

Grupo de pesquisa:

**CFD, propulsão e
aerodinâmica de foguetes**

(CFD/UFPR) – junho/2002

15 Fev 2014

Laboratórios (136 m²):

Lena 1: alunos

Lena 2: professores

LAE: minifoguetes

Localização:

salas 7-16, 7-30 e 7-31 do DEMEC

Equipamentos principais:

23 computadores (192 GB, Xeon, 12 núcleos)

5 impressoras laser

sensores F, T, p, h, V, α , GPS, filmadora etc

PESQUISADORES atuais (11)

Da UFPR:

Prof. Carlos Henrique Marchi (líder)

Prof. Luciano Kiyoshi Araki

Prof. Márcio Augusto Villela Pinto

De outras instituições:

UEPG = 3

UNICENTRO = 1

UTFPR = 2

UNIBRASIL = 1

IFPR = 1

COLABORAÇÕES atuais: 6

ITA

UnB

IAE/DCTA

INPE/CP

UFABC

UFSC/Joinville

ORIENTANDOS atuais na UFPR: 24

IC = 3

TG = 2

M = 4

D = 8

PD = 0

outros = 7

ORIENTAÇÕES concluídas na UFPR, 2002 →: 48

IC = 8

TG = 16

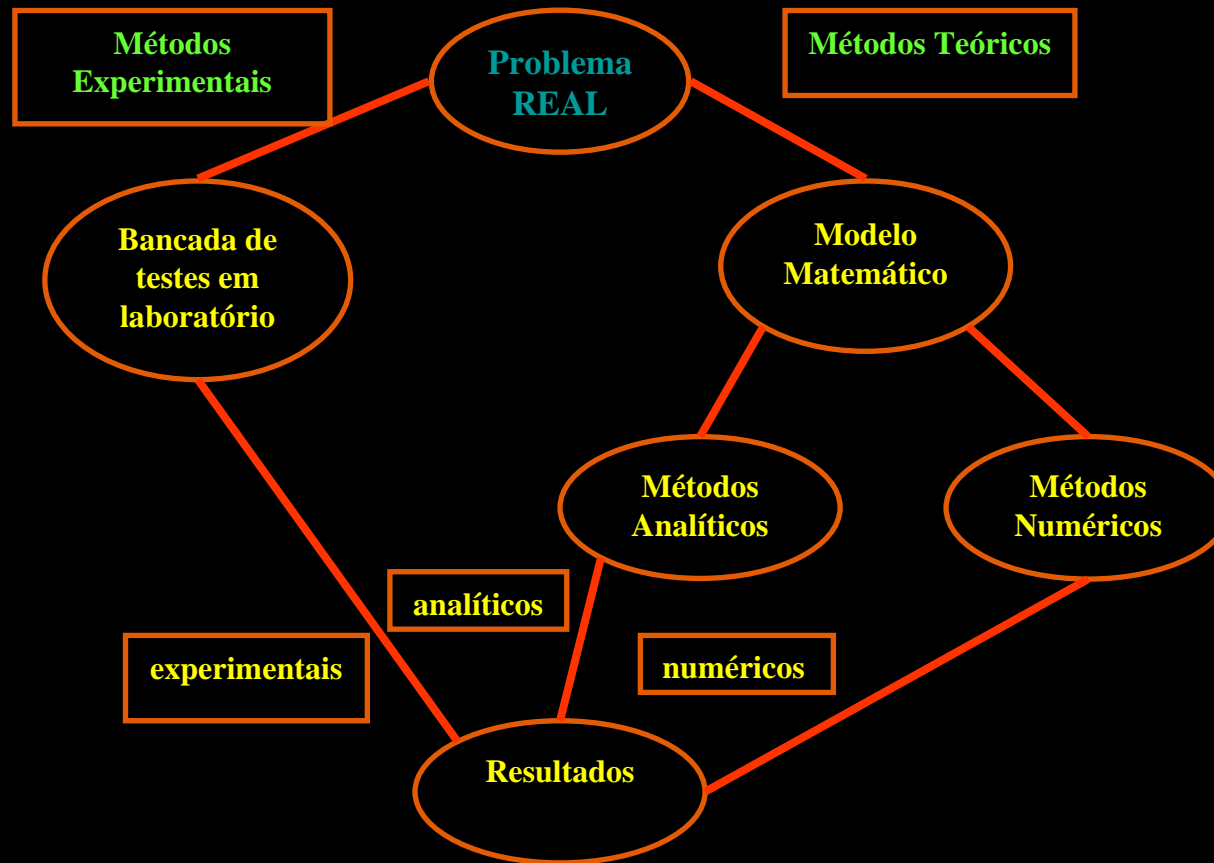
M = 11

D = 13

PD = 0

outros = 0

Métodos usados na engenharia



Linhas de pesquisa

- Propulsão de foguetes
- Aerodinâmica de foguetes
- Otimização de métodos numéricos
- Verificação e validação de soluções numéricas

Modelos matemáticos

Equações (1D/2D/3D/t):

Laplace

Poisson

Fourier

Advecção-difusão

Burgers

Euler

Navier-Stokes

Turbulência

Metodologia

Métodos numéricos:

Diferenças finitas

Volumes Finitos

Ordem das aproximações numéricas: 1, 2, 3 e 4

Tipos de malhas:

