Principali attività di ricerca in corso e possibili sviluppi

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Incontro promozione attività di ricerca DIMA Roma, 6 febbraio 2017





MULTI-SCALE SIMULATION OF REACTIVE FLOWS IN THRUST CHAMBERS

- TURBULENT COMBUSTION CLOSURE (LES VIA CONDITIONAL MOMENT CLOSURE)
- Ignition Transient in Combustion Chambers (URANS)
- SUPERCRITICAL COMBUSTION IN LRE CHAMBERS (RANS, URANS, LES)
- DETERMINISTIC AND PROBABILISTIC MODEL REDUCTION OF CHEMICAL KINETICS USING CSPTK
- PREDICTION OF STRONG AND WEAK IGNITION REGIMES IN TURBULENT REACTING FLOWS WITH TEMPERATURE FLUCTUATIONS
- FLAME INITIATION AND FORMATION (DNS VIA WAVELETS)
- SPRAY MODELING OF PRESSURE-SWIRL ATOMIZERS USING OPENFOAM
- DEVELOPMENT OF THE CSP TOOL KIT (CSPTK) LIBRARY

AN EARLY CASE OF CRO-SSD COLLABORATION (06+07)

DETACHED EDDY SIMULATION SHOCK UNSTEADINESS IN AN OVER-EXPANDED PLANAR NOZZLE

MAIN TOPICS



Target test case: Sandia flame A jet diffusion flames (<u>www.sandia.gov/TNF/DataArch/FlameA/</u> <u>SandiaPilotDoc21.pdf</u>)

TURBULENT COMBUSTION MODELING OF LABSCALE FLAMES (KAUST) OPENFOAM LES (P.P.CIOTTOLI, P.E.LAPENNA, F.CRETA, M.VALORANI)



The experiment consists of triggering ignition in a well controlled gas/gas injection configuration, using a laser beam in order to control the ignition point location and energy release

The flame kernel propagates downstream near the symmetry axis as convected by the fast central jet

The flame kernel propagates across the recirculation region away from the axis

When methane is not entering the chamber anymore, the cold oxygen jet is not consumed and leaves the chamber unburned-> the temperature field at the axis becomes very cold

A significant amount of hot products is still present in the chamber ready to reignite the propellants when the chamber pressure is lowered by the mass loss through the choked nozzle



0.117021

0.117021

Temperature

HCO



IGNITION TRANSIENT IN COMBUSTION CHAMBERS URANS (M.VALORANI, E.MARTELLI, P.P.CIOTTOLI, G.GARGIULO)



Supercritical combustion involves real gas equations of state.

Very strong density gradients occur in the mixing region formed by cryogenic oxygen and gaseous methane.

Anchoring is hindered by the high heat transfer from the flame to the cold liquid oxygen jet

HCO



SUPERCRITICAL COMBUSTION IN LRE CHAMBERS RANS, URANS, LES (G.GARGIULO, F.CRETA, M.VALORANI)



IGNITION IN A CAVITY

Flames are characterized by a large spectrum of spatial and temporale scales \Rightarrow multi-scale problems

Direct Numerical Simulations (DNS) involves a very large number of unknowns (if a uniform mesh is used)

Dynamically adaptive wavelet collocation algorithms are ideally suited for DNS of combustion with realistic chemistry:

the state functions are represented in terms of multiscale basis functions (scaling functions & wavelets), characterized by excellent localization properties both in physical and spectral space.

adaptation is obtained by retaining only wavelets with an amplitude greater than a user defined threshold, thus providing a verified solution of prescribed accuracy and saving in computer time and memory storage.

