DEVELOPMENT OF THE COUPLING BETWEEN DPLR AND NEQAIR

Entry System and Technology Division
NASA Ames Research Center
Summer internship 2017

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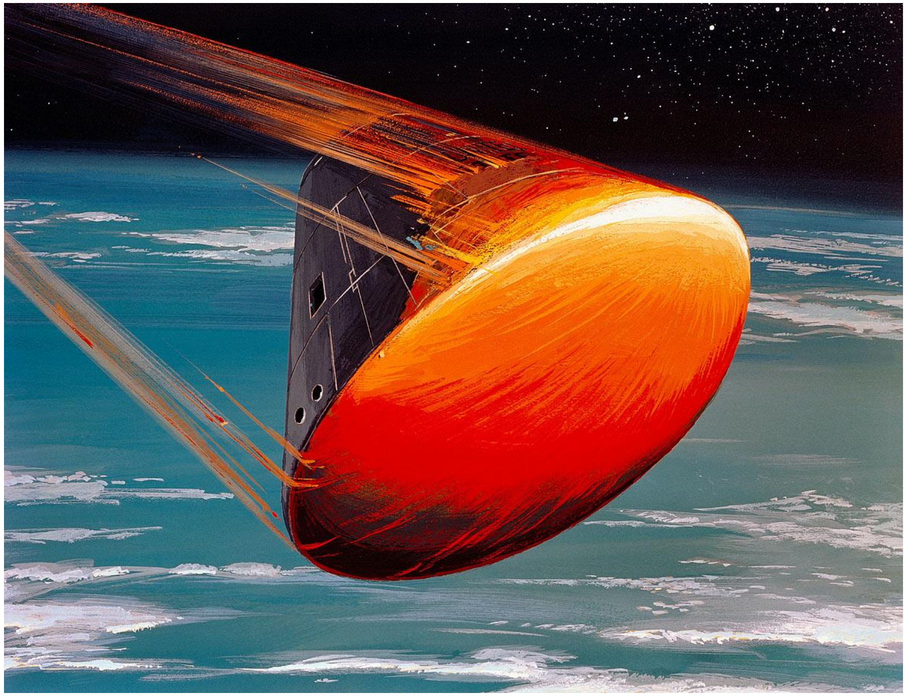
Motivations

- The heatshield of a spacecraft entering an atmosphere at high velocities will experience high heat loads.
- The heat transfer to the spacecraft is one the most important parameters for Thermal Protection System (TPS) design and one of the most difficult to calculate numerically.
- TPS design requires an accurate prediction of the heating rates (material selection) and the total integrated heat load (material thickness).



MOTIVATIONS

- Consider two components of the energy balance: ***CONVECTIVE*** and ***RADIATIVE*** heating;
  - radiant energy can be a significant fraction of the total energy
- Including radiative heating can:
  - Reduce bow shock standoff distance
  - Reduce the total surface heat load through radiative cooling

ENERGY BALANCE

$$\frac{\partial e}{\partial t} + \underbrace{\frac{\partial}{\partial x_j}\left((e+p)u_j\right)}_{\text{Convective Energy Term}} = \underbrace{-\Theta^R}_{\text{Radiant Energy Source Term}} + \underbrace{\frac{\partial}{\partial x_j}\left(q + q_{vj} + q_{ej}\right) - \frac{\partial}{\partial x_j}\left(u_i \tau_{ij}\right) - \frac{\partial}{\partial x_j}\left(u_{si}\left(h_s \delta_{ij} + \tau_{sij}\right)\right)}_{\text{Viscous flux terms}}$$

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FLUID – RADIATION COUPLING

- Data-Parallel Line Relaxation (DPLR) Code:
  - 2-D/3-D nonequilibrium Navier–Stokes flow solver,
  - accurate analysis of the flow under hypersonic conditions;
- The NEQAIR code is a line-by-line radiation code:
  - radiation computation along each line of sight;
  - flow information provided by DPLR;
- The Coupler code is a Python interface:
  - sets up all the directories and files for a coupled calculation;
  - creates the required couple tools.

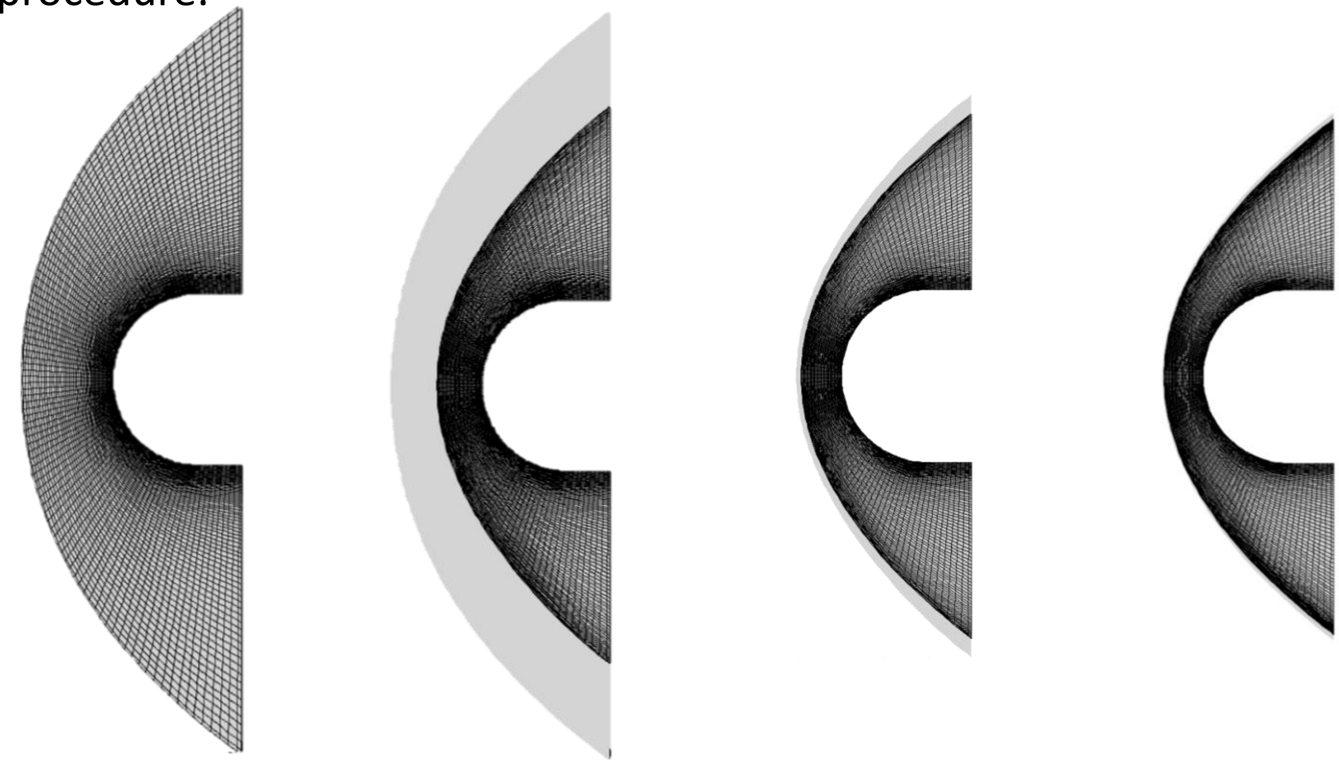
Fluid – Radiation Coupling

Iteration 0

Uncoupled DPLR run

- Grid alignment necessary for accurate CFD analysis:
  - reduces number of grid cells from the free stream
  - adjusts the outer boundary to align with the shock wave
  - decreases wall spacing to resolve boundary layer
- A simple geometry was analyzed to get familiar with the grid alignment procedure.