Uniformes e não-uniformes

Quadradas e triangulares

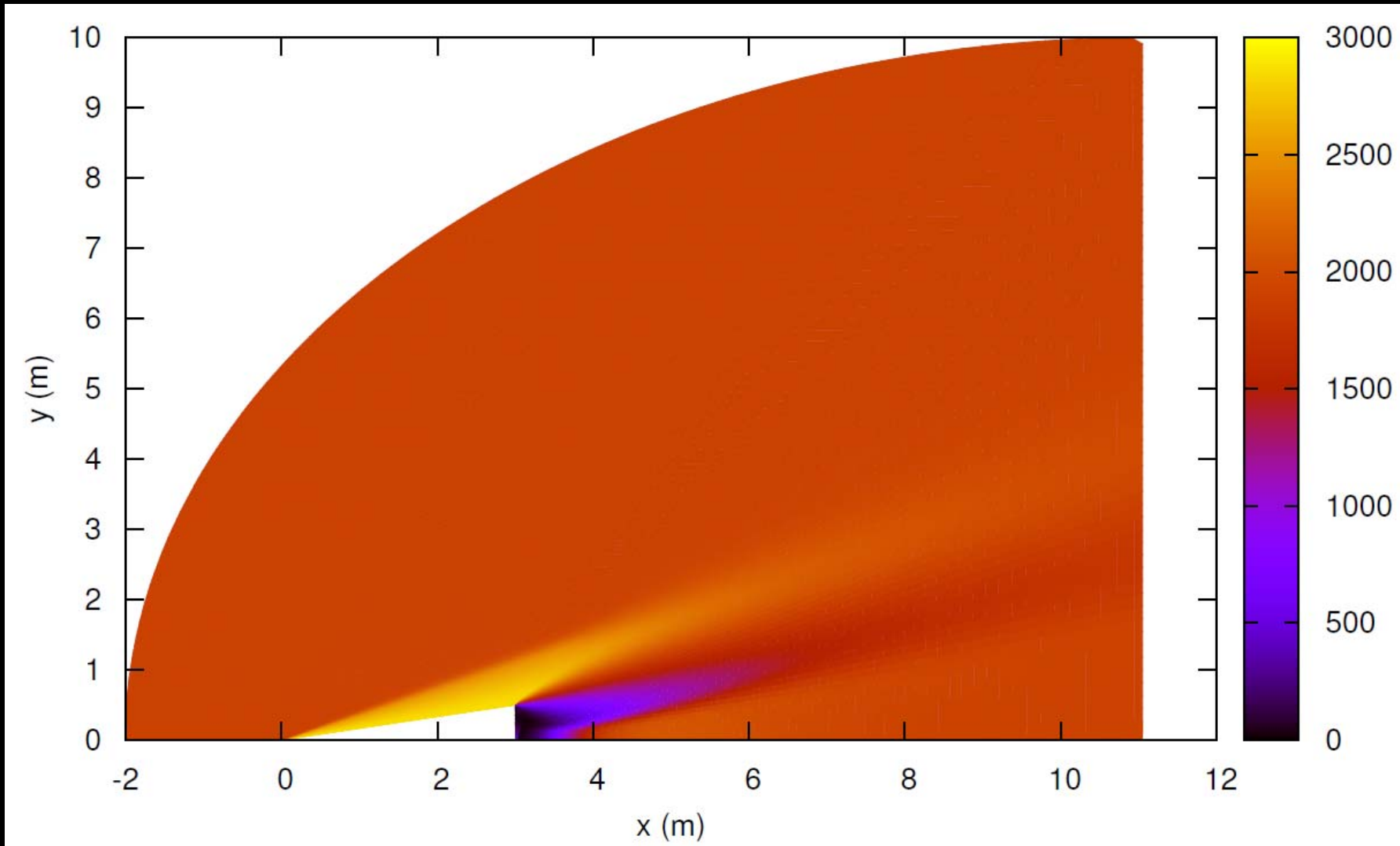
Estruturadas e não-estruturadas

Não-ortogonais

Solvers: GS, TDMA, ADI e MSI com *multigrid*

Linguagem de programação: Fortran 90

Ar sobre cone (L/D = 3): campo p



Ar sobre cone ($L/D = 3$): C_{Df}

M	Re	Exp	Mach2D
3	$4,00 \times 10^6$	$0,084 \pm 0,003$	$0,08406 \pm 0,00007$
4	$2,16 \times 10^6$	$0,078 \pm 0,005$	$0,07779 \pm 0,00009$
5	$1,05 \times 10^6$	$0,076 \pm 0,005$	$0,07556 \pm 0,00009$



O foguete brasileiro VLS

Ar sobre o foguete VLS

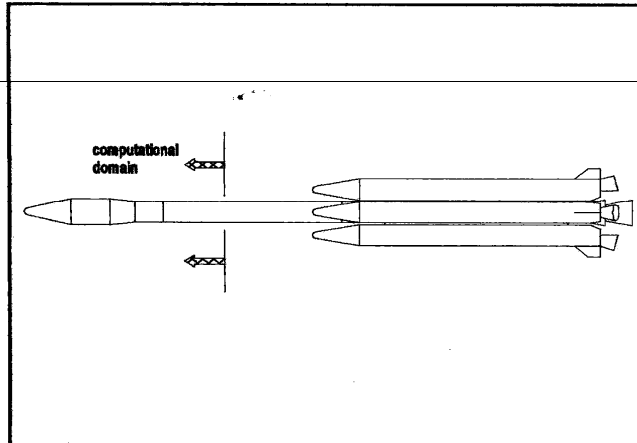


Fig. 1 Configuração completa do foguete VLS.

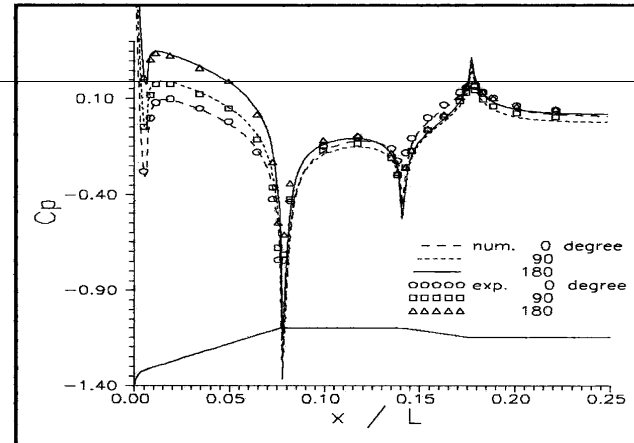


Fig. 2 C_p para $M_\infty = 0,50$ e $\alpha = 6,0^\circ$.

