



**Достижения и проблемы разработки моделей и
численных исследований высокоскоростного
турбулентного горения в силовых установках**

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TsAGI, Zhukovski, Russia; ONERA, DEFA/PRA, Palaiseau, France

*Лаборатория: Исследования и разработки физических
моделей и численных технологий описания режимов
горения в двигателях летательных аппаратов*

High Speed Propulsion Applications

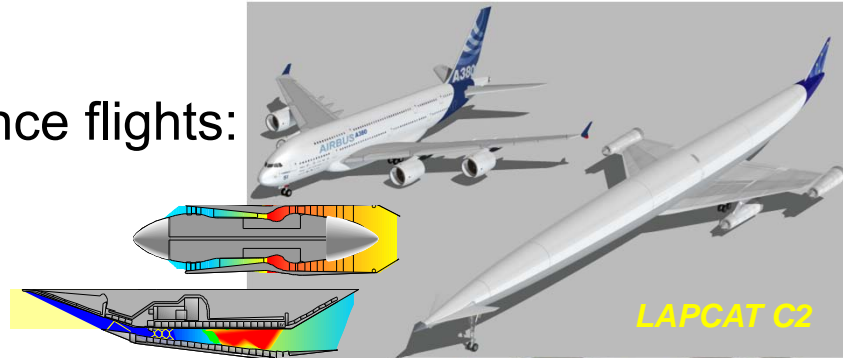
High-speed (supersonic) air-breathing combustion is a key ingredient in

Aerospaceplanes

Reduce traveling time at long distance flights:

Brussels to Sydney in 2 to 4 hours

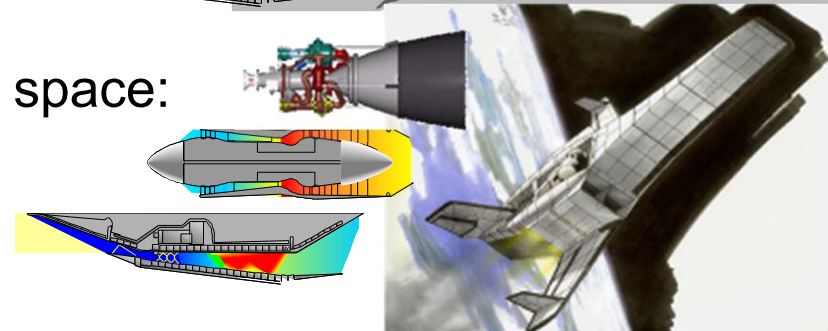
- TBCC ramjets
- TBCC dual-mode ramjets and scramjets



Space Launchers

Easier, cheaper and safer access to space:

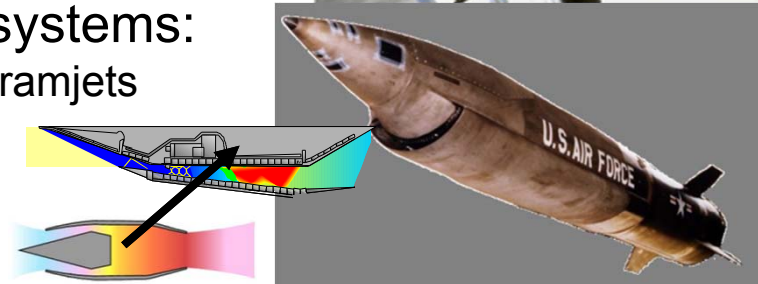
- Solid propellant and hybrid rockets
- RBCC scramjets



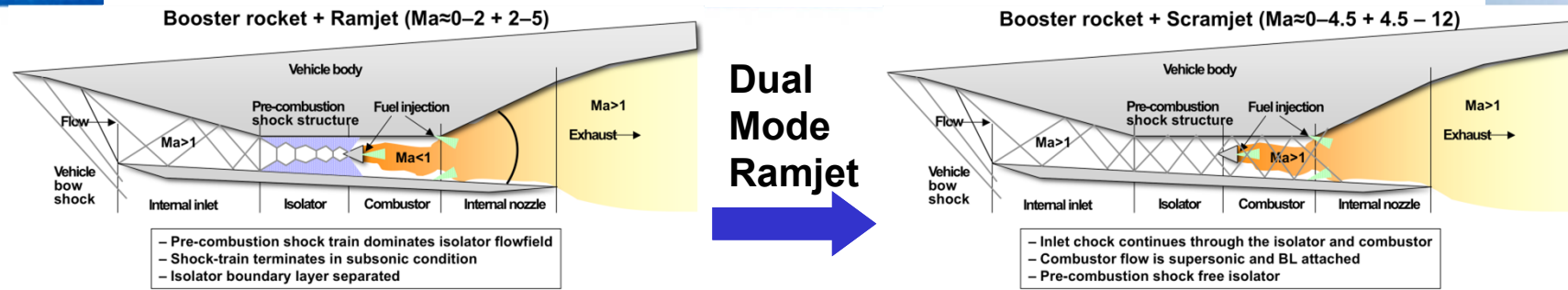
Military Applications

Faster and more long-range weapons systems:

- Intercept, standoff and cruise missiles – ram/scramjets
- Reconnaissance drones – ram/scramjet
- Global range aircraft – ram/scramjet
- Long range indirect fire – solid prop. scramjets



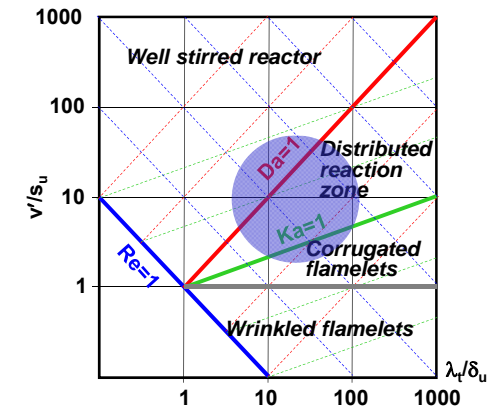
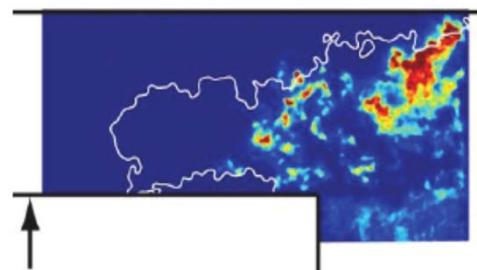
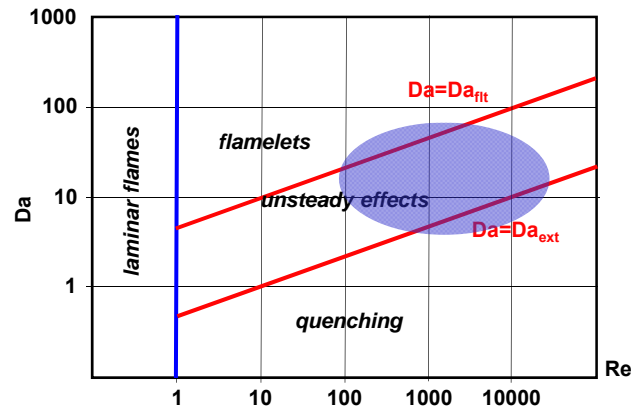
High Speed Combustion Challenges



