IMPLEMENTATION AND VALIDATION OF CONJUGATE HEAT TRANSFER AND SURFACE RADIATIVE HEAT TRANSFER USING P_1 THERMAL RADIATION MODEL

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Thermal radiation rules, or strongly influences, many different environmental and industrial systems. In applications involving high-temperature phenomena, thermal radiation overcomes the others heat transfer modes. This is the case of the devices characterised by combustion processes (engines, rocket nozzles, furnaces), sun emission (greenhouses, solar collectors), nuclear reaction (nuclear power plant). Radiation can also influence low-temperature systems, leading to non-negligible effects if combined with convection and conduction (*e.g.* electric ovens, lamp bulb enclosures, room heating systems).

In all these cases, a reliable numerical simulation cannot neglect radiative heat transfer (RHT) within the fluid medium, along with the thermal interaction between fluid and the surrounding solids, due to surface heat transfer by conduction and radiation. Indeed, the temperature distribution arising into the solid boundaries can influence the fluid motion (with the rise of a turbulent buoyancy driven flow) and the overall thermodynamic equilibrium.

Despite the wide range of applications, the numerical reproduction of thermal radiation and solid-fluid thermal interaction is a formidable challenge from both theoretical and numerical point of view.

From the theoretical side, the physics governing the thermal radiation is extremely complex, and governing equations can be derived just under simplified hypothesis. In many applications, the medium participates to RHT (it can absorb, emit and scatter radiation) and the RHT equations can be written as a set of integro-differential equations.

From a numerical point of view, a direct numerical resolution of such equations can require a large computational effort. When the surface radiative heat transfer (SRHT) is also simulated, a coupling loop between temperature and radiation needs to be performed. Thus, the computational power required to solve the radiative equation is multiplied by the number of coupling loop iterations, eventually leading to unfeasible simulations.

The present contribution aims to present a numerical solver that simulates the mentioned phenomena; to validate it against literature results, pointing out the advantages and the limits of the model adopted; to investigate the SRHT effects, introducing also a new benchmark case for SRHT validation. The attention is focused on three main issues:

(i) *Thermal radiation*: the P_1-model is adopted in order to solve the thermal radiation field inside a participating medium with linear and linear-anisotropic scattering (ref. Modest [1]); hence, the RHT equations are approximated by first order series expansion in spherical harmonics function. The governing equations reduce to simple diffusive-like equation, that are fast to solve numerically:

$$\left\{ \begin{aligned} \nabla^2 G(\boldsymbol{r}) &= \kappa(3\kappa + 3\sigma_s - \sigma_s A)\big[G(\boldsymbol{r}) - 4\sigma T^4(\boldsymbol{r})\big] \\ \boldsymbol{n}\cdot\nabla G(\boldsymbol{r}_w) &= \frac{\epsilon}{2-\epsilon}\,\frac{3\kappa + 3\sigma_s - \sigma_s A}{2}\big[G(\boldsymbol{r}_w) - 4\sigma T^4(\boldsymbol{r}_w)\big] \end{aligned} \right. \tag{1}$$

where we denote with: G the incident radiation, T the absolute temperature, σ the Stefan-Boltzmann constant, κ the absorption coefficient, ϵ the surface emission coefficient, σ_s and A the linear and linear-anisotropic scattering factor (respectively), $\boldsymbol{r}$ and $\boldsymbol{r}_w$ the points into the medium and onto the surface (respectively), $\boldsymbol{n}$ the surface normal.

(ii) *Solid-fluid thermal coupling*: the conjugate heat transfer technique developed by Sosnowski *et. al* [2] and employed by Cintolesi *et al.* [3], is used to simulate the heat transfer by conduction through the solid-fluid interface Γ. The continuity of temperature and the balance of the heat fluxes are enforced:

$$T_s\big|_\Gamma = T_f\big|_\Gamma \qquad \text{and} \qquad k_s\left(\frac{\partial T_s}{\partial n}\right) = k_f\left(\frac{\partial T_f}{\partial n}\right), \tag{2}$$

where $k_{s/f}$ is the thermal conductivity of solid/fluid medium.