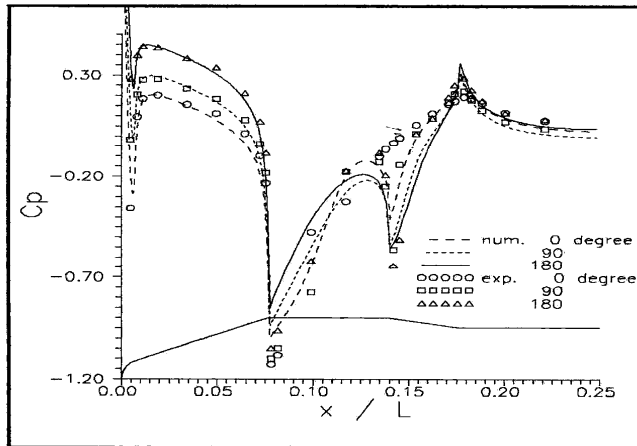


Fig. 3 C_p para $M_\infty = 0,90$ e $\alpha = 6,0^\circ$.

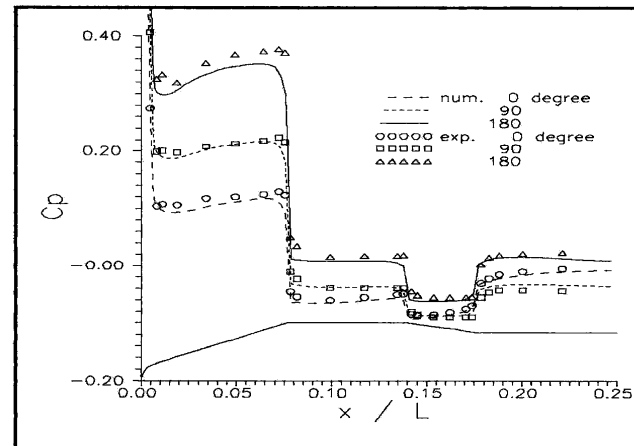
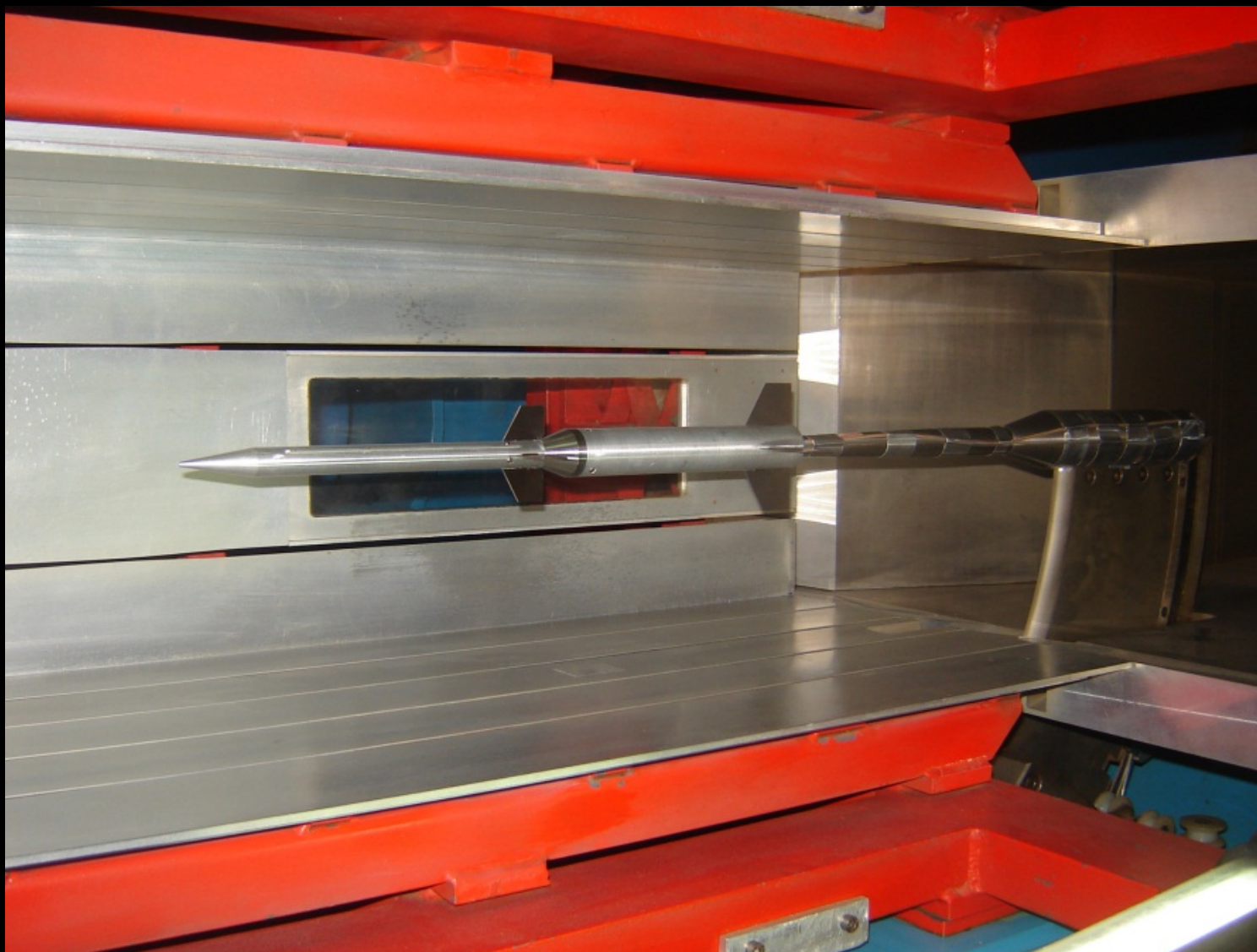
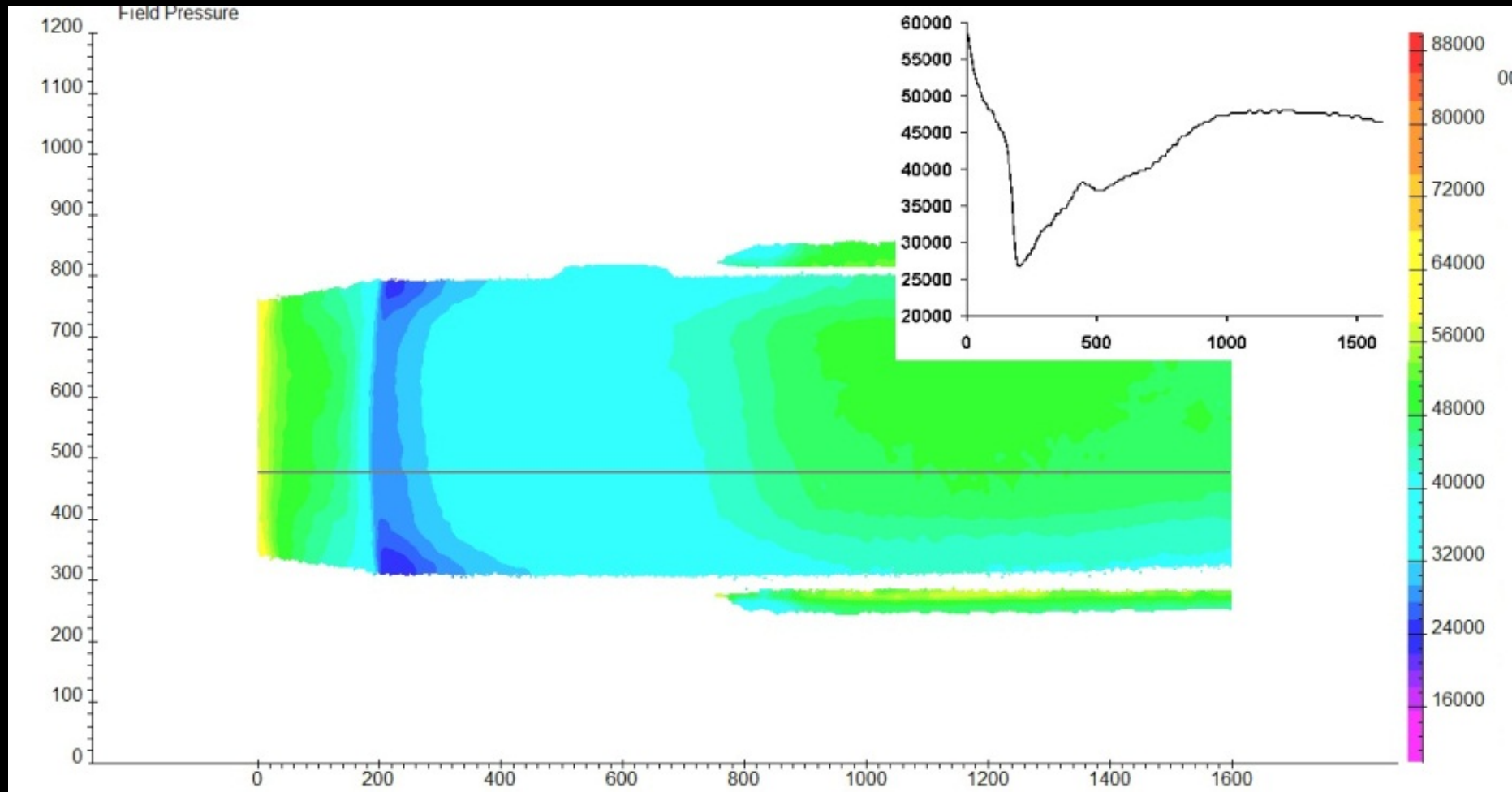