Fuel (H_2 or HC) injected into a high-speed ($Ma > 0.5$) stream of high temperature (> 550 K) air. Ensure *mixing, self-ignition, flame-stabilization, stable combustion, ... emissions, ...*

Wide range of technical solutions: *jet-in-cross flow, cavity, cavity injection, ...*

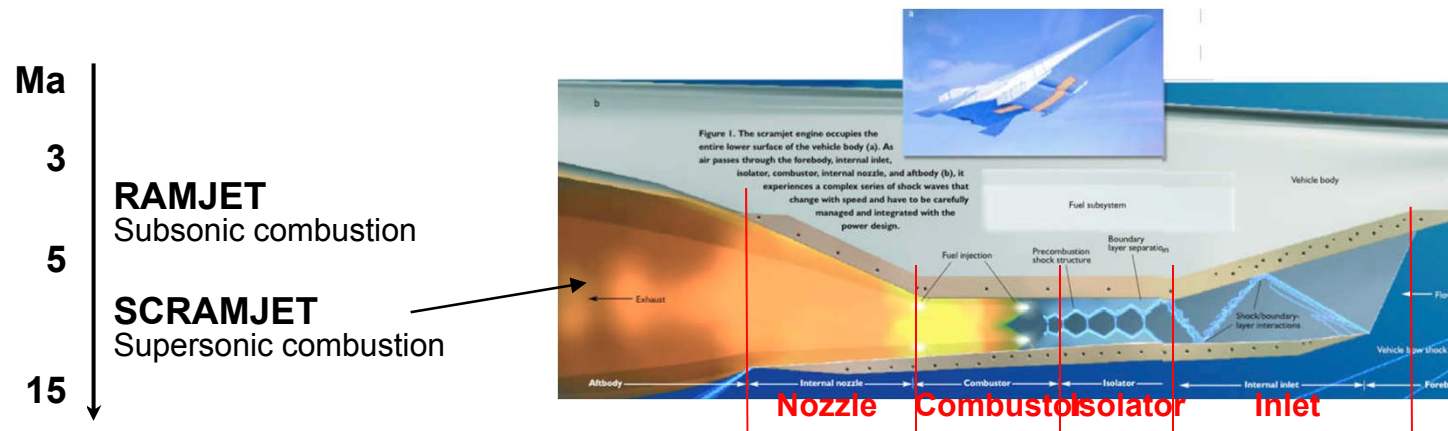
Experimental investigations needs to be supplemented with high-fidelity simulations



Scramjet combustors

are still of increasing interest but the challenges are many.

- Complex aerothermodynamics (no moving parts)
- Hard to experimentally reproduce the operating conditions of a scramjet
- Modeling in CFD



Aims: Understand *self-ignition, mixing and combustion* in hot/vitiated air
Investigate the influence of turbulence-chemistry interactions in LES modeling
Examine key features relative to scramjet combustion

Objectives

- **Develop a high-fidelity physical/numerical model for high-speed turbulent reacting flows**
- **Study “laboratory combustors” (including developed and tested in TsAGI) of interest to industry for various flow and combustion parameters with the new model**
- **Improve basic understanding of turbulent combustion in supersonic and hypersonic flows**

Technical Approach

- **RANS-PaSR, RANS-TPaSR, LES-PaSR, LES-TPaSR: Partially Stirred Reactor (PaSR) and Transported PaSR models, applicable to subsonic and supersonic turbulent combustion in complex configurations**
- **Experimental data (including obtained in TsAGI) for validation and improvement of PaSR, TPaSR models**

Progress

- **New high-order numerical schemes are developed/validated for supersonic reacting turbulent flows,**
- **Compressible subgrid stress and energy flux models are implemented and tested,**
- **PaSR and TPaSR models are applied to compressible (supersonic) reacting flows,**
- **Numerical predictions are compared with experimental data (ONERA-France, DLR-Germany, JAXA-Japon, University of Queensland, Australia, TsAGI)**

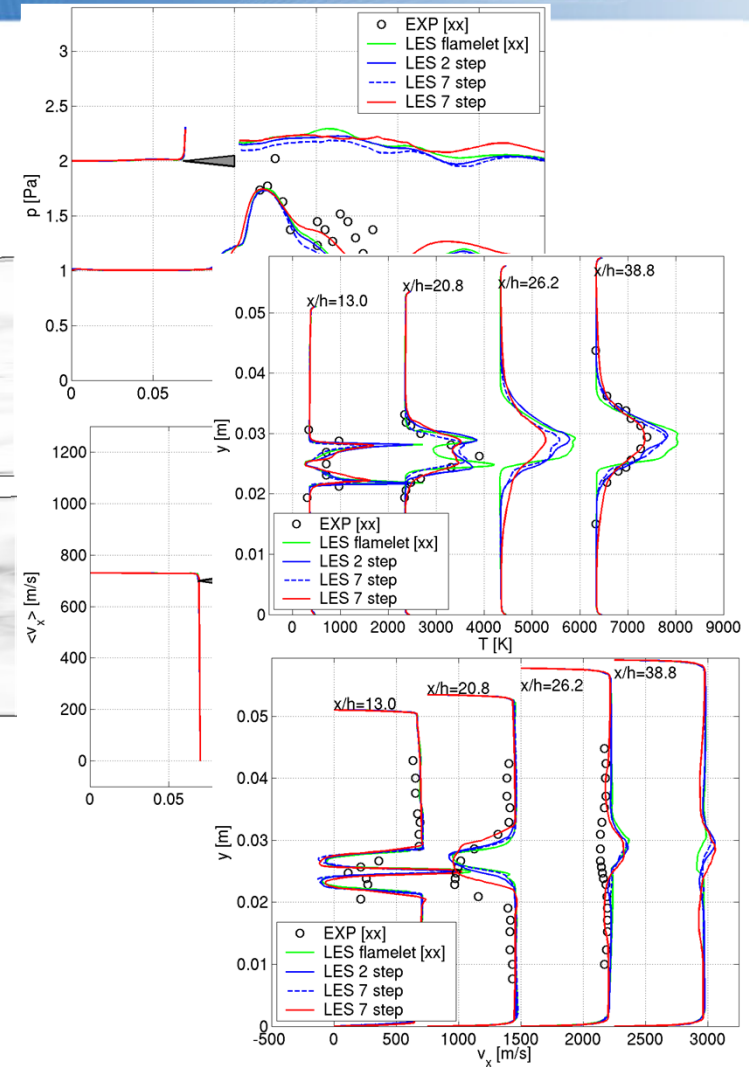
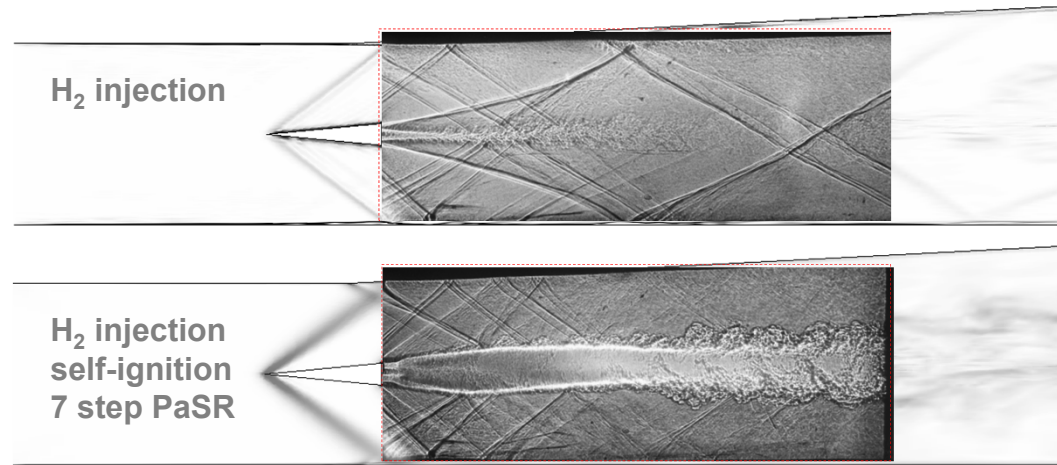
Impact

