbrace{\frac{1}{\rho C_p} \nabla \cdot \mathbf{q}_w ,}_{\textit{wall radiative source}}$$

where

$$\mathbf{q}_w(\mathbf{r}_w) = -\frac{1}{2}\left(\frac{\epsilon}{2-\epsilon}\right)\left[G(\mathbf{r}_w) - 4\sigma T^4(\mathbf{r}_w)\right]\hat{\mathbf{n}}.$$

Fluid-Solid conjugate heat transfer

- The conjugate heat transfer is obtained enforcing the balance of the heat fluxes:

$$k_s \left(\frac{\partial T_s}{\partial n} \right) \quad = \quad k_f \left(\frac{\partial T_f}{\partial n} \right)$$

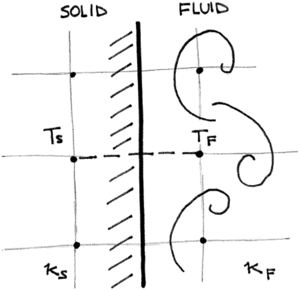
and the continuity of temperature:

$$T_s \big|_{\Gamma} \quad = \quad T_f \big|_{\Gamma}$$

in the boundary condition (Γ interface).

Ref. P. Sosnowsky, PhD Thesis (2013)

Ref. Sosnowsky *et al.* (2013)



Coupling sub-loops

Sketch of thermodynamics resolution algorithm:

1. fluid resolution: G and T solved for fluid medium;
2. thermal-radiation coupling sub-loop: G and T resolved n-times till

   $$\max_{cells} |T_n - T_{n-1}| < \varepsilon_0$$

   is globally satisfied ($\varepsilon_0 = 10^6$ recommended);
3. solid resolution: T solved for solid medium;
4. fluid-solid thermal coupling sub-loop: iteration of steps *1-2-3* till

   $$\max_{\Gamma} |T_s - T_f| < \varepsilon_1 \qquad \text{and} \qquad \max_{cells} \left| k_s \frac{\partial T_s}{\partial n} - k_f \frac{\partial T_f}{\partial n} \right| < \varepsilon_2$$

   are globally satisfied.

Outline

1. Introduction
2. Numerical models
3. Validation of RHT
4. Benchmark on surface RHT
5. Conclusions

Non-dimensional parameters: radiation

- The linear scattering albedo, defined as:

  $$\omega = \frac{\sigma_s}{\kappa + \sigma_s},$$

  relative importance between medium scattering and absorption/emission.
- The optical thickness (or *opacity*), defined as:

  $$\tau_L = (\kappa + \sigma_s)L,$$

  measure of the medium ability to attenuate radiation, where L is the characteristic length of the system.

Validation

The model is tested in all its parts in two geometries:

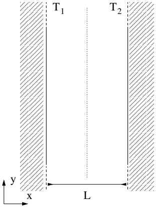
❶ Numerical implementation;

❷ Pure radiations;

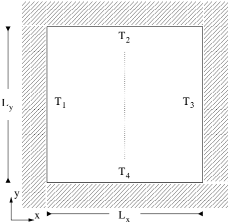
❸ Conduction and radiation;

❹ Convection, conduction and radiation;

Ref. for validation: Modest (2013), Howell *et al.* (2001), Rousse *et al.* (2000), Crosbie and Schrenker (1984), Viskanta (1963).

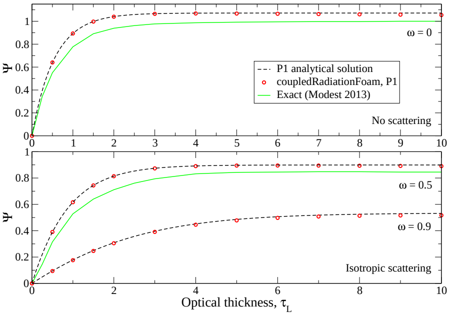


(a) Two infinite plates

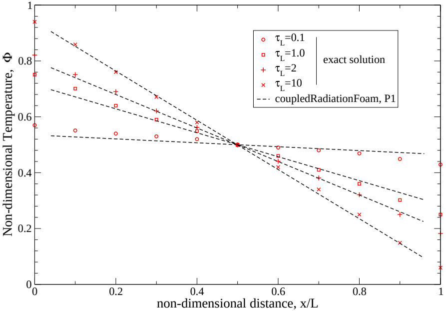


(b) Square enclosure

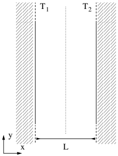
Validation: two infinite parallel plates



(a) Implementation VS analytical sol.

