Duplication of atmospheric entry in laboratories: what about radiatively coupled flows?

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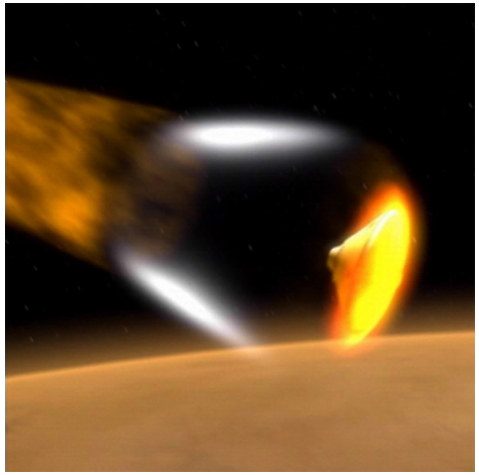
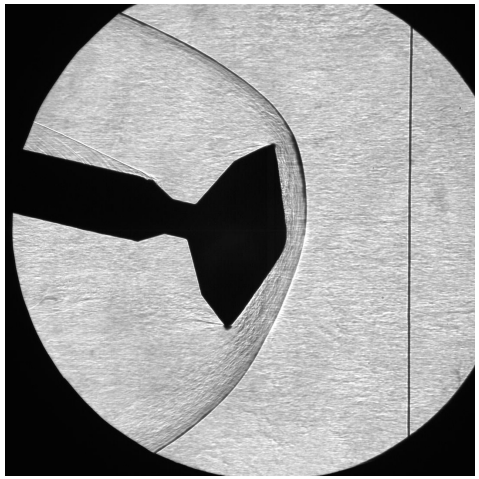
19/06/2015

Binary Scaling (1)



Artist's rendering of Mars Science Laboratory entering the martian atmosphere (JPL photo).

$\Updownarrow$



Schlieren image of a 1/30 scale model of the MSL aeroshell in AEDC's Hypersonic Tunnel 9 (AEDC photo).

Momentum equation (Mach-Reynolds scaling):

$$\frac{\partial}{\partial x_i}\left(\rho v_i v_j\right) = -\frac{\partial p}{\partial x_j} + \mu\left(\frac{\partial^2 v_i}{\partial^2 x_i} + \frac{1}{3}\frac{\partial^2 v_i}{\partial x_j \partial x_i}\right)$$

$$\frac{\partial}{\partial \overline{x}_i}\left(\overline{\rho}\overline{v}_i\overline{v}_j\right) = -\frac{1}{\gamma M^2}\frac{\partial \overline{p}}{\partial \overline{x}_j} + \frac{1}{Re}\overline{\mu}\left(\frac{\partial^2 \overline{v}_i}{\partial^2 \overline{x}_i} + \frac{1}{3}\frac{\partial^2 \overline{v}_i}{\partial \overline{x}_j \partial \overline{x}_i}\right)$$

Mass equation (Binary scaling):