- **Numerical Simulations of a scramjet combustor is now possible but reliability and accuracy of predictions are dependent on compressible models**
- **Numerical experimental: A systematic and detailed study of various flow/reaction parameters on combustion stability and efficiency**
- **Better understanding of supersonic combustion**
- **Feedback to experimentalists and designers**

Validations: DLR Supersonic Combustor

Supersonic combustion experiment by DLR

Exp. by Waidman *et al.*, 1994-1996
 Ma 1 H₂ injection in Ma 2 air stream
 Kulite, LDV, CARS & OH PLIF data



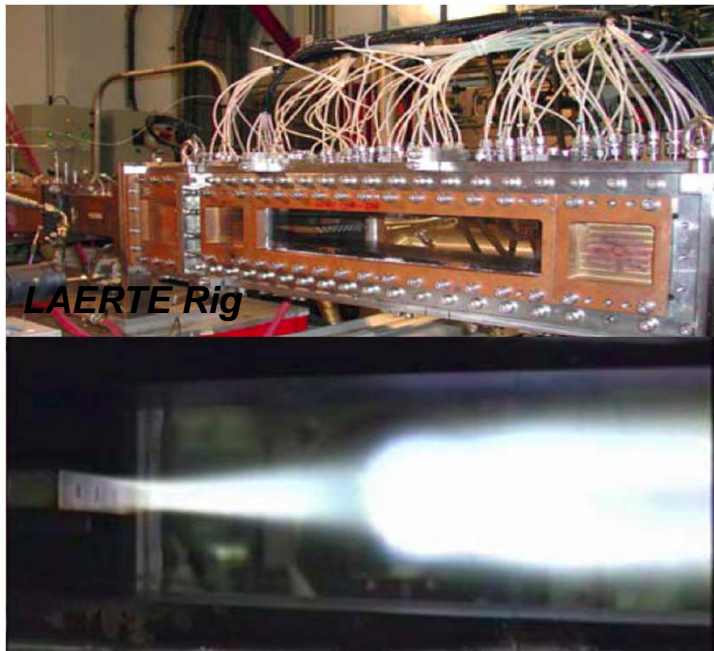
Fureby *et al.*, 2006, 31st Int. Symp on Comb.
 Fureby; 2009, Unpublished

The ONERA/JAXA Experiments

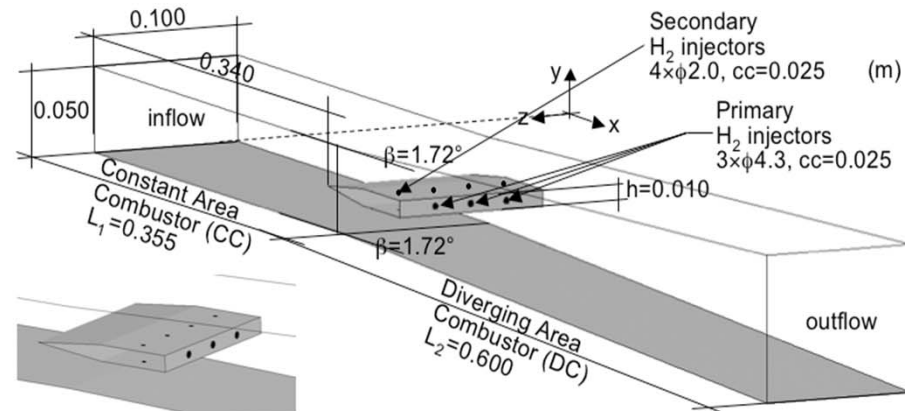
Joint ONERA / JAXA experimental investigation

Sunami T., Murakami A., Kudo K., Koderu M. & Nishioka M., AIAA 2002-5116,

Sunami T., Magré P., Bresson A., Grisch F., Orain M., & Koderu M., AIAA 2005-3304



LAERTE Rig



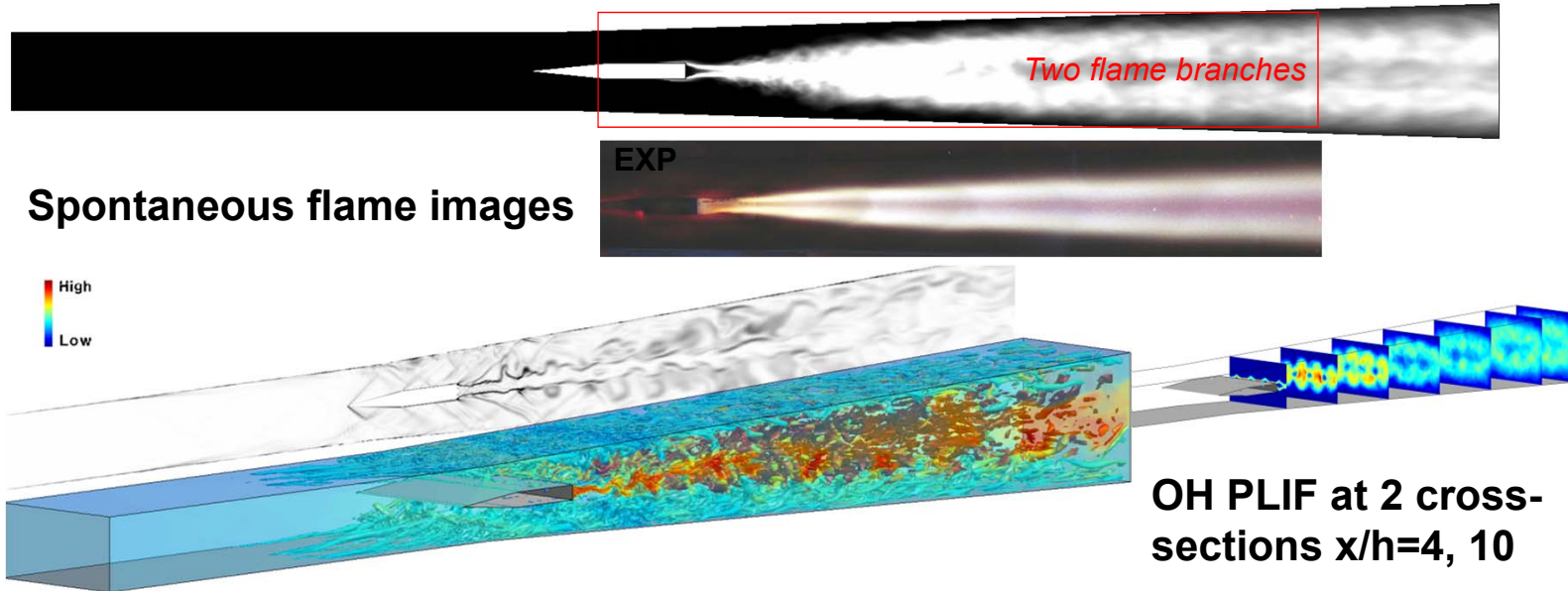
Overall conditions for the scramjet combustor

mean inlet axial velocity	1449	m/s
mean inlet temperature	830	K
mean inlet pressure	34.2	kPa
mean inlet density	0.1335	kg/m ³
freestream composition	Y _{O2} =0.23 Y _{N2} =0.70 Y _{H2O} =0.07	
injector velocity	2149	m/s
injector temperature	124	K
injector composition	Y _{H2} = 1	