Free stream →



No alignment | 1st alignment | 2nd alignment | 3rd alignment

Fluid – Radiation Coupling

Iteration 0

Uncoupled DPLR run

Write LOS files

Write LOS_1 ••• Write LOS_ j ••• Write LOS_M

NEQAIR runs

NEQAIR_1 ••• NEQAIR_ j ••• NEQAIR_M

Extract radiation data at the wall

Post-process Radiation

Loops over $line_1$ to $line_k$

Loops over $line_{j+1}$ to $line_{j+k}$

Loops over $line_{Mj+1}$ to $line_{Mj+k}$

Source term

Optional simulation parameters

Coupled DPLR run

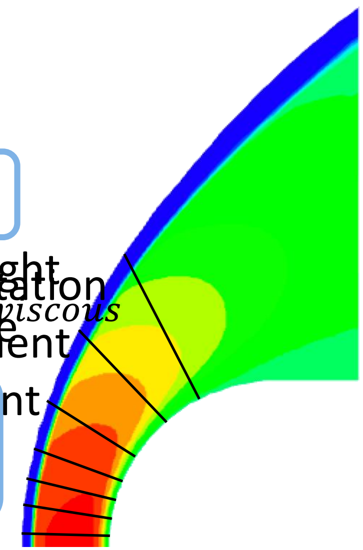
Grid alignment parameter

$$\frac{\partial e}{\partial t} + \frac{\partial}{\partial x_j}\left((e+p)u_j\right) = -\alpha\, Q^R + \dots_{viscous}$$

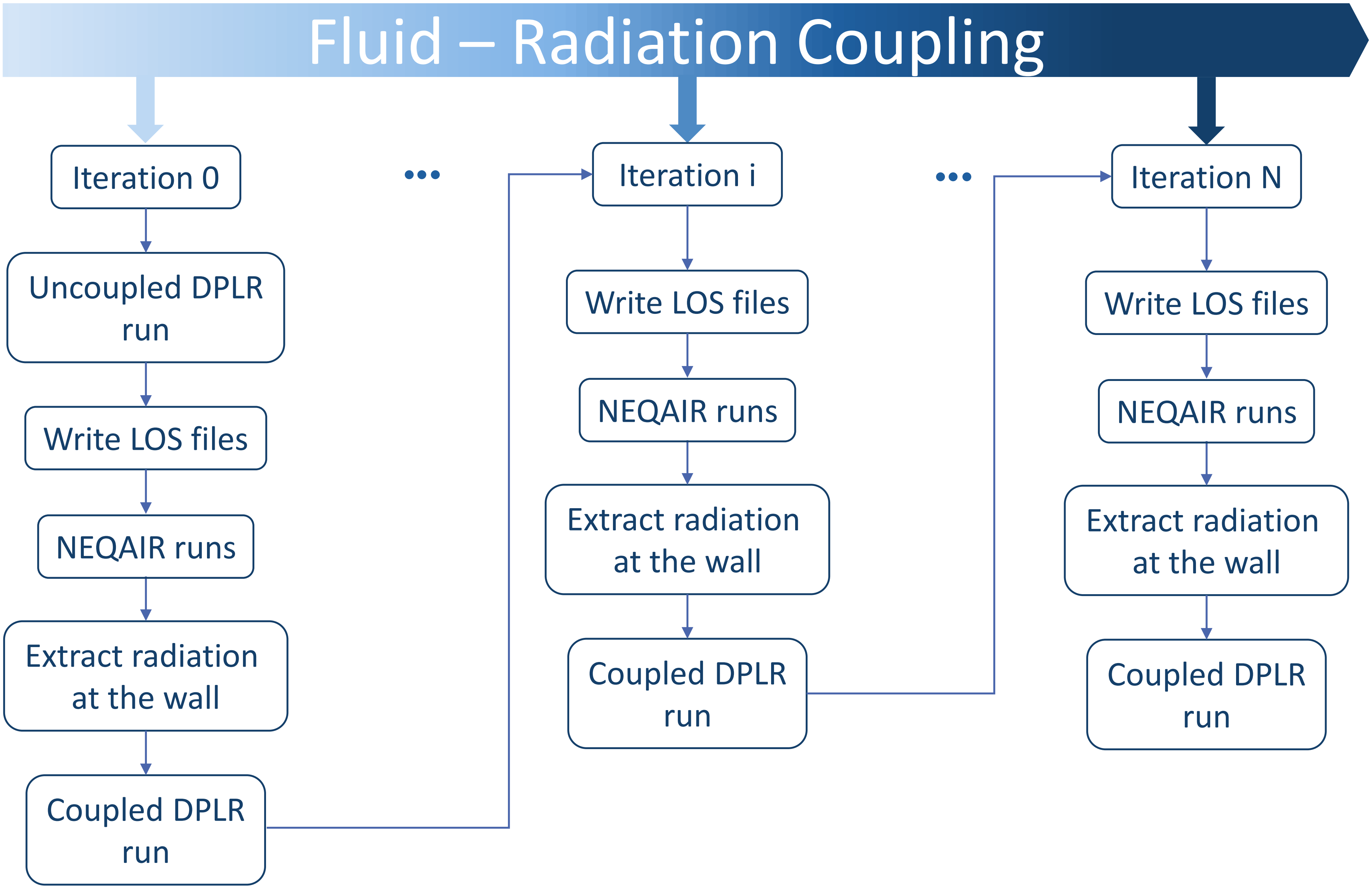
- Igalign: enables the grid adaptation
- 0: do not perform alignment
- 1: perform basic alignment

M Lines of Sight normal to the surface

Scale factor for radiative term



- Each line of sight is independent of all the other LOS. Therefore, it is possible to divide the LOS in groups and save them in separated files.
- This method allows parallelizing and accelerating the process


Fluid – Radiation Coupling
Iteration 0
Uncoupled DPLR run
Write LOS files
NEQAIR runs
Extract radiation at the wall
Coupled DPLR run
•••
Iteration i
Write LOS files
NEQAIR runs
Extract radiation at the wall
Coupled DPLR run
•••
Iteration N
Write LOS files
NEQAIR runs
Extract radiation at the wall
Coupled DPLR run

Coupler Input File

```
[INPUT_FILES]
!----------------------------------------------------------------------------!
dplr_dir = /User_dir/DPLR-NEQAIR/testcase/dplr
dplr_input = dplr.inp
dplr_post = post.inp
dplr_grid = grid.pgrx
dplr_flow = flow_sol.pslx
neqair_dir = /User_dir/DPLR-NEQAIR/testcase/neqair
neqair_input = neqair.inp
!----------------------------------------------------------------------------!
[/INPUT_FILES]
```