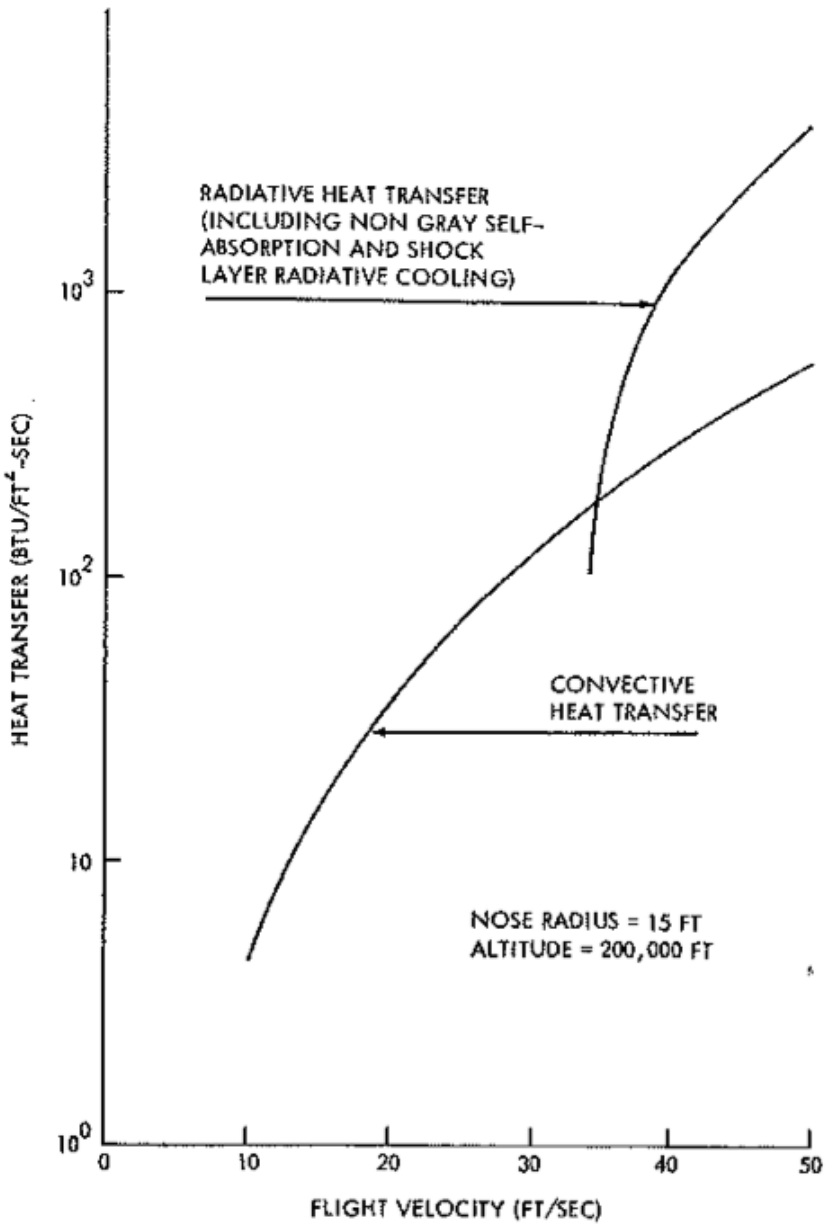
$$\frac{\partial}{\partial x_i}\left(\rho v_i + j_{s,i}\right) = \dot{w}_s$$

$$\frac{\partial\left(\overline{\rho}\overline{v}_i\right)}{\partial \overline{x}_i} - \frac{1}{Pe}\frac{\partial^2\left(\overline{\rho}\alpha\right)}{\partial^2 \overline{x}_i} = Da$$

Similitude parameters:

1. velocity v_∞ (or enthalpy H_∞);
2. density-length product $\rho_\infty R$;
3. nature of test gas and geometry of model.

What about radiative coupling?



Anderson, J., *An Engineering Survey of Radiating Shock Layer*, JSR 7(1):1665-1675, 1969.

Goulard number

Quantifies radiative coupling.

$$\Gamma = \frac{2Q_{\text{ad}}^{\text{rad}}}{0.5\rho_\infty v_\infty^3} = \frac{\text{Radiative energy flux}}{\text{Kinetic energy flux}}$$

Rule of thumb: if $\Gamma > 0.01$ ($\simeq$ Stardust peak) the flow and the radiation are coupled.

Binary scaled flows

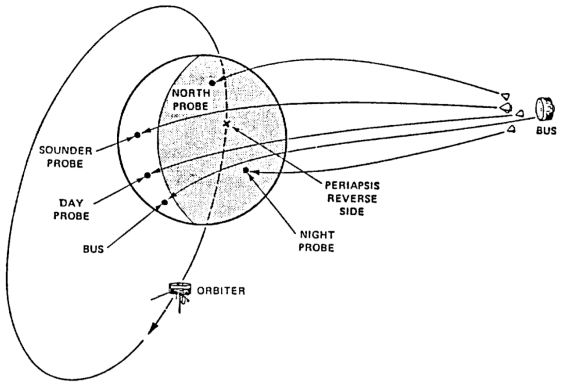
$$\Gamma \propto \frac{v_\infty^5}{\rho_\infty} = \frac{v_\infty^5 \; R}{\rho_\infty R}$$