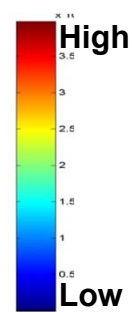
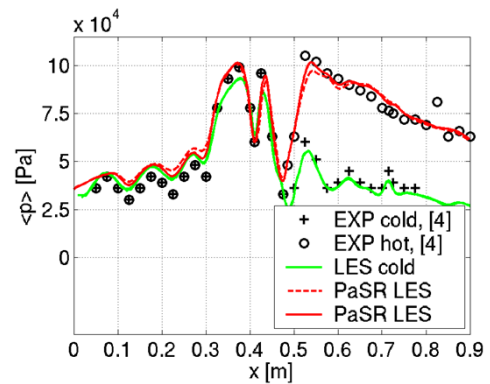
- Spontaneous flame images
- Wall pressure measurements
- OH PLIF at 2 cross-sections $x/h=4, 10$

Berglund *et al*, 2009, AIAA J.

The ONERA/JAXA Experiments

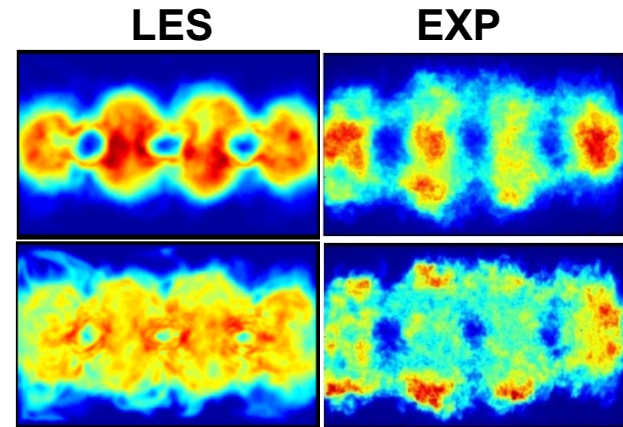


Wall pressure comparison



$\langle C_{OH} \rangle$

C_{OH}^{rms}

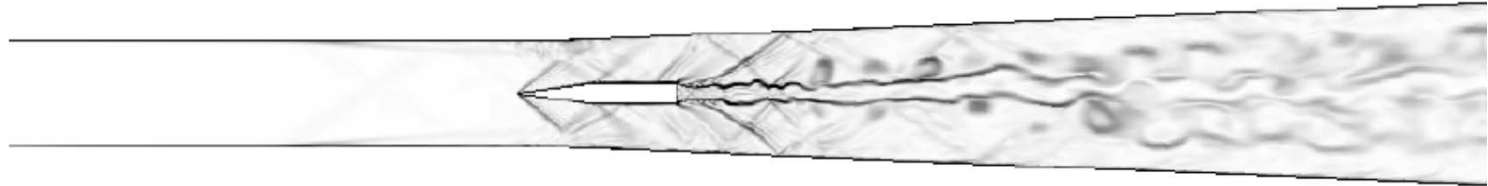


C. Fureby, K. Nordin-Bates, K. Petterson, A. Bresson, V. Sabelnikov. A computational study of supersonic combustion in strut injector and hypermixer flow fields. Proceedings of the Combustion Institute, 35 (2015)

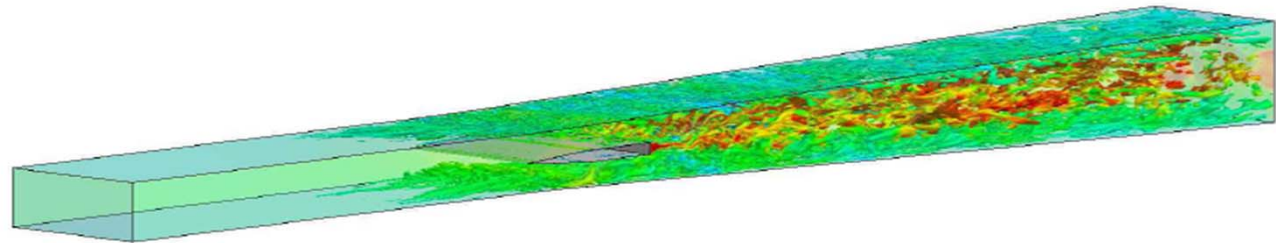
Berglund *et al*, 2009, AIAA J.

The ONERA/JAXA Experiments

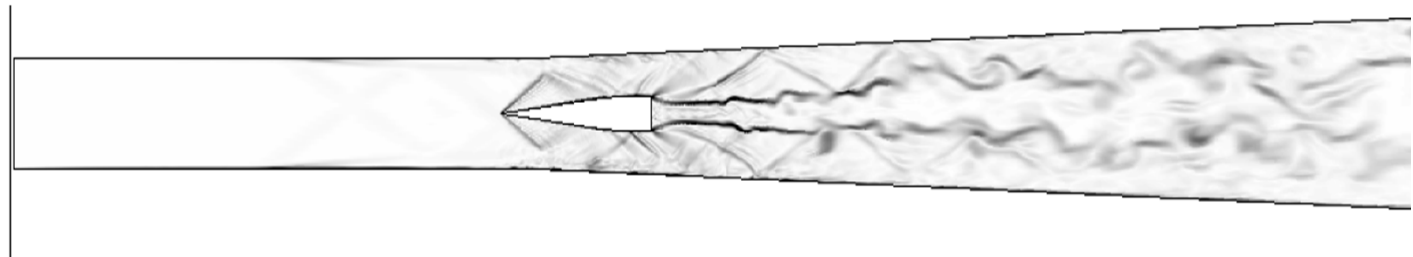
Schlieren, strut
ONERA10



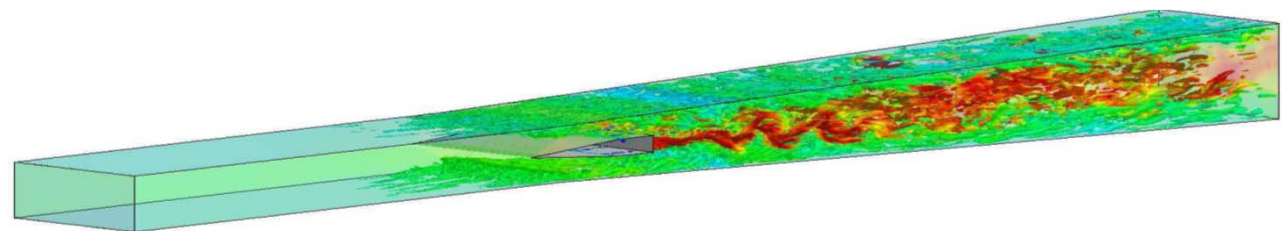
Temperature and λ_2
strut ONERA10



Schlieren, strut
ONERA15



Temperature and λ_2
strut ONERA15



M. Berglund, E. Fedina, C. Fureby, V. Sabel'nikov and J. Tegnér. Finite Rate Chemistry Large-Eddy Simulation of Self-Ignition in Supersonic Combustion Ramjet, AIAA Journal Volume 48, Number 3, 2010

HyShot V (HiFiRE 4)— A free-flying hypersonic glider (University of Queensland, Australia)



US-Australia had a successful Mach 8 HiFire 4 (A free-flying hypersonic glider) hypersonic missile test (round of experiments concluded on 12 July 2017)

The \$54m joint initiative involves the US Air Force, Boeing, the Australian Department of Defence's Defence Science and Technology Group, BAE Systems Australia, and the University of Queensland.