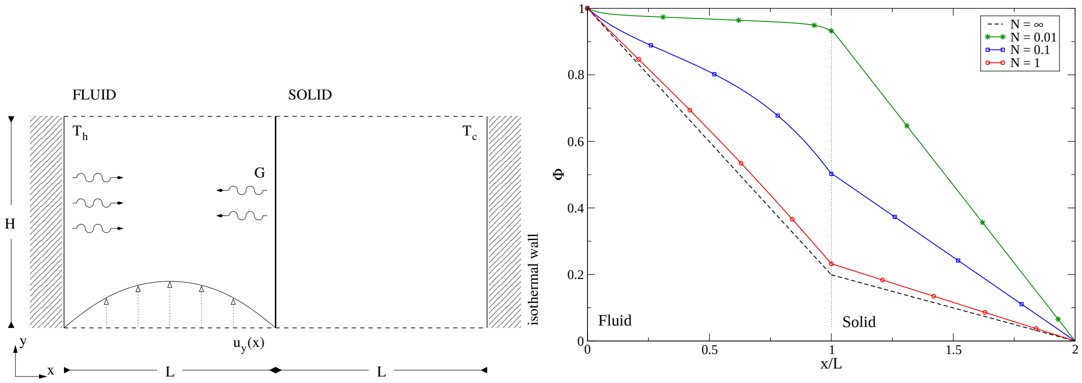

Figure 1: Investigation on SRHT effects; (left) geometry of the benchmark case, (right) conduction and radiation with SRHT.

(iii) *SRHT*: the heat transfer by radiation into the solid is simulated by the technique of virtual source term. The radiative heat flux on the interface is turned into a heat source therm that is added to the temperature equation in the first cell near the interface:

$$S_w = -\frac{1}{(\rho C_p)_s}\nabla\cdot\boldsymbol{q}_w, \qquad \text{and} \qquad \boldsymbol{q}_w = -\frac{1}{2}\left(\frac{\epsilon}{2-\epsilon}\right)\left[G(\boldsymbol{r}_w) - 4\sigma T^4(\boldsymbol{r}_w)\right]\boldsymbol{n}, \tag{3}$$

where $(\rho C_p)_s$ is the solid heat capacity.

The numerical implementation is carried out within the OpenFOAM framework. We use a numerical solver developed by the *Environmental and Industrial Fluid Mechanics* group of the University of Trieste, that is based on large-eddy simulation approach and includes the computation of conjugate heat transfer between solid and fluid domains. The authors extended the code in order to simulate the effects of RHT and SRHT, and used to perform simulations. The study is divided in three parts:

First, the numerical model is presented and the main implementation issues are discussed.

Second, the different simulations are performed to carefully validate the radiative model and to investigate the theoretical limits of the P_1-model with respect to other models proposed in literature (ref. Rousse *et al.* [4]). The following points are analysed (using different combinations of radiative parameters) and the simulations compared with literature results: numerical implementation correctness; pure radiation (*i.e.* in absence of conduction and convection); combined conduction and radiation; combined convection, conduction and radiation.

Third, the SRHT effects are investigated in the simplified geometry reported in Figure 1-left, in presence of radiation-conduction and radiation-conduction-convection. Simulations are performed for a wide range of non-dimensional radiative numbers.

Figure 1-right shows the non-dimensional temperature Φ over a line $y = cost$, in case of radiation and convection, for different radiation-conduction parameter N. The case of no radiation ($N = \infty$) is reported as reference. With $N = 1$ (low radiation) the fluid and the solid surfaces are slightly heated up by the radiative effects, but the temperature distribution in the medium is still linear. At $N = 0.1$ the radiation significantly heats up the solid surface and adulterates the medium temperature that is not linear anymore. When radiation dominates ($N = 0.01$) the fluid domain is almost at the same temperature of the hot wall.

It is found that P_1-model gives a satisfactory prediction of thermal radiation effects. The SRHT strongly influences the fluid thermodynamic, especially in case of high RHT. To the best of our knowledge, no validation cases are reported in literature for the SRHT. Thus, this work can provide a benchmark case in this field.

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