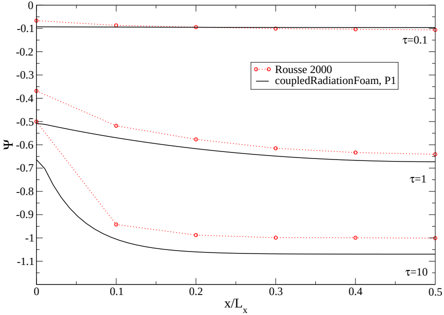


(b) Pure radiation (no scattering)

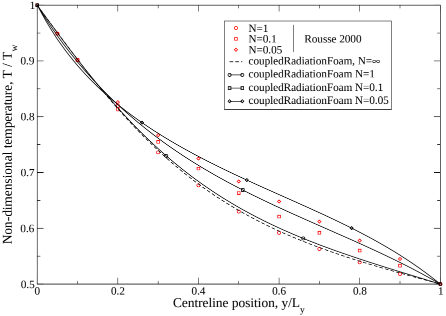


- Ψ is the non-dimensional heat flux onto the plates,
- Φ is the non-dimensional temperature.

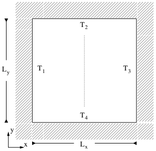
Validation: square enclosure



(c) Pure radiation (no scattering)



(d) Radiation and conduction



- Ψ is the non-dimensional heat flux on bottom wall,
- T/T_w is the non-dimensional temperature.

Prediction capability limits of P_1-model

The P_1-model gives satisfactory results, despite its simplicity.

The main prediction limits are:

❶ tendency to overestimate the RHT effects;

❷ loss of accuracy in case of collimated radiation;

❸ incorrect results for low participating media,
because of Marshak's boundary condition influence;

❹ imprecise for optical tick medium ($\tau \gg 1$).

Note: P_1-model appears more trustworthy in non idealised cases.

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Non-dimensional parameters: heat transfer

- The Stark number, ratio of energy transported by conduction and radiation:

$$N = \frac{(\kappa + \sigma_s)k}{4\sigma \Delta T^3} = 1, 0.1, 0.01$$

- The Boltzmann number, ratio of energy transported by radiation and convection:

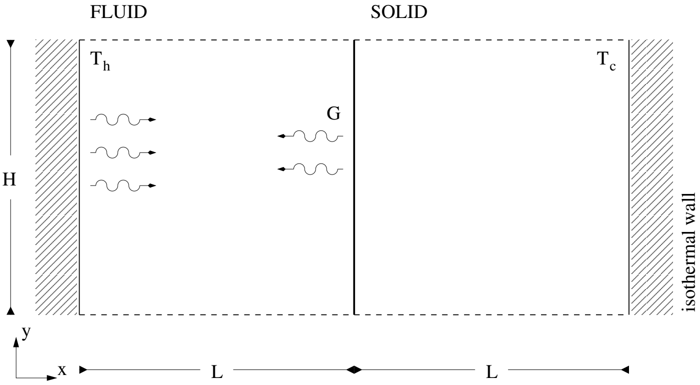
$$Bo = \frac{U\rho C_p \Delta T}{\kappa \sigma \Delta T^4} = 10, 1, 0.1,$$

- The convection-conduction number, ratio of heat flux generated by forced convection and radiation:

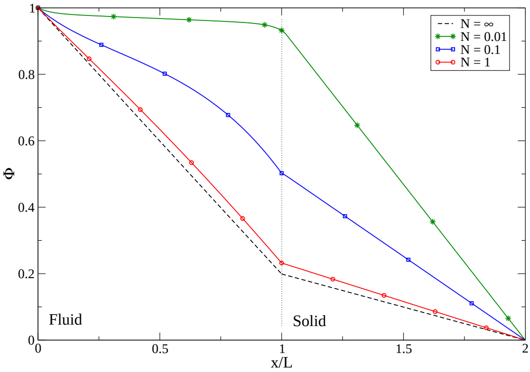
$$Cn = \frac{U\rho C_p}{k} L = 100, 10, 1$$

where U is the characteristic velocity of the system.