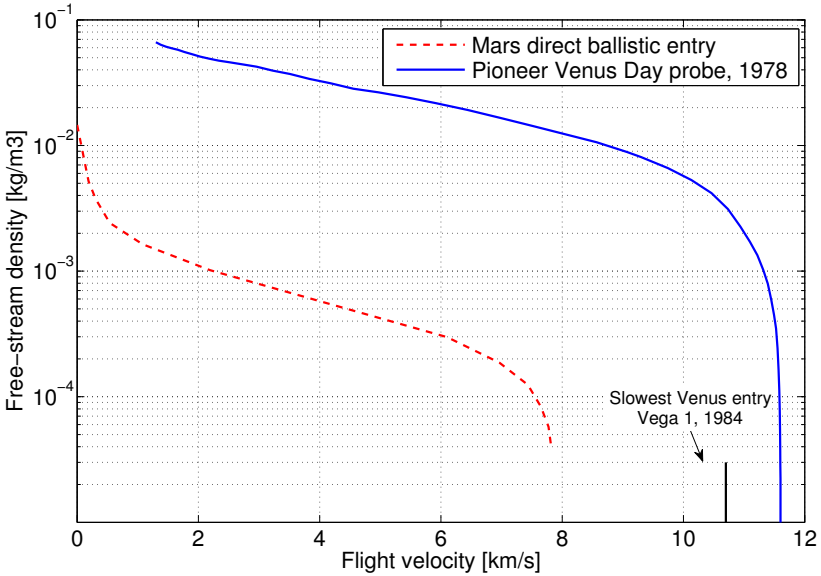
Strongly coupled flow (i.e. interplanetary entry) duplicated in laboratory
$\rightarrow$ smaller length-scale R
$\rightarrow$ radiative coupling diminished.

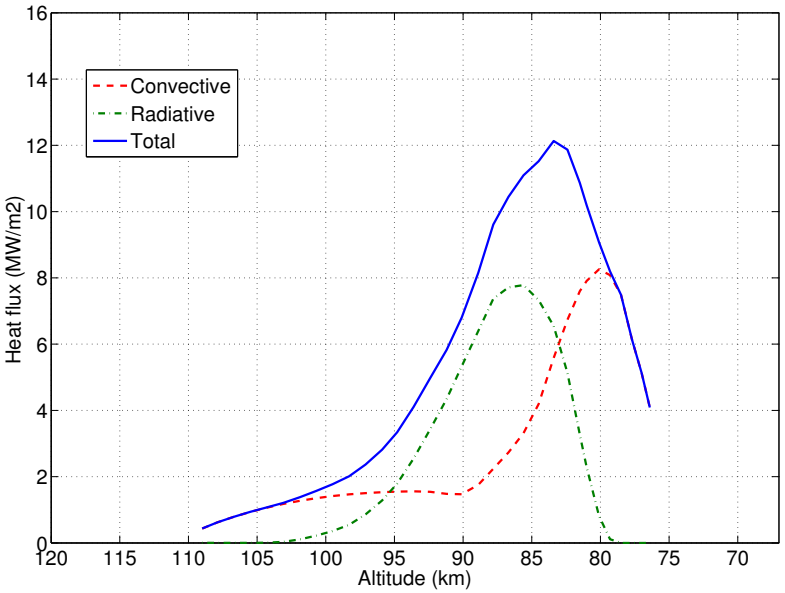
Test condition design (1)

Test case: Venus atmospheric entry

1. High temperature $CO_2 - N_2$ mixtures are populated with efficient radiators;
2. Venus atmospheric entry is much faster than Mars;
3. State-of-the-art models could benefit from good experimental data.