Input directories for uncoupled flow solution and NEQAIR input file

```
dplr_runs_per_iteration = 1
coupling_run_dirs = iter_
dplr_run_dirs = dplr_
neqair_run_dirs = neqair_
dimensions = 2
normal_line = j
!----------------------------------------------------------------------------!
```

Run directories numbered by prefix and iteration count. Separate directories created for DPLR and NEQAIR runs.

```
[DPLR_OPTIONS]
!----------------------------------------------------------------------------!
scale_divq = [0.2, 0.5, 0.75, 1.0]
!----------------------------------------------------------------------------!
[/DPLR_OPTIONS]
```

Scale factor for the radiative term

```
nodes = 1
cores = 64
days = 0
hours = 2
minutes = 0
jobname = test2couple
neqair_mpi_procs = 64
neqair_log = neqair-log
neqair_runs = 4
neqair_batch_mode = independent
dplr_mpi_procs = 32
dplr_log = dplr-log
!----------------------------------------------------------------------------!
[/BATCH]
```

Number of NEQAIR and LOS iterations, and SLURM variables.

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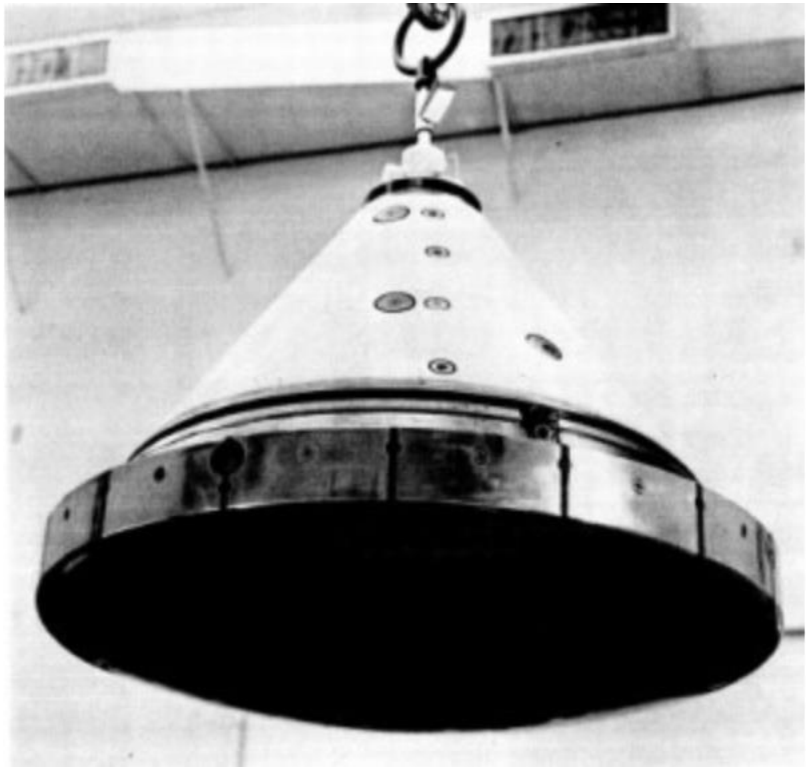
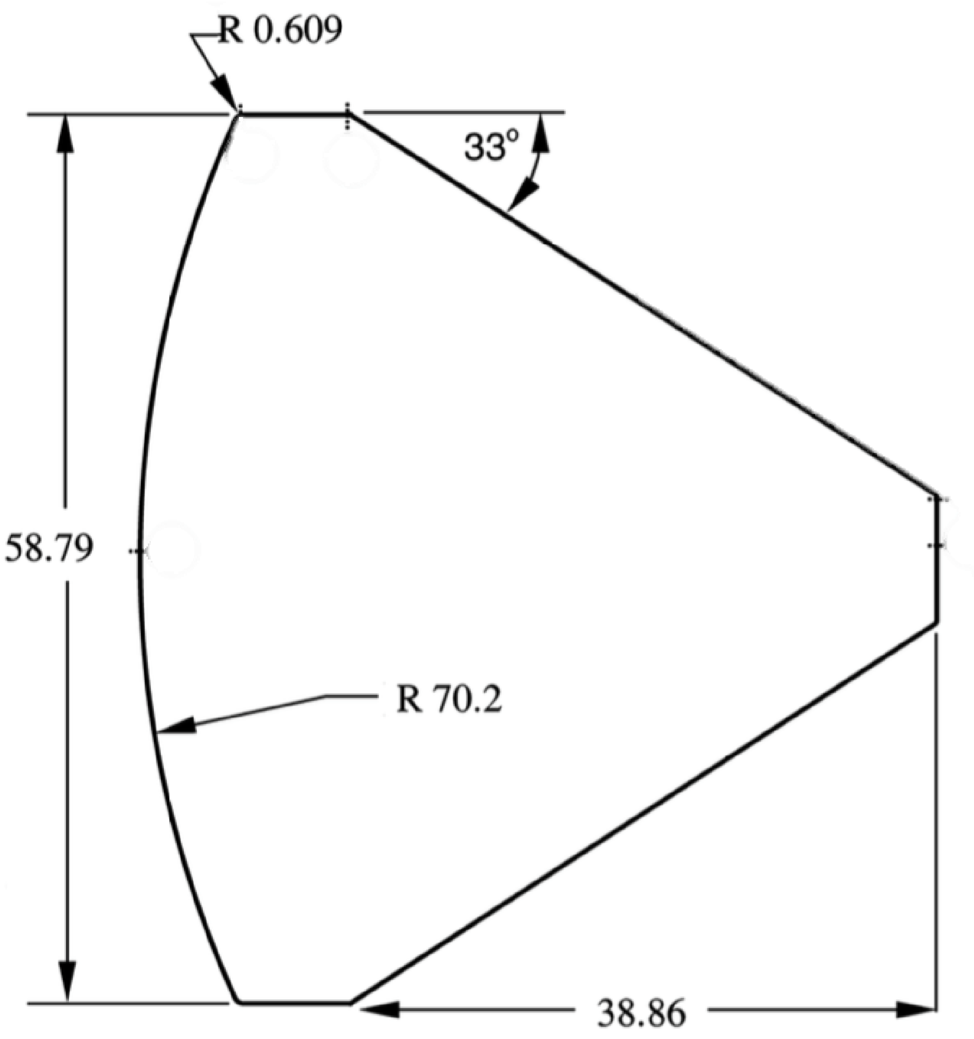
FIRE II CAPSULE