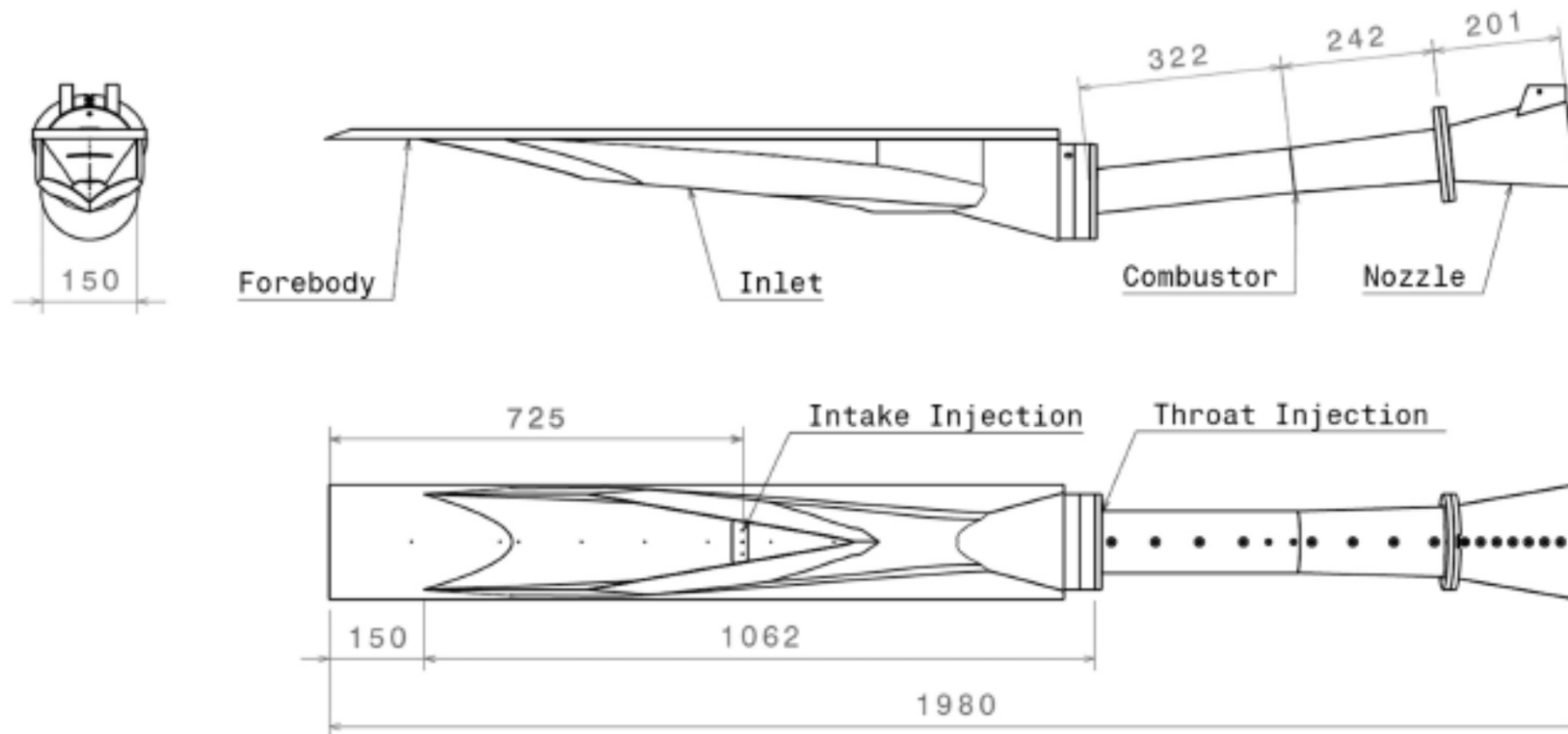
<https://www.nextbigfuture.com/2017/07/us-australia-had-a-successful-mach-8-hifire-4-hypersonic-missile-test-last-week.html>

Computational Fluid Dynamics Investigation of a Mach 12 Scramjet Engine (University of Queensland, Australia)