Fig. 4 C_p para $M_\infty = 3,0$ e $\alpha = 6,1^\circ$.

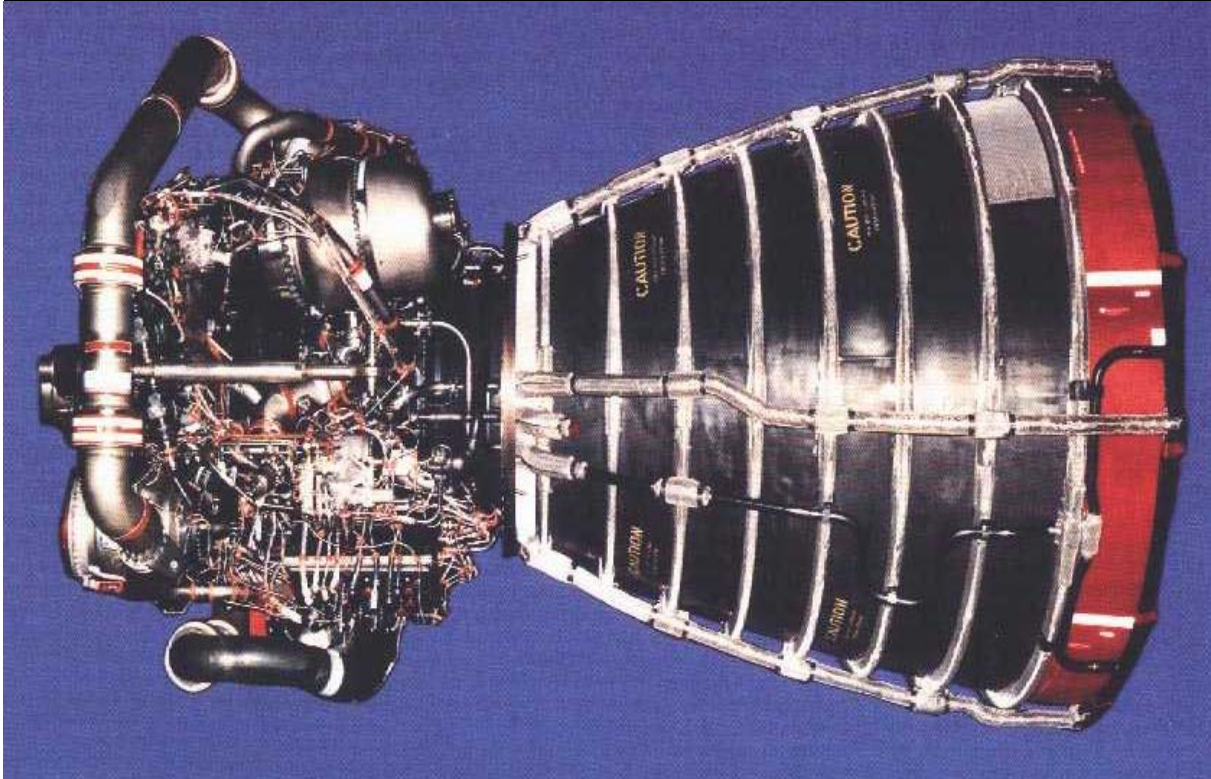
Foguete VS-30 (IAE) em túnel de vento

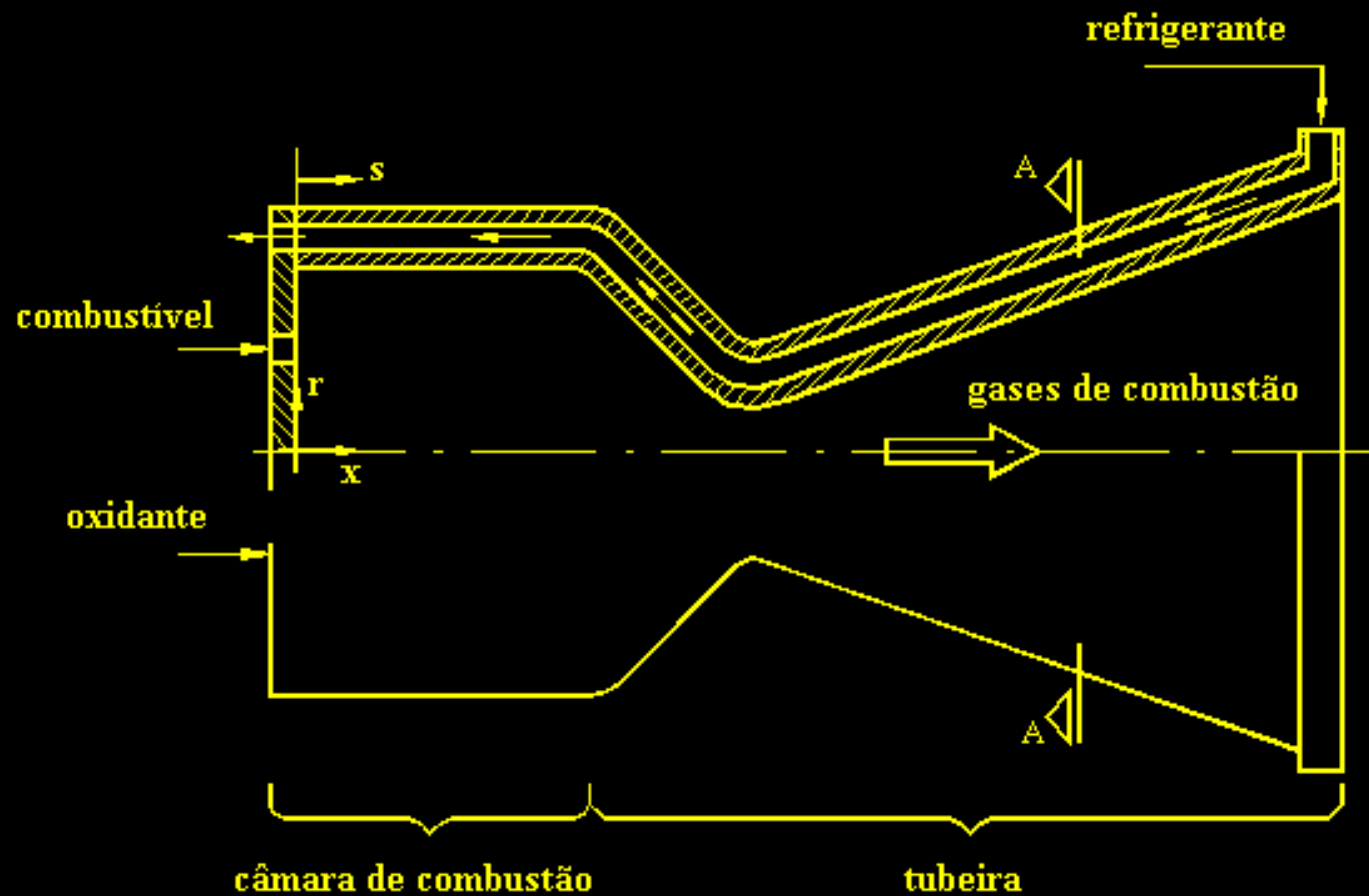


Foguete VS-40 (IAE), Mach 1, PSP



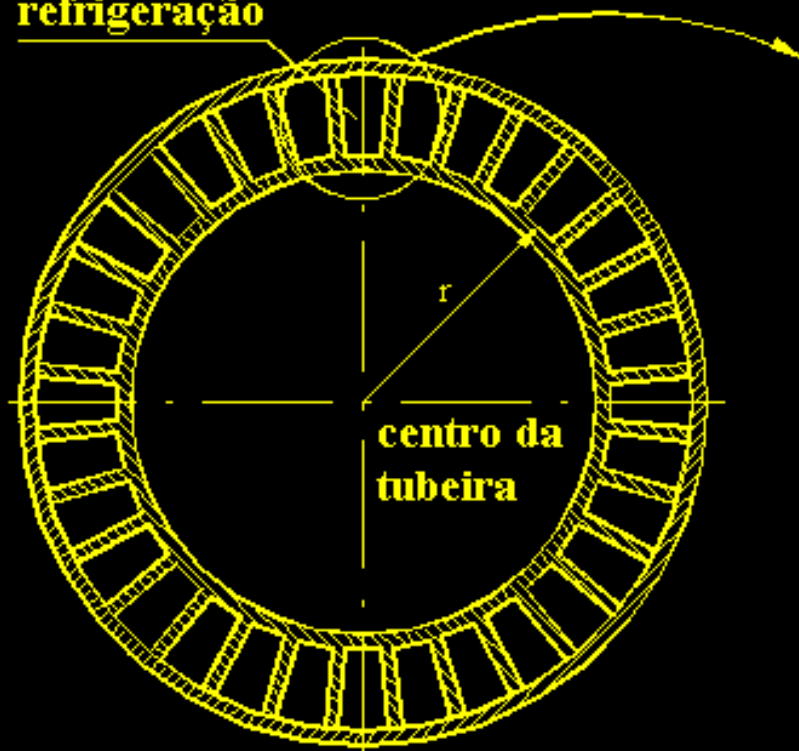
Motor-foguete SSME e Space Shuttle