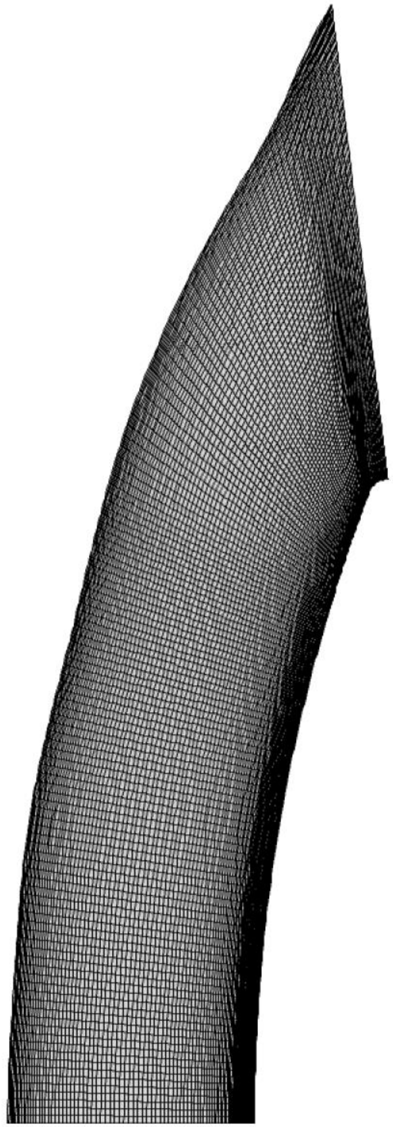
- Project FIRE (Flight Investigation of the Reentry Environment) , which flew in 1965, was conducted expressly for the purpose of measuring radiative heating at Lunar return velocities.

- The FIRE-II experiment is considered to be the best documented data set available on radiative heating.



FIRE II GEOMETRY





FIRE II CONDITIONS

DPLR

- Two-temperature model describes the thermochemical nonequilibrium:
  - translational-rotational temperature T
  - vibrational-electronic temperature T_v ;
- An 11 species gas model is used to simulate the flow: N_2, O_2, NO, NO^+, N_2^+, O_2^+, N, O, N^+, O^+, e^-;
- Park's 1993 21-reaction, 11-species kinetic model.

NEQAIR

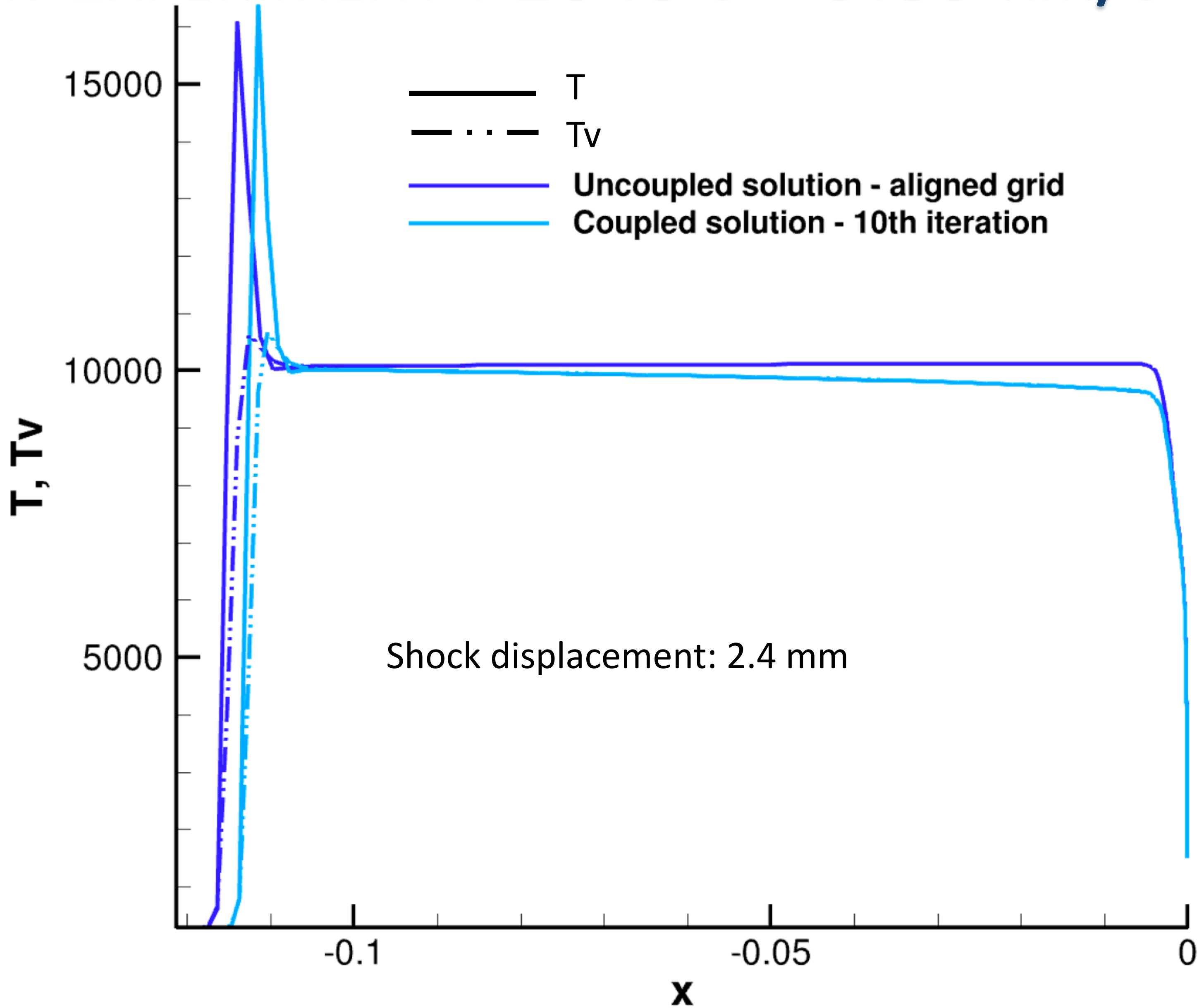
- The calculations were performed using a Boltzmann distribution assumption;
- The spectral range was analyzed over 85.5-3960 nm;

FREE STREAM CONDITIONS

Experiment	Free Stream Entry Velocity [km/s]	Free Stream Density [kg/m^3]	Free Stream Translational Temperature [K]	Wall temperature [K]
FIRE II 1645 s	9.83	$1.32 \cdot 10^{-3}$	285	1520
FIRE II 1643 s	10.48	$7.8 \cdot 10^{-4}$	276	640
FIRE II 1636 s	11.3	$8.75 \cdot 10^{-5}$	210	810