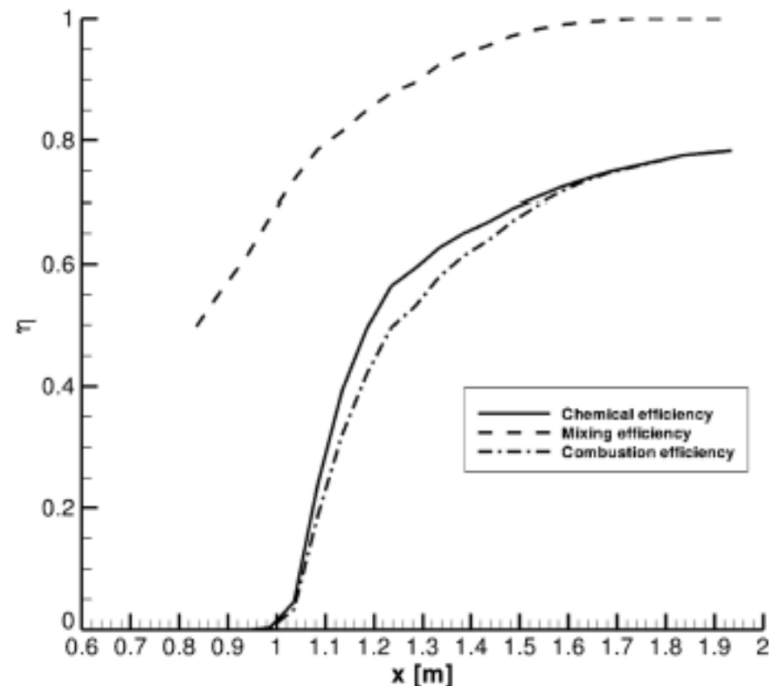
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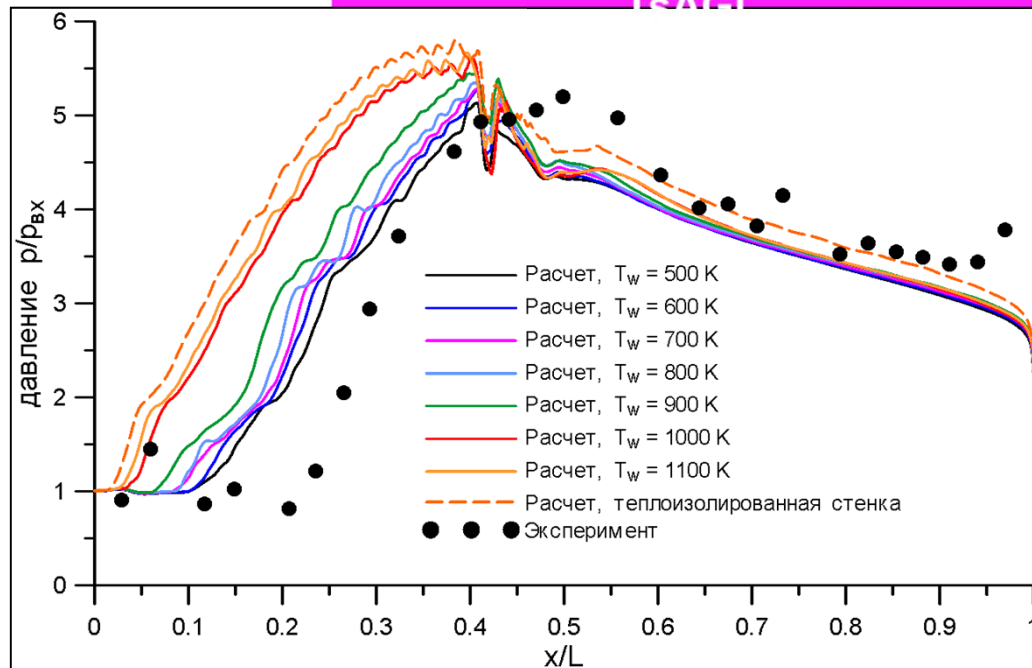
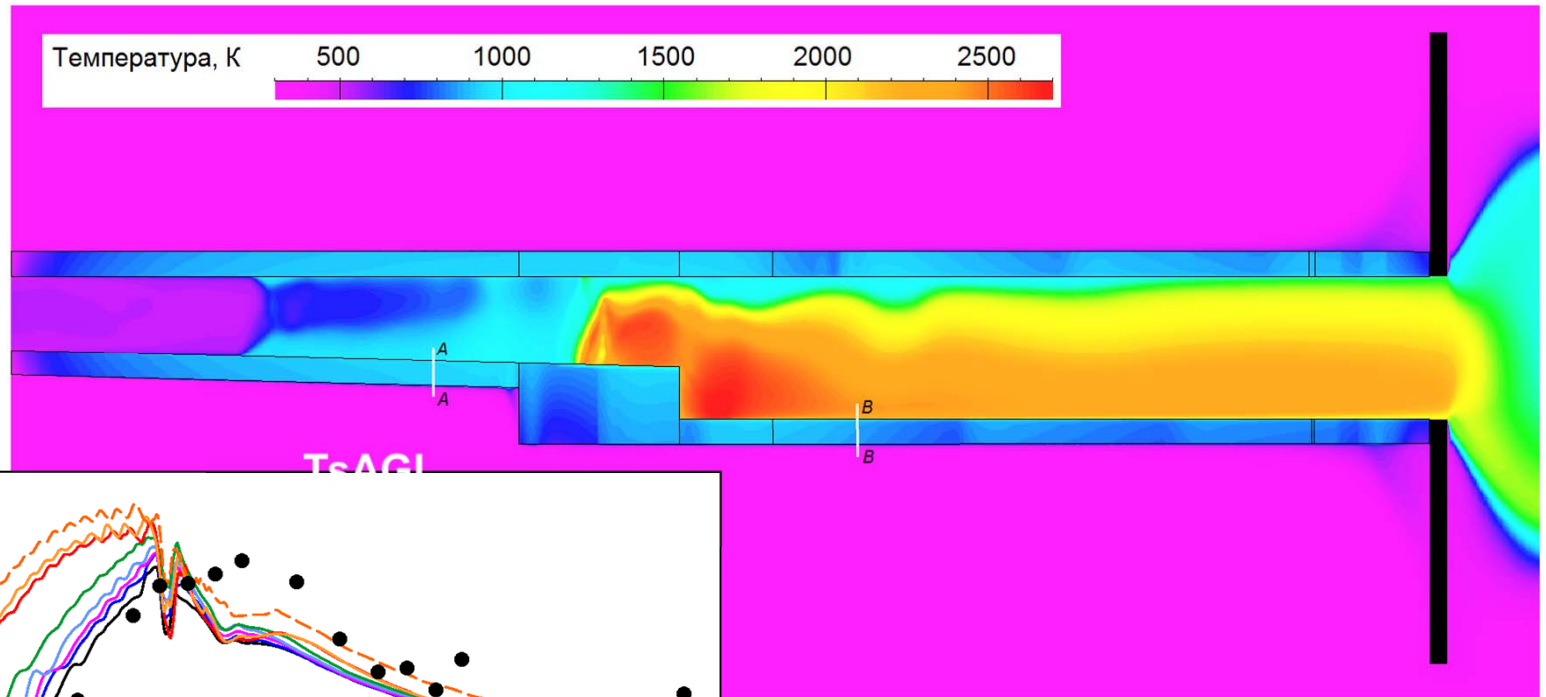


Y. Moule, V. Sabelnikov, A. Mura and M. Smart. Computational Fluid Dynamics Investigation of a Mach 12 Scramjet Engine, Journal of Propulsion and Power Vol. 30, No. 2, March-April 2014

Влияние теплообмена на нагрузки по стенкам тракта

Режим течения: $M=2.5$, $p_0=1.9\text{МПа}$, $T_0=1100\text{К}$, топливо – керосин, $\alpha=1.34$

Эксперимент
на стенде Т-131В
ЦАГИ (авторы:
О.В.Волощенко,
В.Н.Острась,
А.А.Николаев,
С.А.Зосимов)



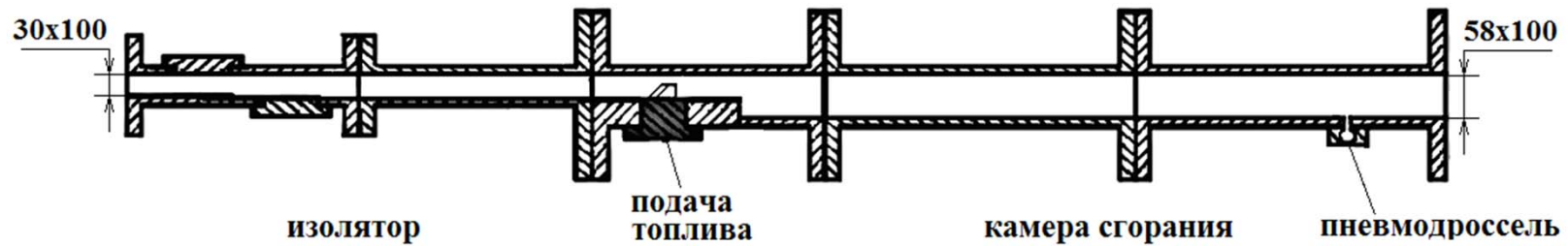
▲ Двумерный расчет с моделированием теплообмена поперек стенок камеры