FLAME INITIATION AND FORMATION

"WAVELET ADAPTIVE MESH RESOLUTION" (S.GEMINI, S.PAOLUCCI, E.MARTELLI, M.VALORANI)



Detached Eddy Simulation shock unsteadiness in an over-expanded planar nozzle E.Martelli, P.P. Ciottoli, M. Bernardini, F. Nasuti, S. Pirozzoli, M. Valorani

Back pressure

Sponge

'1'2'

10

8

6

7

8





The shock movement and the recirculating region have been recognized to be characterized, in the time-frequency space, by a collection of events with a modulation of the oscillation amplitude and a modulation of the frequency

GdR DIMA - 6 Febbraio 2017



Multi-phase CFD simulations with InterFOAM solver based on the volume of fluid (VoF) method. Top: Two dimensional axisymmetric simulation of a swirl atomizer Bottom: Liquid jet breakup detail of the injector

MULTI-PHASE FLOW: SWIRL ATOMIZER

OPENFOAM RANS, LES WITH VOF (A. SALEM, P.P.CIOTTOLI, M.VALORANI)



M. VALORANI, F. CRETA, H.N. NAJM, D.A. GOUSSIS, P.P. CIOTTOLI, R.MALPICA

	region #	time @ beginning	T @ beginning	Species	Reactions Av	verage PI [%] Bar Chart	region #	time @ beginning	T @ beginning	Species	Reactions	Average PI [%]	Bar Chart
SYNGAS MECH (H2+CO/AIR)	1	0.0000513803	900.	H O HO2	Rf 10 - H+02(+M)<->H02(+M) Rf 1 - H+02<>>H02(+M) Rf 28 - C0+02<>>C02+0 Rf 1 - H+02<>>OH+0	35.4 30.8 19.17 34.00 34.0	1	0.	1200.	H OH O	Rb 12 - H02+H<=>H2+O2 Rf 28 - C0+O2<=>CO2+O	58.36 41.38	Rb 12 - H02+H<=>H2+O2 Rf 28 - C0+O2<=>C02+O
269 REACTIONS	3	0.000123912	900.	HO2	Rf 10 - H+02(+M)cosH02(+M) Rf 28 - C0+02cosC02+0 Rf 1 - H+02cosOH+0 Rf 10 - H+02(+M)cosH02(+M)	33.09 16 923-C0-Glu-C020 36.73 35.69 47 - inc2an-Glu-C020 47	2	8.80654×10 ⁻⁸	1200.	н он	Rb 12 - H02+H<=>H2+O2 Rf 28 - C0+O2<=>C02+O	50.77 42.23	Rb 12 - H02+H4m>H2+02 Rf 28 - C0+02ersC02+0
	4	0.00901972	900.002	HO2	Rf 1 - H+02cx>OH+0 Rf 10 - H+02(+M)cx>H02(+M) Rf 27 - C0+H02cx>C02+0H	38.01 37.03 12.13 R17-0040000000000000000000000000000000000				0	Rf 2 – H2+O<=>OH+H	4.057	Rf 2 - H2+O<>>OH+H
ANALYSIS OF KINETICS ABOUT	5	0.0242431	900.045	H02 H202	Rf 1 - H+02cmOH+0 Rf 10 - H+02(+M)cmH02(+M) Rf 27 - C0+H02cm>C02+0H	36.32 36.11 11.26 82.7-CC-MGhum CO3-GH	3	2.74948×10 ⁻⁷	1200.	н ОН О	Rb 12 - H02+H<=>H2+02 Rf 28 - C0+02<=>C02+0 Rf 2 - H2+0<=>OH+0 Rf 1 - H402<=>OH+0	45.27 42.58 5.46 5.173	Ri 12 - H02+H<=>H2+O2 Ri 28 - CO+O2<=>CO2+O Ri 2 - H2+O<=>OH+H
CROSSOVER TEMPERATURE	6	0.0345474	900.274	H02 H2O2 NaS	Rf 10 - H+02(+M) Rf 1 - H+02 Rf 1 - H+02 Rf 1 - H+02	35.56 PT 0 = Red (R)(u=R(0)=0) 34.43 PT 1 = Red (R)(u=R(0)=0) PT 0 =				Ũ	Rf 3 – H2+OH<=>H2O+H	0.6622	Rf 1 - H+02<=>0H+0 Rf 3 - H2+0H<=>H20+H