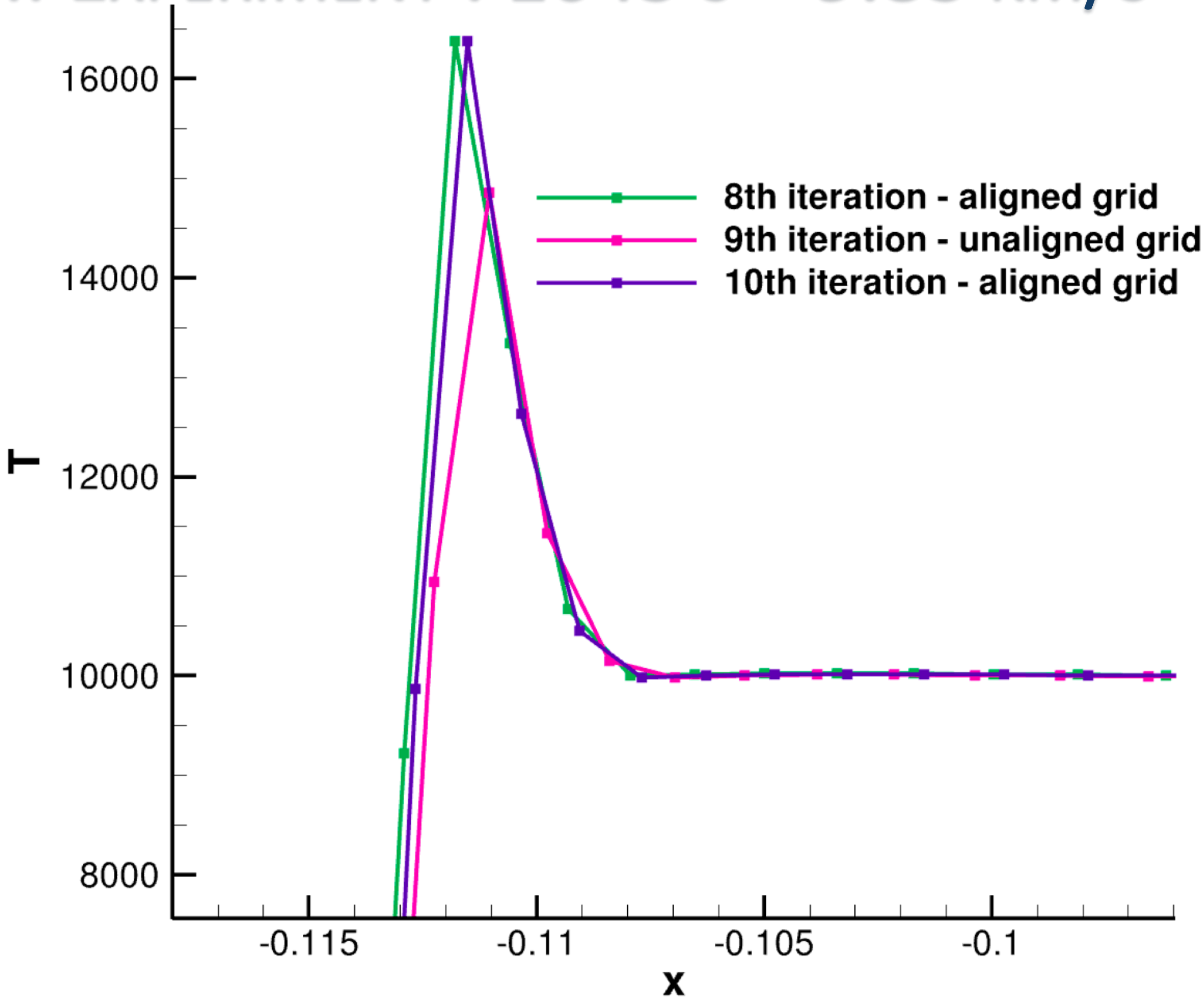
Lewis Jr, John H., and William I. Scallion. "Flight parameters and vehicle performance for Project Fire flight II, launched May 22, 1965." (1966). NASA Langley Research Center