Эксперимент: только распределения давления по стенкам тракта

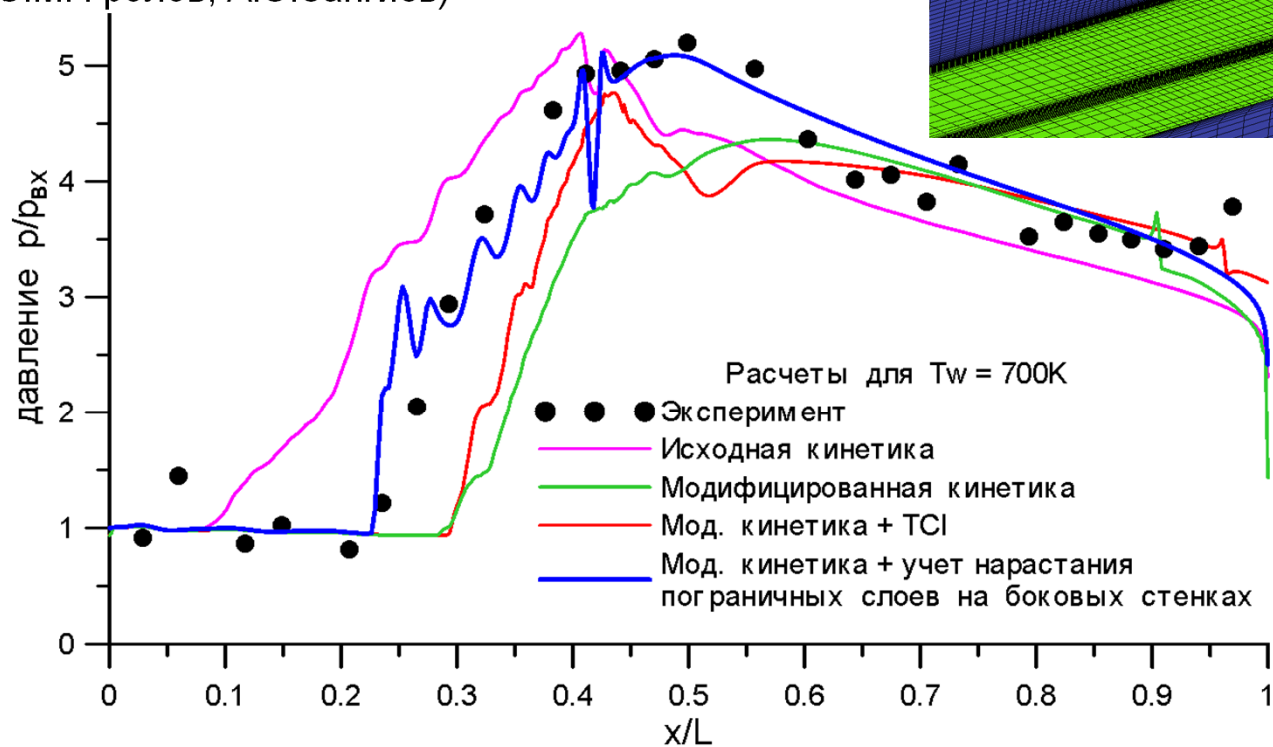
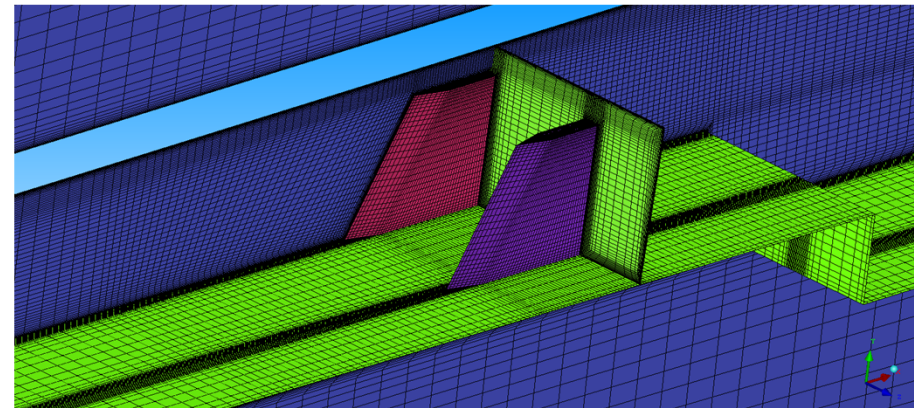
Расчет: детальная картина течения

◀ Влияние температуры стенок на распределение давления по верхней стенке камеры

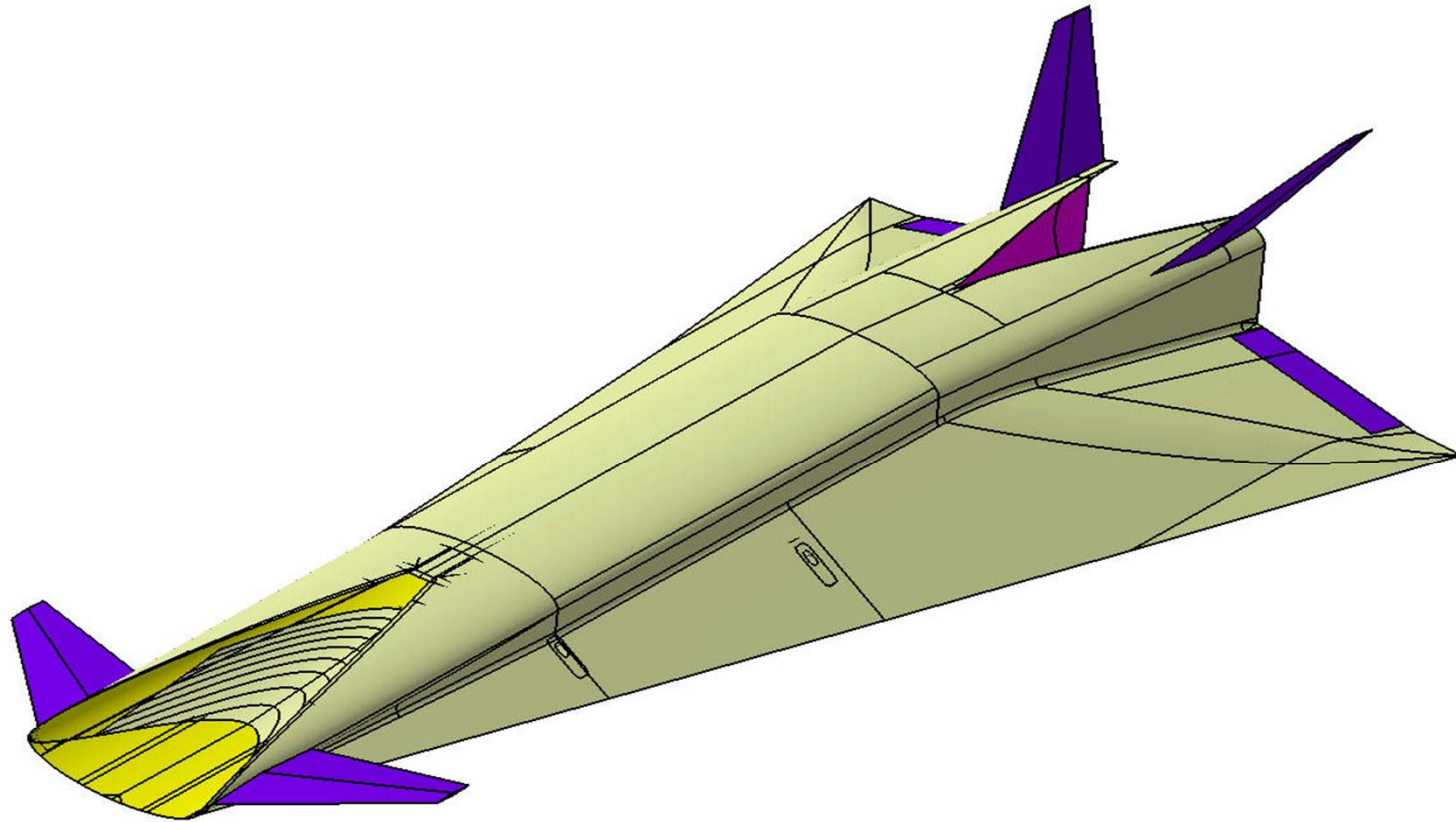
Влияние кинетики, TCI и трехмерных эффектов