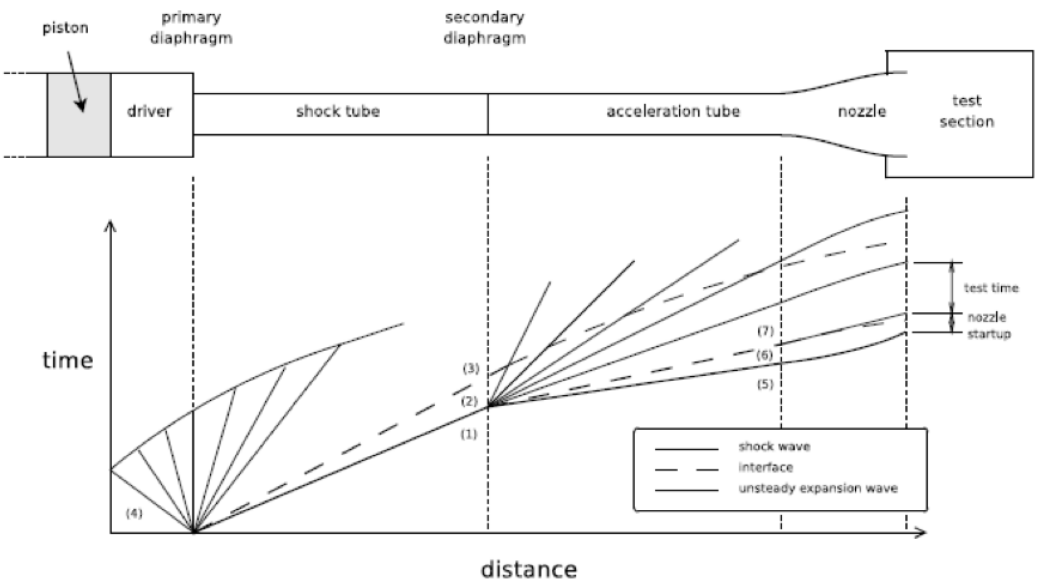


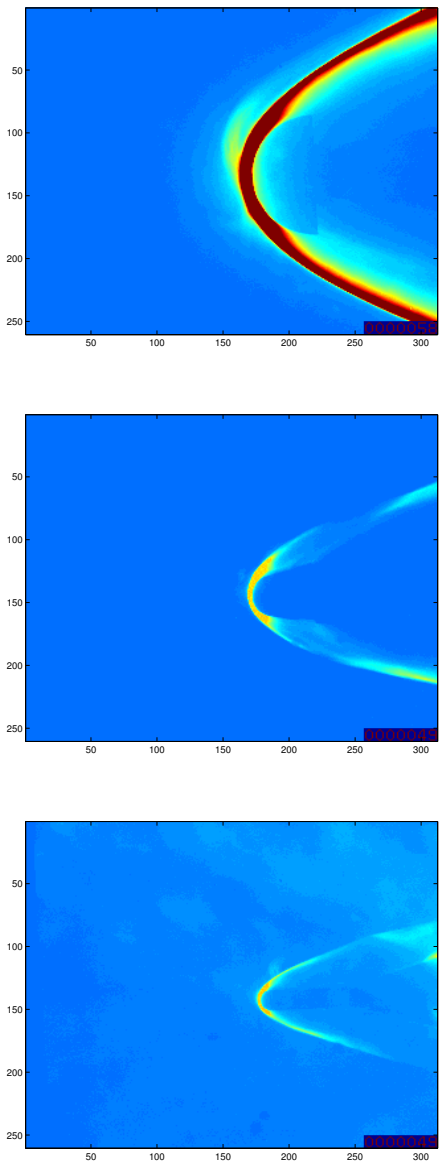
Based on: Park, C., and Ahn, H.-J. *Stagnation-Point Heat Transfer Rates for Pioneer-Venus probes*, JTHT 12(1):33-41, 1999.

Test condition design (2)

Tests were conducted in the X2 expansion tube (University of Queensland) in flow of similar H_∞ and different ρ_∞, using cylindrical models of which the radius was adapted so that $\rho_\infty R \simeq 30$.

Plate thickness [mm]	H_∞ [MJ/kg]	ρ_∞ [g/m^3]	R [mm]	Γ [−]
1.2	43	1.7	17.5	0.06
2.0	46	5.0	6.0	0.03
2.5	42	9.9	3.0	0.02