FIRE II EXPERIMENT : 1645 S – 9.83 KM/S

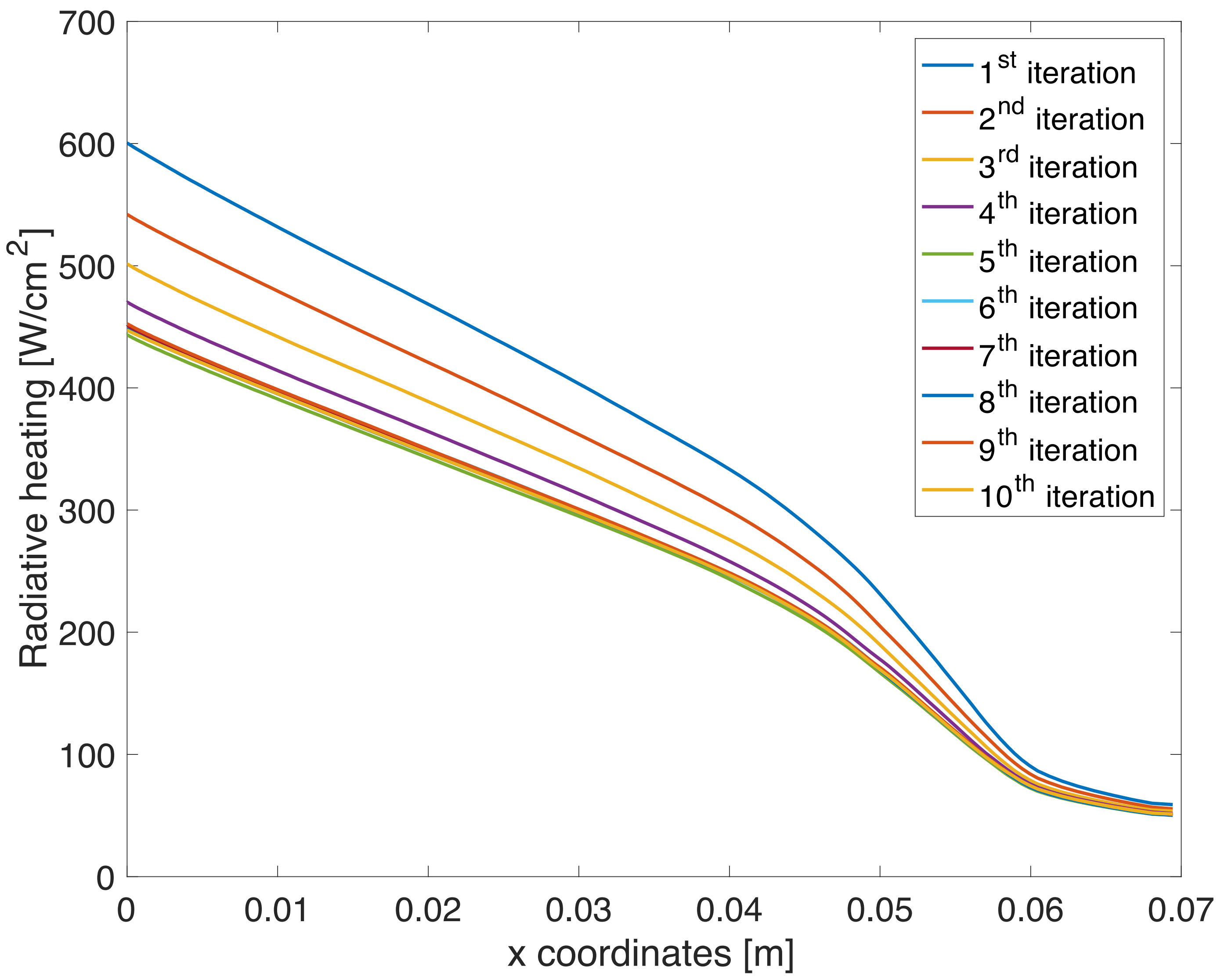


Shock displacement: 2.4 mm

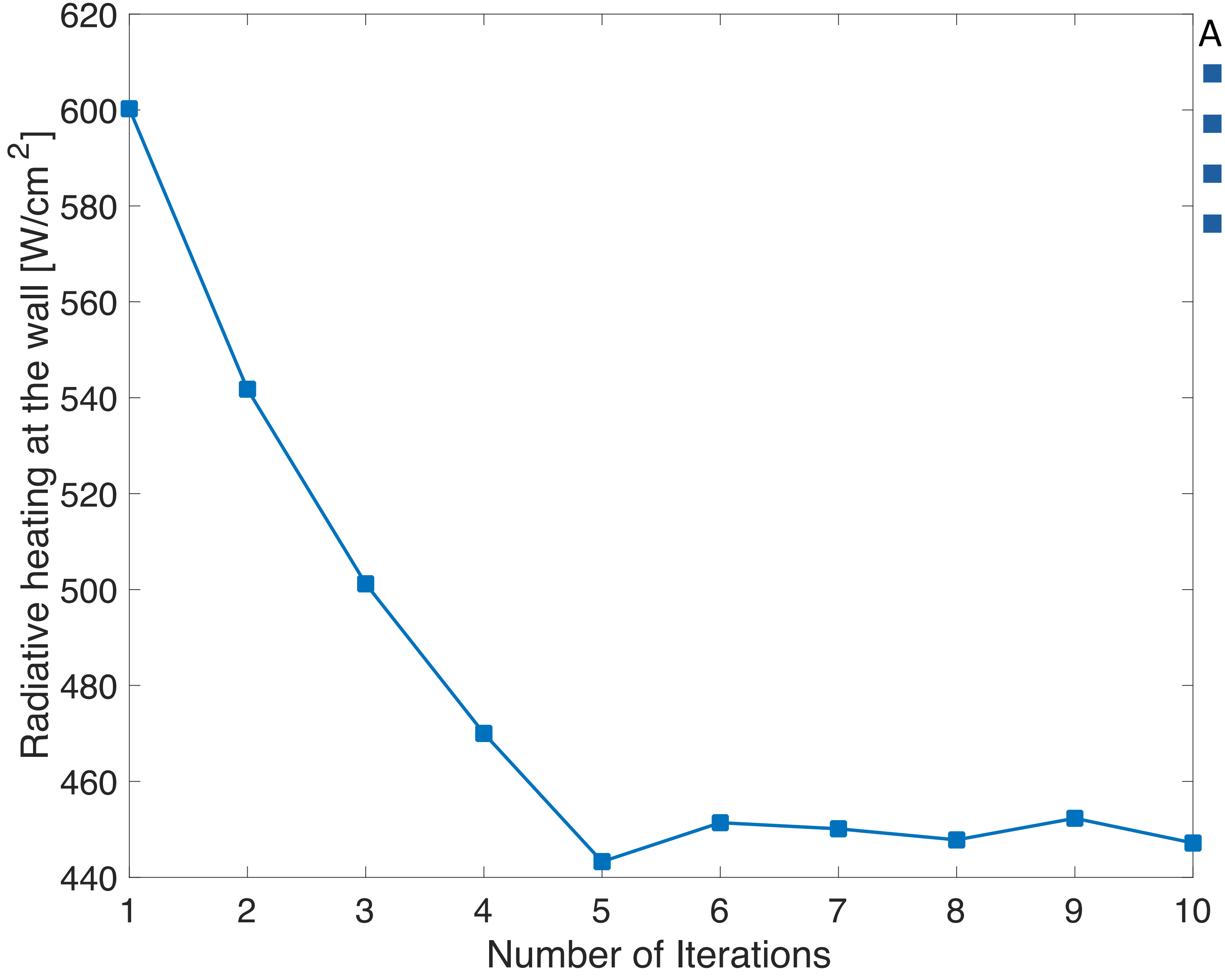
FIRE II EXPERIMENT : 1645 S – 9.83 KM/S



FIRE II EXPERIMENT : 1645 S – 9.83 KM/S



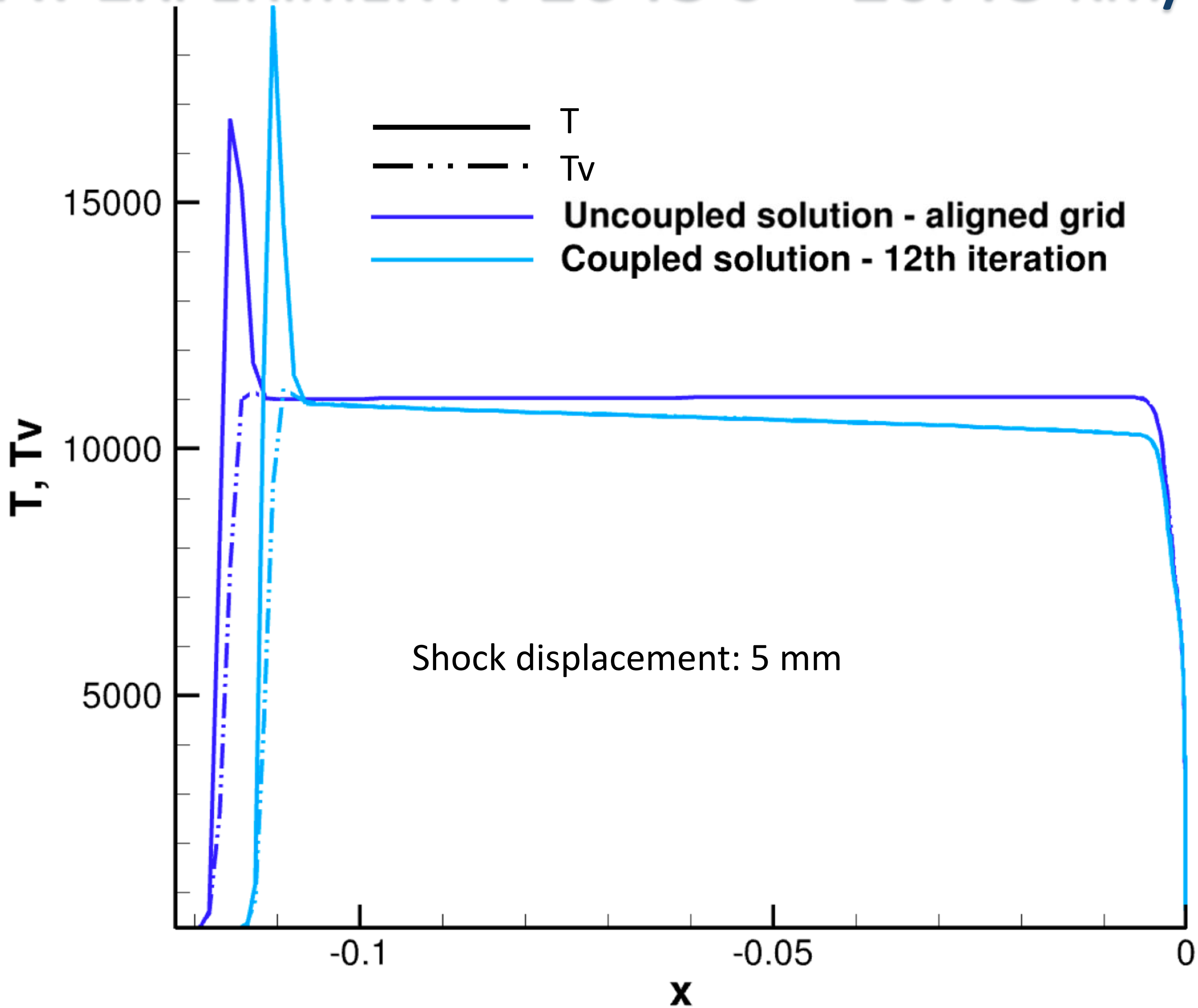
FIRE II EXPERIMENT : 1645 S – 9.83 KM/S



Applied scale factor:

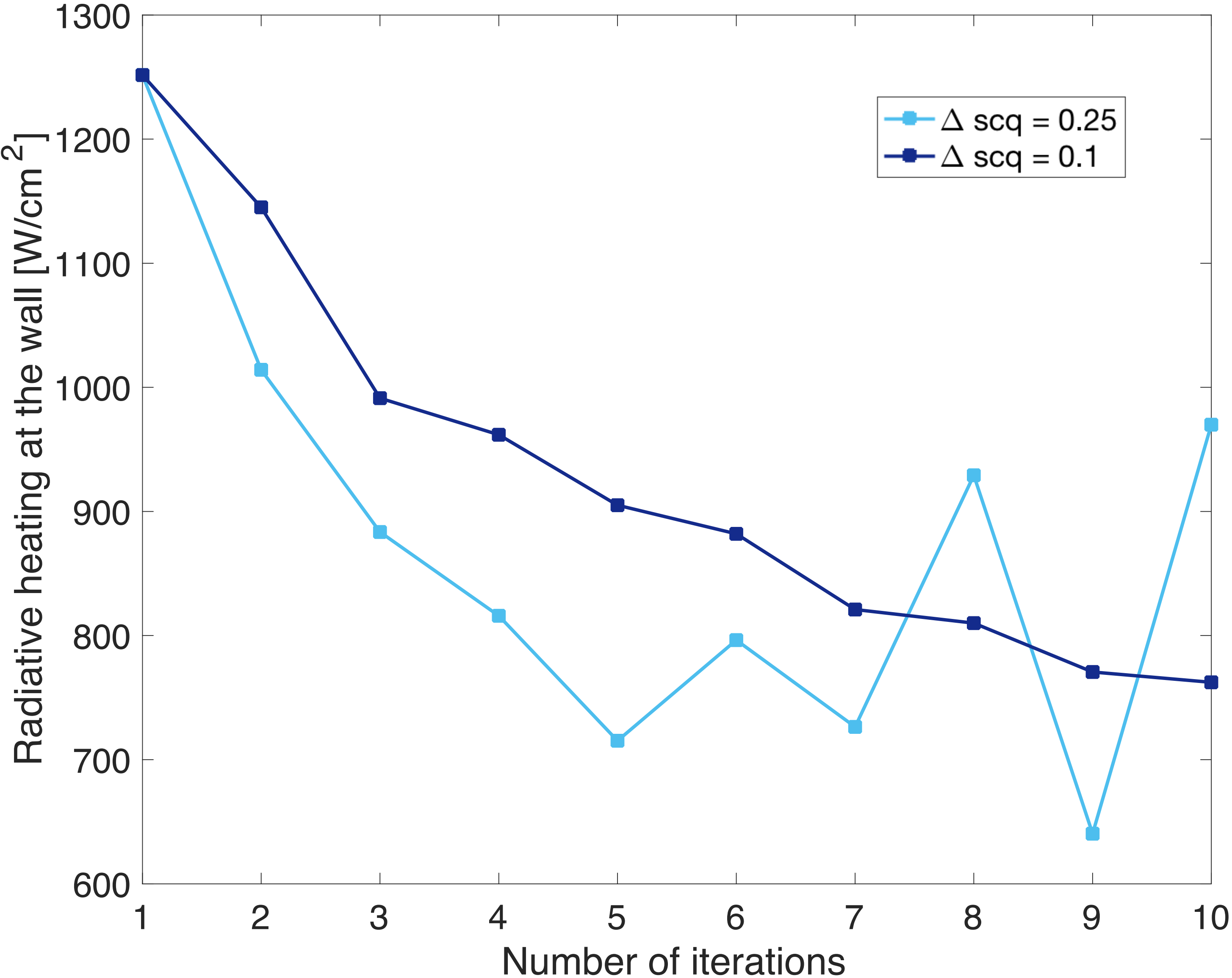
- 1st it.→scq=0.25
- 2nd it.→scq=0.5
- 3rd it.→scq=0.75
- 4th : 10th its.→ scq=1