- Тот же эксперимент
- В расчетах использована современная кинетическая схема, разработанная в ИХФ РАН (С.М.Фролов, В.Я.Басевич)
- Расчеты с учетом TCI выполнены ИХФ РАН (С.М.Фролов, А.Э.Зангиев)

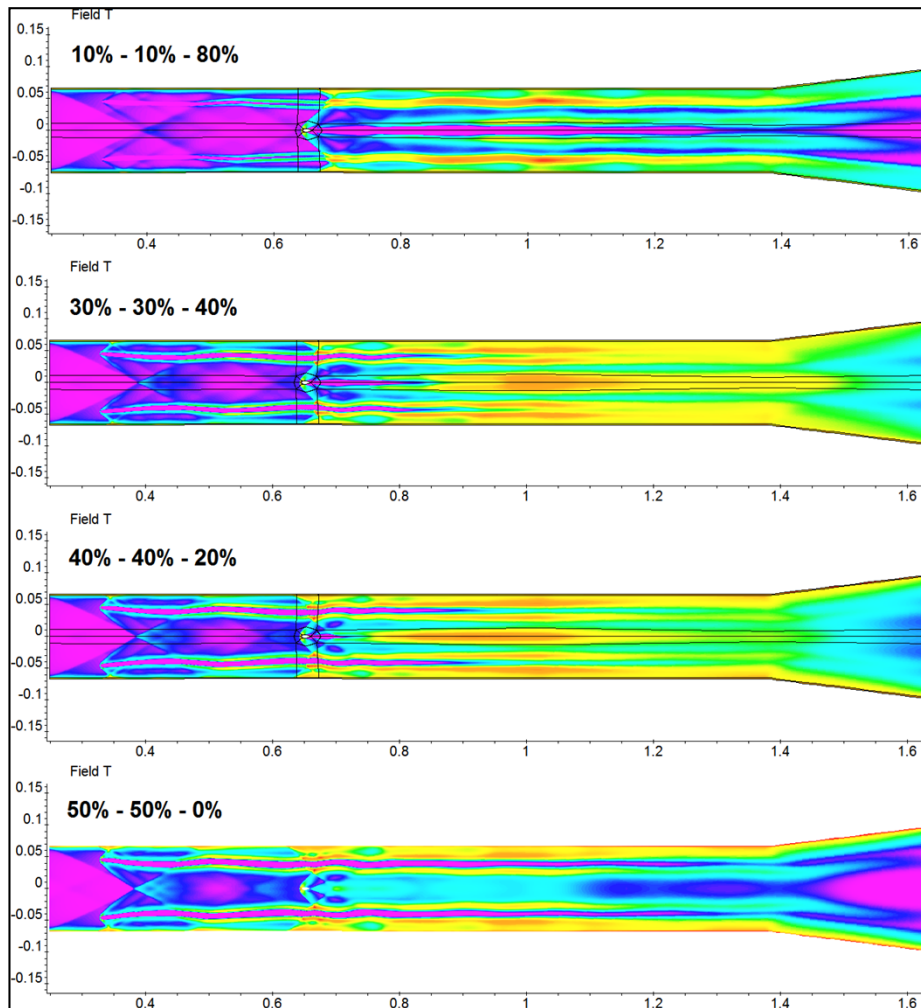


High-Speed Experimental Fly Vehicles (HEXAFLY). ESA. Completely integrated vehicle concept for Mach 8 flight

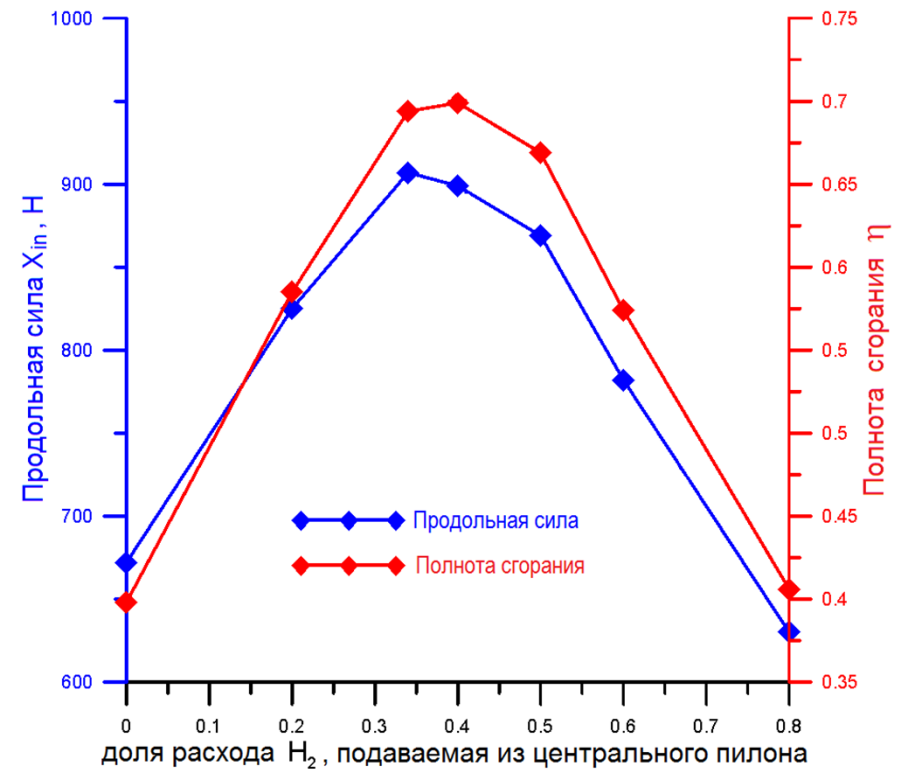


Влияние схемы подачи топлива на полноту сгорания и тягу двигателя

- ГПВРД, рассматриваемый в рамках проекта ЕС HEXAFly-INT



Параметры на входе:
 $T_0=2350\text{K}$, $P_0=12$ атм, $M\sim 2.6$
топливо – водород, $\alpha = 1$
(режим полета $M\sim 7.5$, $H=33$ км)



Поля температуры для разных схем подачи топлива
(например, 30%-30%-40%: по 30% из двух боковых пилонов 1-го пояса, 40% - из центрального пилона 2-го пояса)