(950K)	7	0.0435632	900.919 904.771	H02 H2O2 NaS H H02 H2O2	Rf 10 - H+02(+M) Rf 1 - H+02(+M) Rf 10 - H+02(+M) Rf 10 - H+02(+M) Rf 11 - H+02(+M) Rf 11 - H+02(+H) Rf 11 - H02+Hos20H	37.93 22.58 11.22 R1-RC(hundle)	4	6.64043×10 ⁻⁷	1200.	н	Rf 1 - H+02<=>0H+0 Rb 12 - H02+H<=>H2+02 Rf 28 - C0+02<=>C02+0	27.79 26.7 26.5	Rf 1 - H+02c=>0H+0 Rb 12 - H02+Hc=>H2+02
	9	0.0584542	0.0584542 905.757 0 HO2		Rf 10 - H+O2(+M)<∞>HO2(+M) Rf 1 - H+O2<∞>OH+O Rf 11 - HO2+H<∞>2OH	38.1 28.71 13.36 R11-HC2(H)cuHC2(H) R11-HC2(H)cuHC2(H) R11-HC2(H)cuHC2(H)				0	Rf 28 – C0+02<=>C02+0 Rf 2 – H2+0<=>OH+H	26.5 12.18	Rf 2 - H2+Oc=>OH+H
	10	0.0586682	906.306	H O HO2	Rf 10 - H+O2(+M)<=>HO2(+M) Rf 1 - H+O2<=>HO2(+M) Rf 11 - HO2+H==>20H	36.17 27.42 10.2 10.2 10.2	5	4.45471×10 ⁻⁶	1200.	H O	Rf 1 - H+02<=>0H+0 Rf 2 - H2+0<=>0H+H	62.88 19.39	Rf 1 - H+02c=>0H+0 Rf 2 - H2+0c=>0H+H
	11	0.0589165	908.509	H O NaS	Rf 10 - H+02(+M) Rf 1 - H+02(+M) Rf 1 - H+02 Rf 11 - H02+Hos20H Rf 1 - H+02 Rf 1 - H+02	29.9 27.4 18.0 27.4 29.1 27.4 27.4 27.4 27.4 27.4 27.4 27.4 27.4	6	0.0000441018	1220.55	NaS H O	Rf 1 - H+02<=>0H+0 Rf 2 - H2+0<=>0H+H Rf 3 - H2+0H<=>H20+H	51.02 21.17 11.67	Rf 1 - H+02<=>0H+0 Rf 2 - H2+0<=>0H+H
	12	0.0590093	915.732	H O	Rf 10 - H+02(+M)-co-H02(+M) Rf 11 - H02+H-co-20H	24.08 R11-InCQr4(poundCQ)48 16.6 R11-InCQr4(poundCQ)48 R11-InCQr4(poundCQ)48 R11-InCQr4(poundCQ)48				0	KI 3 - n2+0n<=>n20+n	11.07	Rf 3 - H2+OH<=>H2O+H
	13	0.059041	926.094	NaS H O	Rf 10 - H+024MOHHO(2(M) Rf 20 - H+02(M)(=00000HH Rf 21 - H+02+Hox>OHH Rf 11 - H+02+MOHHO Rf 1 - H+02+mOHHO	42.94	7	0.0000472151	1260.31	NaS H O H2	Rf 1 – H+02<=>0H+0 Rf 2 – H2+0<=>0H+H Rf 3 – H2+0H<=>H20+H	42.53 20.96 13.17	R12 - H2+0Kes>H4H
				 850 K 865 K 880 K 895 K 910 K 925 K 	N2 1 1 <th>1 220 # 1 - 000 - 000 # 1 - 000 # 1</th> <th>8</th> <th>0.0000477381</th> <th>1271.88</th> <th>NaS H O H2</th> <th>Rf 1 – H+O2<=>OH+O Rf 2 – H2+O<=>OH+H Rf 3 – H2+OH<=>H2OH+ Rf 10 – H+O2(+M)<=>HO2(+M)</th> <th>40.88 20.86 13.3 5.435</th> <th>Rf 1 - H+02c=>OH+0 Rf 2 - H2+0c=>OH+H Rf 3 - H2+OHc=>H20+H Rf 10 - H+02(+M)(=>H02(+M)</th>	1 220 # 1 - 000 - 000 # 1 - 000 # 1	8	0.0000477381	1271.88	NaS H O H2	Rf 1 – H+O2<=>OH+O Rf 2 – H2+O<=>OH+H Rf 3 – H2+OH<=>H2OH+ Rf 10 – H+O2(+M)<=>HO2(+M)	40.88 20.86 13.3 5.435	Rf 1 - H+02c=>OH+0 Rf 2 - H2+0c=>OH+H Rf 3 - H2+OHc=>H20+H Rf 10 - H+02(+M)(=>H02(+M)