Fire II Experiment : 1643 s – 10.48 km/s



Shock displacement: 5 mm

FIRE II EXPERIMENT : 1643 S – 10.48 KM/S

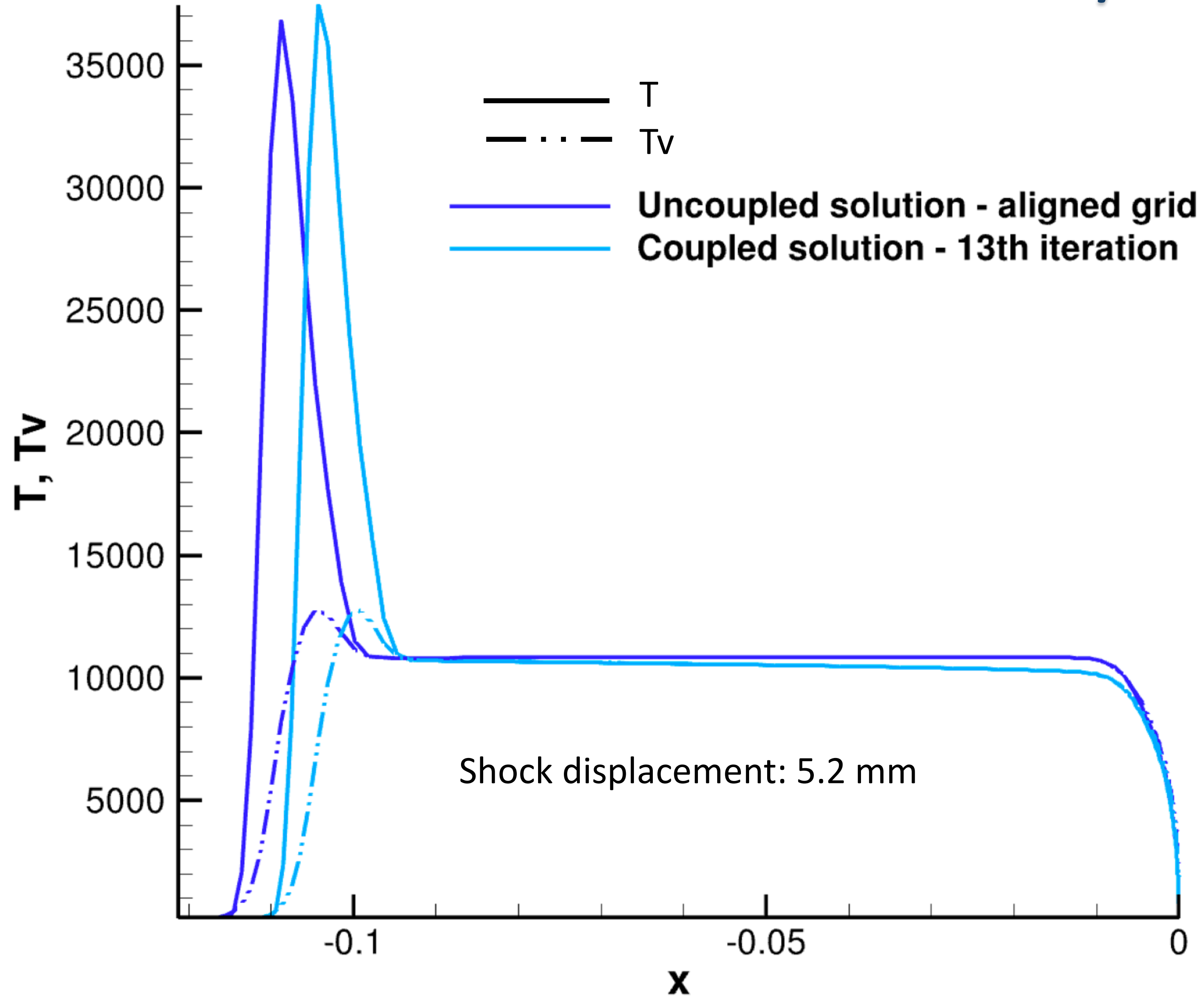


Applied scale factor:

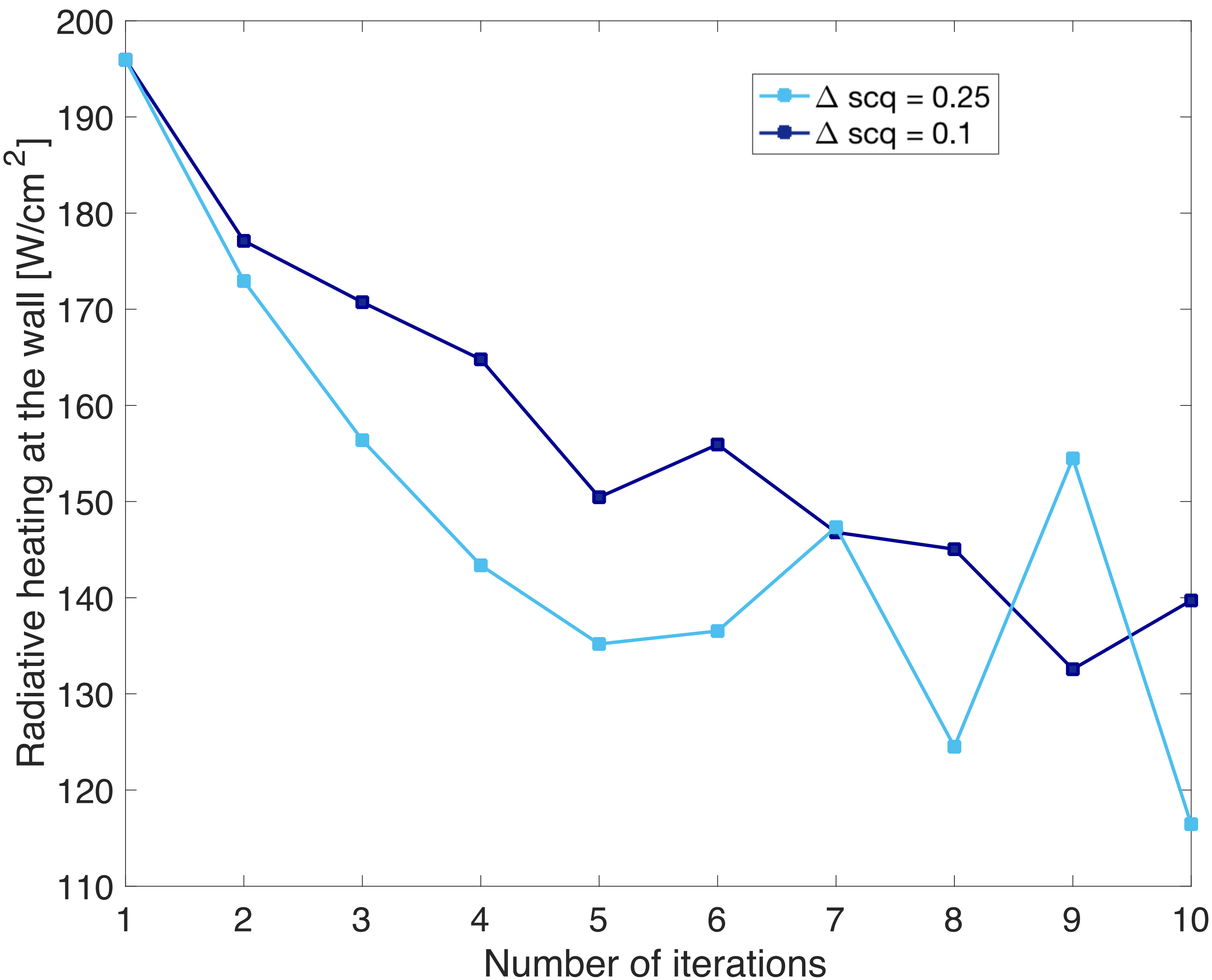
- 1st it.→scq=0.25
- 2nd it.→scq=0.5
- 3rd it.→scq=0.75
- 4th:10th its.→scq=1

- 1st it.→scq=0.2
- 2nd it.→scq=0.3
- 3rd it.→scq=0.4
- 4th it.→scq=0.5
- 5th it.→scq=0.6
- 6th it.→scq=0.7
- 7th it.→scq=0.8
- 8th it.→scq=0.9
- 9th:10th its.→scq=1

Fire II Experiment : 1636 s – 11.3 km/s



Fire II Experiment : 1636 s – 11.3 km/s



Applied scale factor:

- 1st it.→scq=0.25
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- 6th it.→scq=0.7
- 7th it.→scq=0.8
- 8th it.→scq=0.9
- 9th:10th its.→scq=1

CONTENTS

SUMMARY & FUTURE WORK

- Summer Achievements:
  - How the CFD analysis is influenced by different parameters, such as:
    - Grid alignment
    - Flow condition
  - First testing of the script for DPLR and NEQAIR coupling
    - Identifying bugs in the coupling code that were fixed during this work.
    - Now scripts functionally work, and will be soon ready for release
  - How the coupling solution convergence is influenced by:
    - Number of coupling iterations
    - Flow conditions
    - Scale factor
    - Grid alignment

- Future work:
  - Further efficiencies improvements can still be made in the coupling code
  - Ongoing investigation in the convergence of the radiation solution
  - Implementation of the interpolation method for the source term between the LOS
  - Mechanization of the coupler procedure

Thank You for the Attention

Chiara Amato