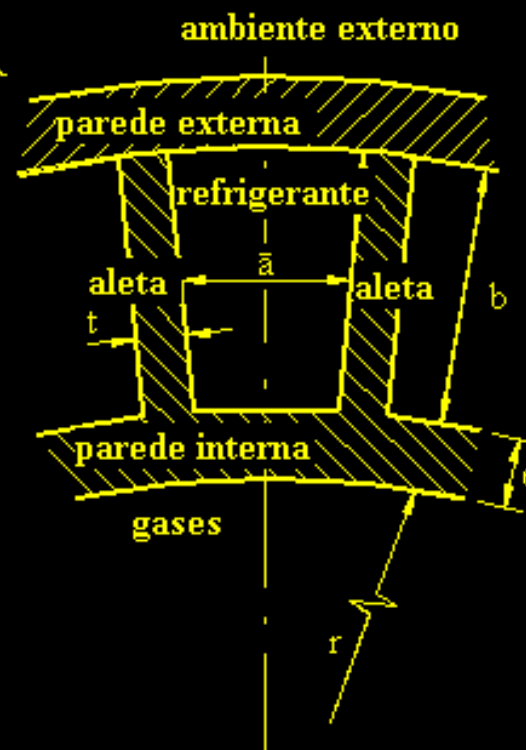


**Esquema de motor-foguete bipropelente com
refrigeração regenerativa**

canais de
refrigeração

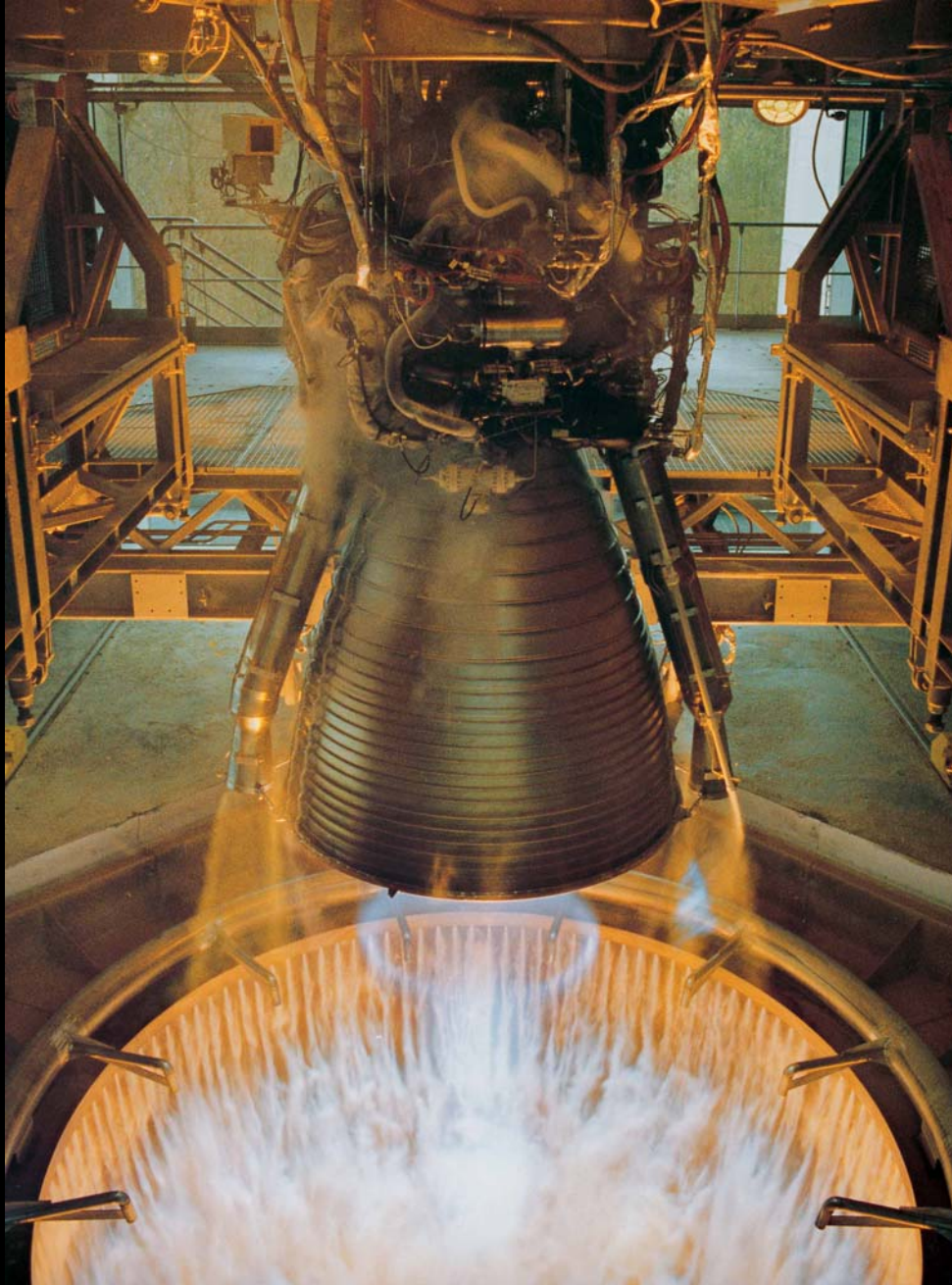


seção A-A



detalhes dos canais

Detalhes dos canais de refrigeração



Motor-foguete

Vulcain do

Ariane V

Motor Vulcain (Ariane V)