				940 K 955 K 970 K 985 K 1000 K	R12-12406xx320HH R13-1240Hxx320H R1-14402xx30H0 R13-12404xx30HH R13-12404xx3420H R13-12404xx3420H R13-12404xx3420H	1933 1243 1243 1243 1243 1243 1243 1243 1243 1243 1243 1243 1243 1243 1243 1243 1245 12 12 12 12 12 12 12 12 12 12 12 12 12 1	9	0.0000479815	1277.92	NaS H O2 O H2	Rf 1 - H+O2<=>OH+O Rf 2 - H2+O<=>OH+H Rf 3 - H2+OH<=>H2OH Rf 10 - H+O2(+M)<=>HO2(+M)	38.43 20.6 13.29 6.296	Rf 1 - H+02<=>OH+0 Rf 2 - H2+OC=>OH+H Rf 3 - H2+OH<=>H20+H Rf 10 - H+02(-M)(=>H02(-M)
Omega					R1 - H+02∞x0H+0 R5 - H+02∞x0H+0 R2 - H240∞x0H+0 R3 - H2+0H×x0H+0 R1 - H+02∞x0H+0 R5 - H+02∞x0H+0 R5 - H+02∞x0H+0	11.9 11.900-04000 11.9 11.900-0400 11.9 11.900-0400 12.20 11.900-0400 12.20 11.900-0400 12.20 11.900-0400 12.20 11.900-0400 12.20 11.900-0400 12.20 11.900-0400 12.20 11.900-0400 12.20 11.900-0400 12.20 11.900-0400 12.20 11.900-0400	10	0.0000491772	1314.53	NaS H O2 O H2 H2O	Rf 1 - H+O2<=>OH+O Rf 2 - H2+O<=>OH+H Rf 3 - H2+OH<=>H2OH+ Rf 10 - H+O2(+M)<=>HO2(+M)	33.3 19.67 12.75 7.762	Rf 1 - H+02c=>OH+0 Rf 2 - H2+0C=>OH+H Rf 3 - H2+OH=>H2O+H Rf 10 - H+02(+M)=>H02(+M)
-2					R3 - H2+OH R1 - H+02+++0H+0 R1 - H+02+++0H+0 R2 - H2+O++++02+++0H+1 R0 - H+02+++0H+0 R1 - H+02+++0H+0 R1 - H+02+++0H+0 R1 - H+02+++0H+0	105 9	11	0.0000493103	1319.36	NaS H O2 OH O H2 H2O	Rf 1 - H+O2<=>OH+O Rb 1 - H+O2<=>OH+O Rf 2 - H2+O<=>OH+H Rf 10 - H+O2(+M)<=>HO2(+M) Rf 3 - H2+OH<=>H2O+H	30.39 18.81 12.13 10.23 8.35	Rf 1 - H+02<=>0H+0 Rb 1 - H+02<=>0H+0 Rf 2 - H2+0<=>0H+H Rf 10 - H+02(+M)<=>H02(+M) Rf 3 - H2+0H<=>H02(+M) Rf 3 - H2+0H<=>H20+H
-4 -0 10 ⁻¹ 10 ⁰		1 1	14	-	10 - H-02(M)-5-H2(2(M) R7 = 1426-5-H4H R7 = -H2-0H+0 R5 = -H2-0	10.8 9 9 - 9 - 0.000 000 000 000 000 000 000 000 000	12	0.0000502275	1356.97	NaS H O2 OH 0 H20 H20 C02	Rf 1 - H+O2<=>OH+O Rb 1 - H+O2<=>OH+O Rf 2 - H2+O<=>OH+H Rf 10 - H+O2(+M)<=>HO2(+M) Rf 3 - H2+OH<=>H2O+H	27.05 17.52 11.48 10.5 8.769	Rt 1 - H+02c=>0H+0 Rb 1 - H+02c=>0H+0 Rt 2 - H2+0c=>0H+H Rt 10 - H+02(+M)c=>H02(+M) Rt 3 - H2+0Hc=>H20+H
t/t_ign	25	0.0591116	1344.16	H20 C02 HaS H H 02 OH 0 H 20 C02	81 - Hid2s=00H0 83 - Hid2s=00H0 10 - Hid2(M)=0H20(M) 82 - Rid2(0=0H4) 83 - Rid2(0=0H4) 83 - Hid2(0=0H4) 83 - Hid2(0=0H4) 83 - Hid2(0=0H4) 84 - Hid2(0=0H4) 85 - Hid2(0=0H4) 87 - Hid2(0=0H4) 87 - Hid2(0=0H4) 88 - Hid2(0=0H4)	223	13	0.0000503559	1362.81	NaS H O2 OH O H2 H2O C0 C02	Rf 1 - H+02<=>0H+0 Rb 1 - H+02<=>0H+0 Rf 2 - H2+0<=>0H+H Rf 10 - H+02(+M)<=>H02(+M) Rf 26 - C0+0H<=>>H02(+M) Rf 26 - C0+0H<=>>C02+H Rf 3 - H2+0H<=>H20+H	22.94 15.26 12.63 10.64 10.45 8.447	Rf 1 - H+02<=>OH+0 Rb 1 - H+02<=>OH+0 Rf 2 - H2+0<=>OH+H Rf 10 - H+02(=M)(=>H02(=M)) Rf 26 - C0+0H=>C02+H Rf 3 - H2+0H<=>H2+0H