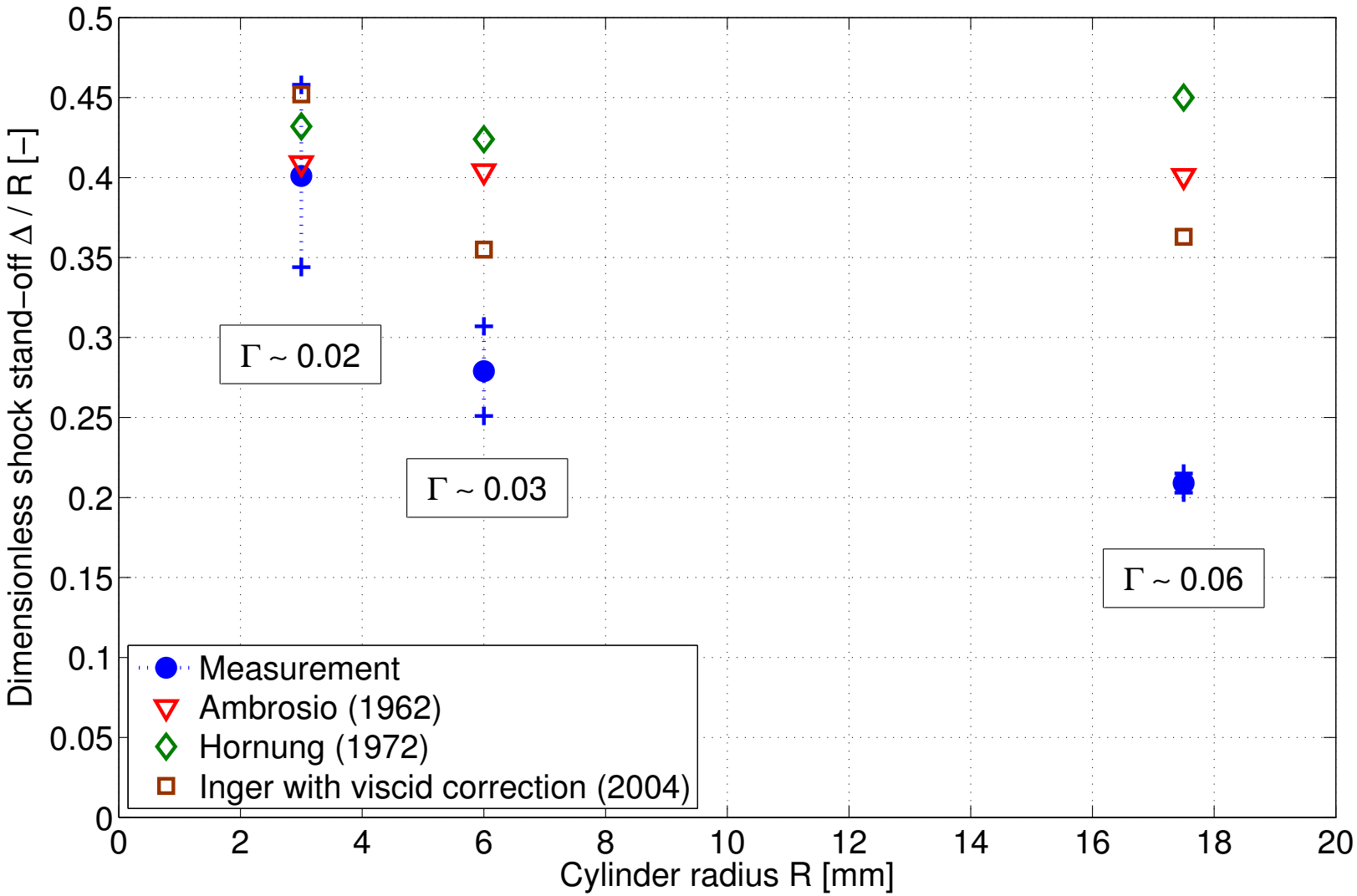




Stills of high speed video recordings corresponding to the passage of the test flow over the models.