Benchmark case: no convection, $Cn = 0$

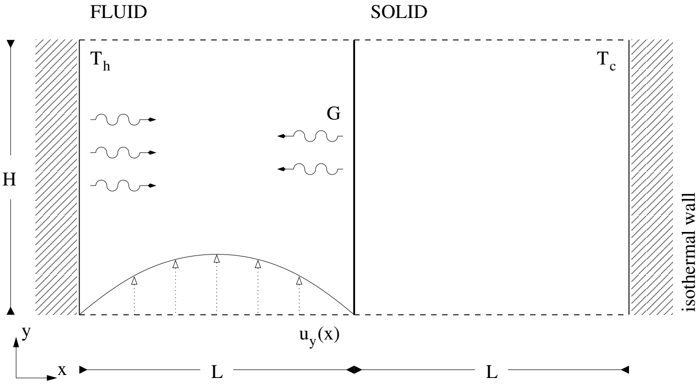


Benchmark case: no convection

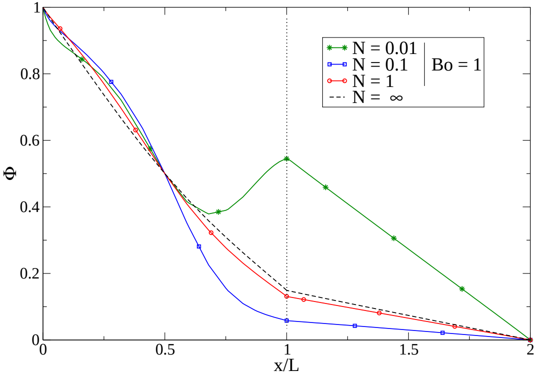


Conduction and radiation: horizontal centreline, profiles of non-dimensional temperature Φ.

Benchmark case: forced convection, $Cn = 10$

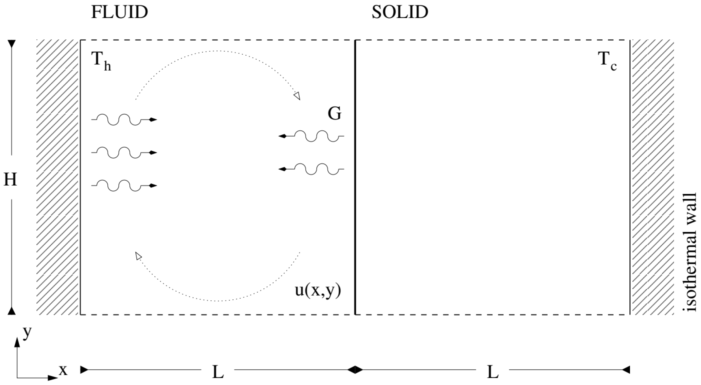


Benchmark case: forced convection

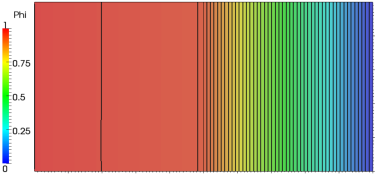


Conduction, radiation and forced convection: horizontal line at level where $T(y/H) = 0.5\Delta T$, profiles of non-dimensional temperature Φ.

Benchmark case: natural convection, $Cn = 10$ and $Bo = 1$

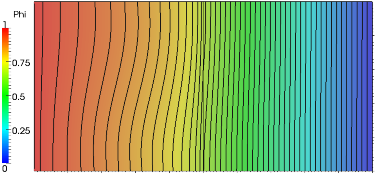


Benchmark case: natural convection



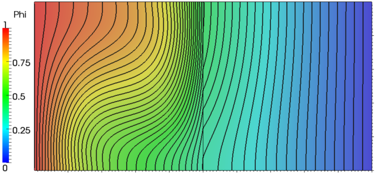
High level of radiation ($N = 0.01$)

$\Leftarrow$



Medium level of radiation ($N = 0.1$)

$\Rightarrow$



Low level of radiation ($N = 1$)

$\Leftarrow$

Outline

Conclusions

- ▷ The transient thermodynamic solver is numerically stable and gives realistic results;
- ▷ A benchmark case for validation of SRHT has been presented, and used for a parametric study;
- ▷ Radiation intensifies the thermal interaction between fluid and solid (increasing interface temperature and developing non-linear temperature profile);
- ▷ In presence of natural convection, radiation tends to decrease the buoyancy force by reducing the thermal gradient.

THANK you