AUTOMATIC DIAGNOSTICS OF KINETIC MECHANISMS

M. VALORANI, P.P.CIOTTOLI, R.MALPICA



PREDICTION OF STRONG AND WEAK IGNITION REGIMES IN TURBULENT REACTING FLOWS WITH TEMPERATURE FLUCTUATIONS P.PINAKI, H. G. IM, P.P.CIOTTOLI, R.MALPICA, M. VALORANI



Outcomes of Year 2 Journal Articles

• GOAL: To predict "strong" and "weak" ignition phenomena in turbulent reacting flows with thermal inhomogeneities.

Case A (Weak ignition)



Case B

(Reaction-controlled strong ignition)



Case C

(Mixing-controlled strong ignition)



Reaction front propagates by virtue of diffusion & convection: deflagration mode

Reaction pockets occur by virtue of chemical reactions: spontaneous ignition mode

Reaction zone occur after mixing is completed: mixingcontrolled strong ignition mode



Uncertain Reactive ODE Systems

H.N.Najm, M.Valorani, "Enforcing positivity in intrusive PC-UQ methods for reactive ODE systems", Journal of Computational Physics 270 (2014) 544–569





Fig. 3. Plot of the time evolution of p(x, y). The frame time sequence is for t = 0.01, 0.02, 0.04, 0.06, 0.07, 0.08, 0.09, 0.10, 0.12, 0.15, ordered left to right and top to bottom. The frames are all on the same scale, with the horizontal axis showing $x \in [0, 1.5]$, and the vertical axis showing $y \in [0, 20]$. Using MC sampling, for the Case 1, superposed on the mean (x, y) trajectory.

Chemical Model Reduction under Uncertainty

 R.Malpica Galassi, M.Valorani, H.N.Najm, C.Safta, M.Khalil, P.P.Ciottoli, "Chemical Model Reduction under Uncertainty", paper submitted to 36th Symposium Combustion 2016.