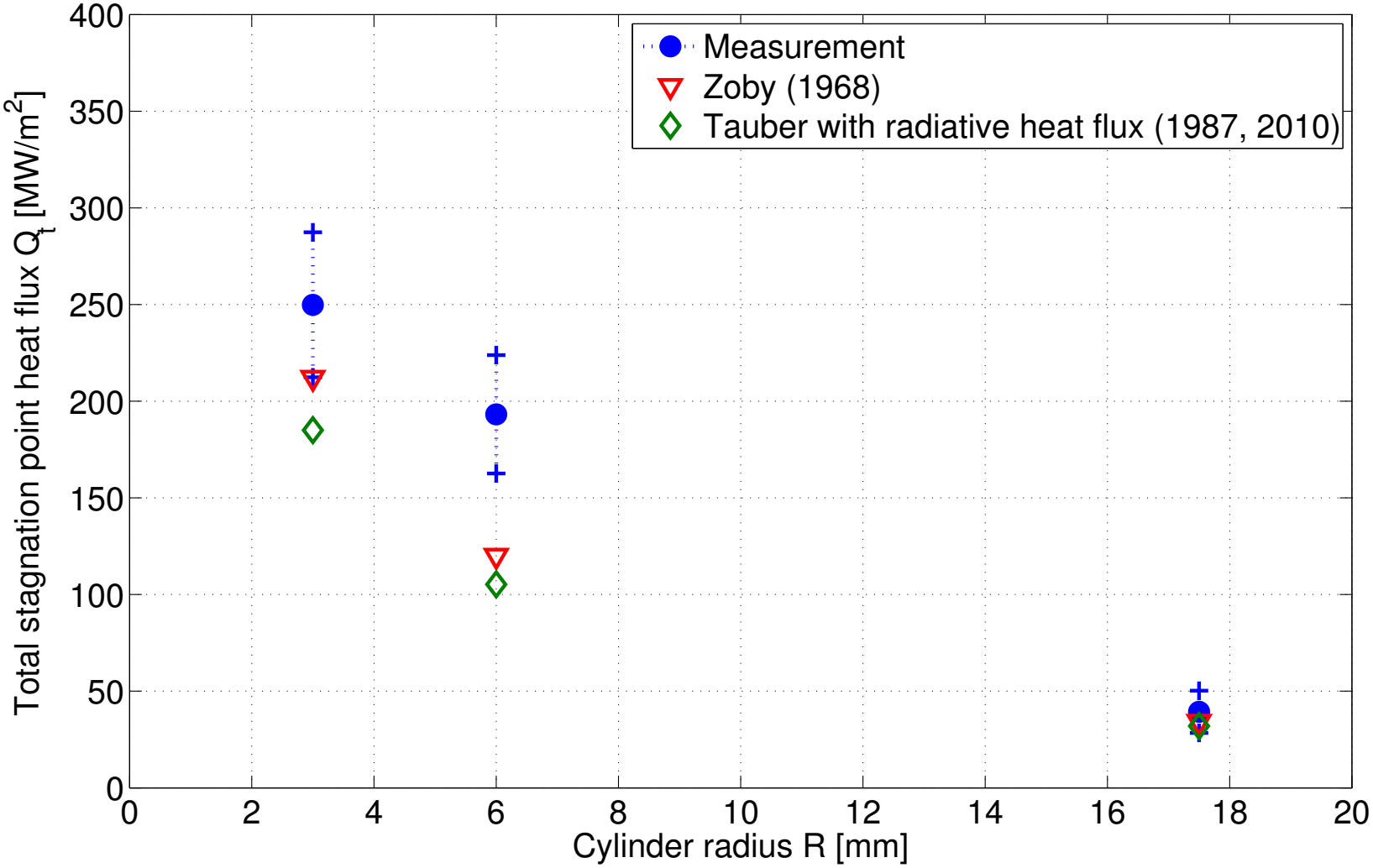
Shock stand-off

Length-scale of the flow L **increases** $\rightarrow$ Radiative coupling Γ increases
$\rightarrow$ Temperature T decreases / Flow less dissociated $\rightarrow$ Density ρ increases
$\rightarrow$ Dimensionless shock stand-off Δ/R **decreases**



