11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
July 20–25, 2014, Barcelona, Spain

RESIDUAL DISTRIBUTION SCHEMES FOR THE COMPUTATION OF HYPERSONIC FLOWS WITH STRONG BOW SHOCK WAVES: ENFORCING TOTAL ENTHALPY CONSERVATION

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Key words: *Residual Distribution, Flux Difference Splitting, Heat Flux, Hypersonic Flow.*

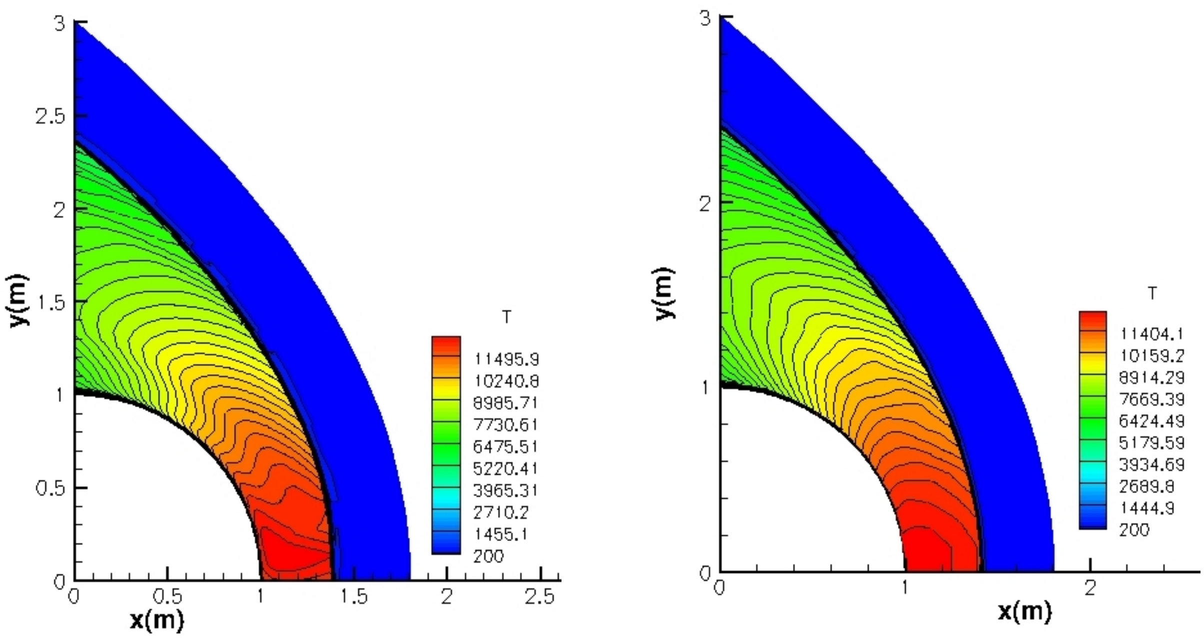
Numerical simulation of hypersonic flows is a challenging activity, since the complexity characterizing compressible flow aerodynamics have to be addressed together with additional high-temperature effects phenomena (see Ref. 1).

Residual Distribution (*RD*[1]) Methods evince several advantageous features for the computation of compressible flows. Among them, we stress the following:

- A maximum principle (Local Extrema Diminishing) borrowed from Finite Volume (*FV*), which allows to capture discontinuities monotonically on general unstructured grids;
- Being based on finite element (*FE*) approximation theory, it is possible to obtain, on a compact stencil, second-order order accurate solutions on unstructured grids;
- Less grid sensitivity on simplicial meshes, thanks to a built-in multidimensional dissipation property.

These reasons make *RD* schemes appealing for the simulation of atmospheric entry flow problems. In a recent study (cfr. Ref 2), the flow field and heat flux prediction capabilities of *RD* methods applied to the computation of high temperature flow fields have been investigated: *RD* methods are capable of producing accurate flow solutions and heat flux prediction for flows where no shock waves are present, irrespective of whether the gas is modeled as ideal and inert or in non-equilibrium; for both 2D and axisymmetric computations. Unfortunately, when applying straightforwardly the same *RD* technique to flows including strong shocks, the heat flux retrieved exhibits severe deficiencies. Considering the $Ma = 17.$ flow around a cylinder,the hottest spot

[1] *RD* methods are also known under the name of Fluctuation Splitting (*FS*) schemes.



(a) *RD* solution.

(b) *RD* solution, enforcing $\frac{H_t}{H_{t,\inf}} = 1.$ across the shock wave.

Figure 1: Hypersonic flow around cylinder, shock wave captured.

in the flow field is not on the stagnation line, see Fig. 1(a), and consequently the predicted heat flux is not correct. As established in Ref. [2], the way *RD* multi-dimensional upwind schemes capture the shock wave is the culprit of the poor results in Fig. 1(a), in particular how the total enthalpy is handled across the shock. In fact, by running the same computation but forcing the flow field to respect $\frac{H_t}{H_{t,\inf}} = 1.$ everywhere but -of course- in the boundary layer: we obtain the expected shape of the temperature isolines in the post-shock region, as seen in shown in Fig. 1(b).

Our priority is thus the derivation of *RD* schemes that are total enthalpy conserving across shock waves. To do so, we will analyze how enthalpy conservation is achieved both in the *FV* (Ref. 3) and the stabilized *FE* (Ref. 4) contexts, study the merits and downsides of either approach and integrate the most suitable of them in the *RD* framework.

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