Figure 1: Average temperature, C₄H₁₀, CO and OH trajectories, with 2 standard deviation bounds



Chemical Model Reduction under Uncertainty

0.8

 R.Malpica Galassi, M.Valorani, H.N.Najm, C.Safta, M.Khalil, P.P.Ciottoli, "Chemical Model Reduction under Uncertainty", paper submitted to 36th Symposium Combustion 2016.

 $\tau = 0.020$

0.047

0.075 0.103

0.131

0.159

0.187 0.214

0.242

0.270



Figure 4: Number of retained/active species and reactions with increasing τ and θ









Performance of deterministic vs probabilistic reduction

Solvers for Systems of Stiff ODEs



• G-Scheme with re-use of CSP basis



Figure 17: n-Butane. Without (left) and with (right) reuse of Jacobian and Basis. Evolution of head (square symbols) and tail (circle) dimensions; temperature evolution (diamond) and update(1)/reuse(0) (gradient)



Figure 18: n-Butane. Without (left) and with (right) reuse of Jacobian and Basis. Evolution of head (square symbols), tail (circle), and fastest (diamond) time scales (reciprocal).

CPU Time: number of state variables $N = N_s + 1$ (Temperature); $rtol = 10^{-4}$, 10^{-3} , 10^{-2}

N vars	CVODE N Iters	GSC N Iters	CPU CVODE (s)	CPU GSC (s)	CPU GSC/CVODE
33	1161	233	0.05013	0.063311	1.26294
54	1310	251	0.095707	0.152625	1.59471
119	1675	298	0.290572	0.705717	2.42872
177	1615	281	0.489075	1.96473	4.01724
562	1434	308	4.65785	47.7425	10.2499
N vars	CVODE N Iters	GSC N Iters	CPU CVODE (s)	CPU GSC (s)	CPU GSC/CVODE
33	1161	200	0.05013	0.055073	1.0986
54	1310	200	0.095707	0.13264	1.3859
119	1675	217	0.290572	0.571197	1.96577
177	1615	203	0.489075	1.60425	3.28017
562	1434	227	4.65785	36.8613	7.9138
N vars	CVODE N Iters	GSC N Iters	CPU CVODE (s)	CPU GSC (s)	CPU GSC/CVODE
33	1161	592	0.05013	0.123645	2.46649
54	1310	497	0.095707	0.241588	2.52425
119	1675	323	0.290572	0.680094	2.34054
177	1615	376	0.489075	2.00814	4.10599
562	1434	327	4.65785	39.2042	8.4168
N vars	CVODE N Iters	GSC N Iters	CPU CVODE (s)	CPU GSC (s)	CPU GSC/CVODE
33	1161	619	0.05013	0.133874	2.67054
54	1310	563	0.095707	0.267126	2.79108
119	1675	656	0.290572	0.980779	3.37534
177	1615	598	0.489075	2.54091	5.19534
562	1434	411	4.65785	41.4817	8.90577



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List of Workflows					info.json		
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Select the local folder in which Workflows are stored:							
/Users/valorani/cspTk_run/							
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Add new Workflow							
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Uniroma1 & NTUA Contribution

What comes out from CSPTk

CSP - Warkflow vcost ×			Master
① localhost/csp/workflow.php			Q. 🕁 🔢
1. Select mechanism			
2. Select simulation workflow and applicable actions			
3. Edit input values and run simulation			
4. Display simulation results			
Table 1 and 1 a			-
Select a mechanism:			
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Select a workflow:			
Complete ODE #			
Model type: Constant volume \$		Solver: cvode #	
Create Data Base			
Execute Analysis and Simplification			
Execute Check			
Compute Errors			
Create Error Plots			
Edit input data:			
▶ Initial conditions			
▶ Initial conditions for re-run			
Simplify options			
▶ Solver options			
▶ Periodic table			
	Run simulation		
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Log files:		Plots:	
► Create Data Base		Create Data Base	
Execute Analysis and Simplification		Execute Analysis and Simplification	
► Execute Check		Execute Check	
► Compute Errors		Create Error Plots	
Create Error Plots			