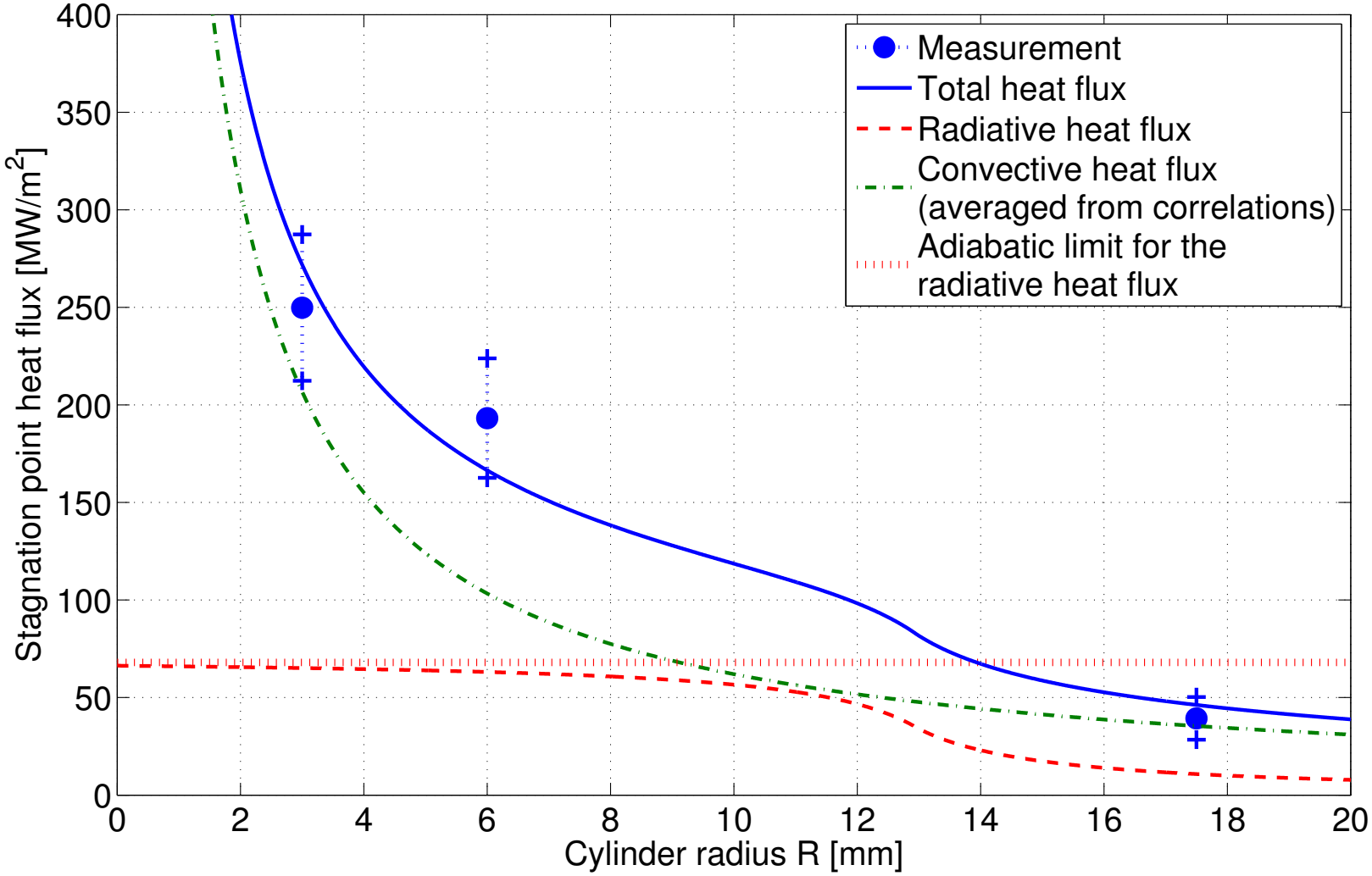
Stagnation point total heat flux (1)

Between binary scales flows:
- **Conductive** heat flux scales as the inverse of the length scale $Q_c R = constant$
- **Adiabatic radiative** heating is constant $Q_r = constant$



Stagnation point total heat flux (2, preliminary fit)

Assuming the non-adiabatic heating rate to follow the shape of a sigmoïde:
- **Satisfying agreement** between theory and experiments
- Only a **first-order** approximation, but confirms what was observed earlier.

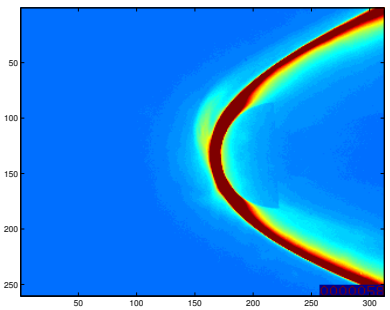


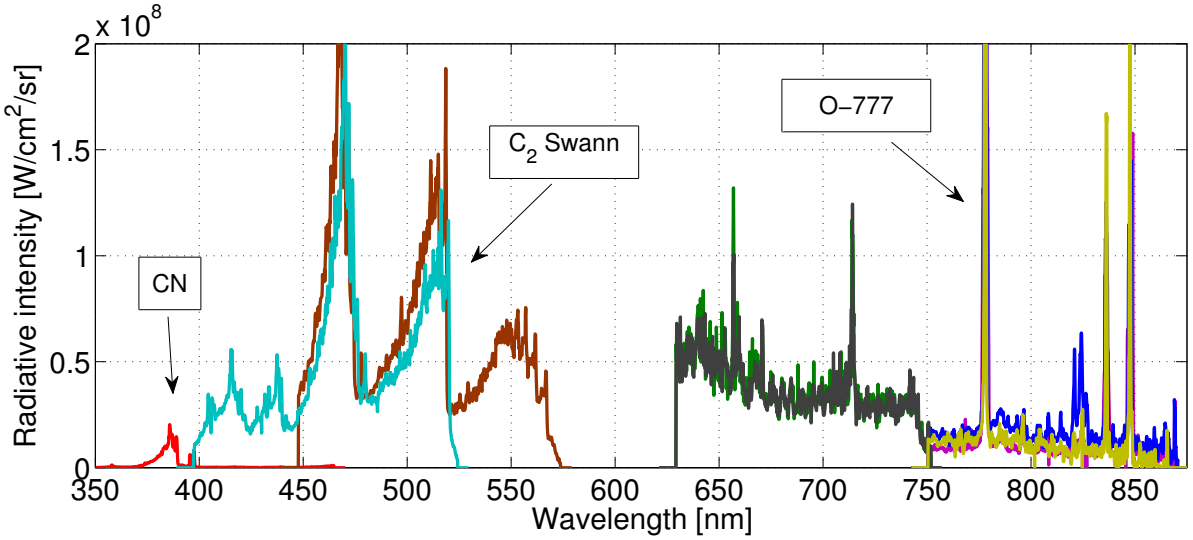
Stagnation line radiative intensity (preliminary results)

The shock layer over small model w.r.t. large model:
- Approximately 10x **brighter**
- **Less molecular** features

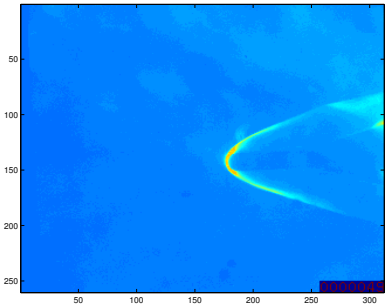
$\rightarrow$ confirms the hypothesis of a hotter shock layer (more work needed)

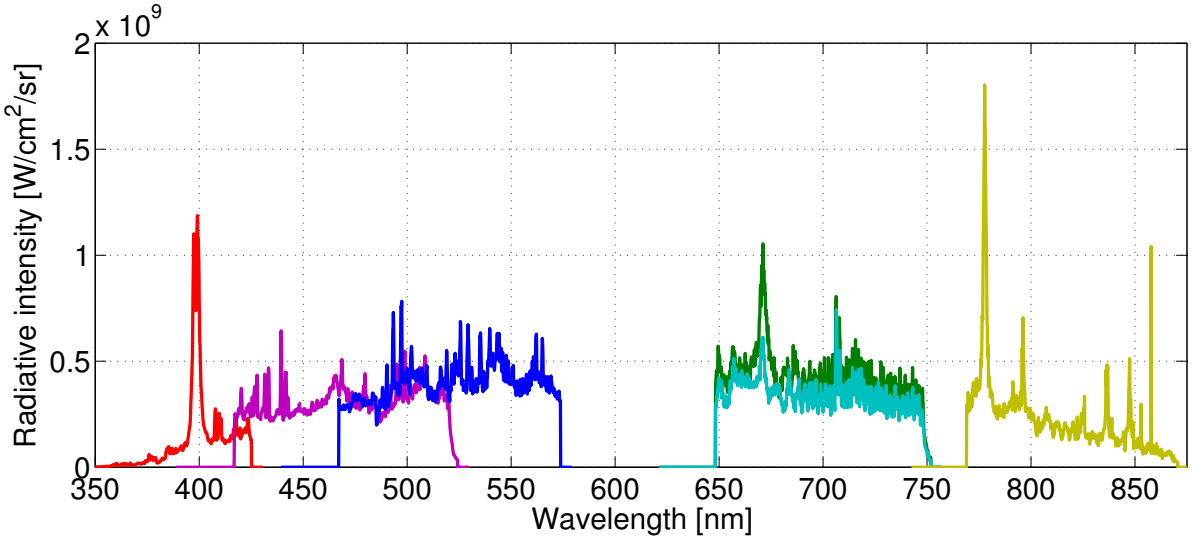
Large probe





Small probe





Conclusion

- Binary scaling is one of the experimental strategy traditionally used to duplicate hypersonic flows in ground-based laboratories (i.e. to prepare and validate interplanetary probes entry vehicle design).
- We have shown that the macroscopic features of the flow are altered if it is coupled with the radiation (i.e. $\Gamma > 0.01$).
- More specifically, the coupling decreases as the length-scale of the flow is reduced, leading to hotter shock layer and thus:
  1. the shock stand-off inflates;
  2. the stagnation point radiative heat flux increases;
  3. the flow is more dissociated (to be confirmed).

ANY QUESTIONS?