- F (nível do mar) = 103 tf
- $T_w\text{-max} = 750 \text{ K}$
- $T_o = 3.500 \text{ K}$
- $P_o = 100 \text{ atm}$
- $q''_{\text{max}} = 60 \text{ MW/m}^2$
- Canais = 360
- Altura = 9,5 a 12 mm
- Largura = 1,3 a 2,6 mm

Modelos físicos para escoamento na tubeira

1: Gás com propriedades constantes

2: Gás com propriedades variáveis

3: Gases congelados

4: Gases em equilíbrio químico local

5: Gases com taxa finita de reação

a) invíscido

b) laminar

c) turbulento

Escoamento relativo 2D laminar

$$C^\phi \left[\frac{\partial}{\partial t} (\rho \phi) + \frac{\partial}{\partial x} (\rho u \phi) + \frac{1}{r} \frac{\partial}{\partial y} (r \rho v \phi) \right] = \frac{\partial}{\partial x} \left(\Gamma^\phi \frac{\partial \phi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial y} \left(r \Gamma^\phi \frac{\partial \phi}{\partial y} \right) + P^\phi + S^\phi$$

Equação	ϕ	C^ϕ	Γ^ϕ	P^ϕ	S^ϕ
Massa	1	1	0	0	0
QML-x	u	1	μ	$-\frac{\partial p}{\partial x}$	$\frac{1}{3} \frac{\partial}{\partial x} \left(\mu \frac{\partial u}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial y} \left(\mu \frac{\partial v}{\partial x} \right) - \frac{2}{3} \frac{\partial}{\partial x} \left[\frac{\mu}{r} \frac{\partial}{\partial y} (r v) \right]$
QML-y	v	1	μ	$-\frac{\partial p}{\partial y}$	$\frac{1}{3r} \frac{\partial}{\partial y} \left(r \mu \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial x} \left(\mu \frac{\partial u}{\partial y} \right) - \frac{2}{3} \frac{\partial}{\partial y} \left(\mu \frac{\partial u}{\partial y} \right) - \frac{4}{3} f \frac{u}{r^2} v - \frac{2}{3r} f v \frac{\partial \mu}{\partial y}$
Energia	T	c_p	k	$\frac{\partial p}{\partial t} - uP^u - vP^v$	$2\mu \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 + f \left(\frac{v}{r} \right)^2 \right] + \mu \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 - \frac{2}{3} \mu \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + f \frac{v}{r} \right)^2 + S_{eq/uf}$
Espécies	Y_i	1	0	0	\dot{w}_i

Escoamento relativo 2D laminar

Equilíbrio químico local

$$S_{eq/tf} = -\frac{\partial}{\partial x} \left(\sum_{i=1}^{N_e} \rho h_i Y_i u \right) - \frac{1}{r} \frac{\partial}{\partial y} \left(\sum_{i=1}^{N_e} r \rho h_i Y_i v \right)$$

Taxa finita:

$$S_{eq/tf} = -\sum_{i=1}^{N_e} h_i \dot{w}_i$$

$$p = \sum_{i=1}^{N_e} p_i$$

$$c_p = \sum_{i=1}^{N_e} Y_i (c_p)_i$$

$$R = \sum_{i=1}^{N_e} Y_i R_i$$

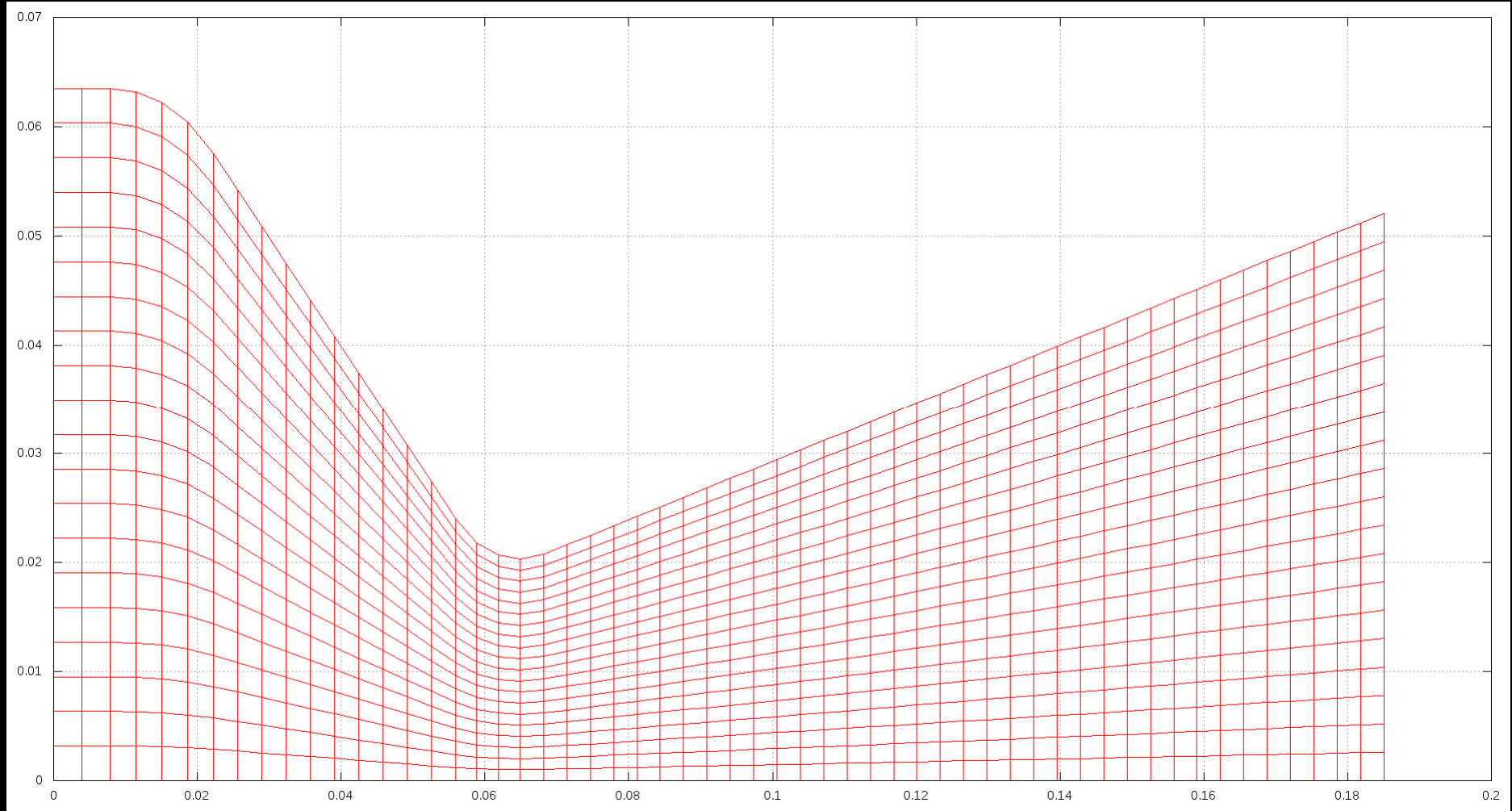
$$p = \rho R T$$

Modelos químicos para H_2/O_2

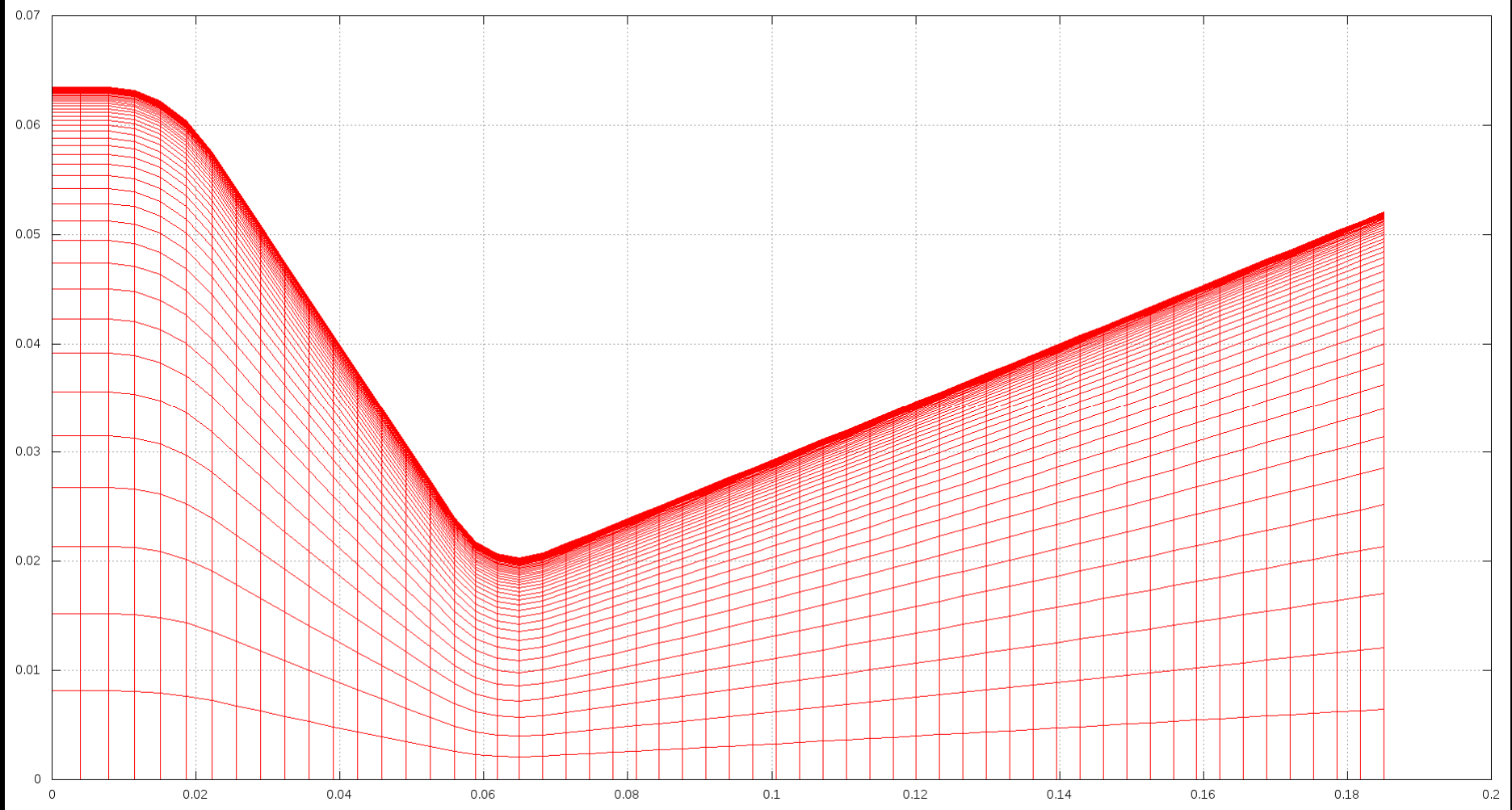
9 equilíbrio e 6 taxa finita

Modelo	Número de reações	Número de espécies	Espécies envolvidas
0	0	3	H_2O , O_2 , H_2
1	1	3	H_2O , O_2 , H_2
2	2	4	H_2O , O_2 , H_2 , OH
3	4	6	H_2O , O_2 , H_2 , OH , O , H
4	4	6	H_2O , O_2 , H_2 , OH , O , H
5	8	6	H_2O , O_2 , H_2 , OH , O , H
7	8	6	H_2O , O_2 , H_2 , OH , O , H
10	6	8	H_2O , O_2 , H_2 , OH , O , H , HO_2 , H_2O_2
9	18	8	H_2O , O_2 , H_2 , OH , O , H , HO_2 , H_2O_2

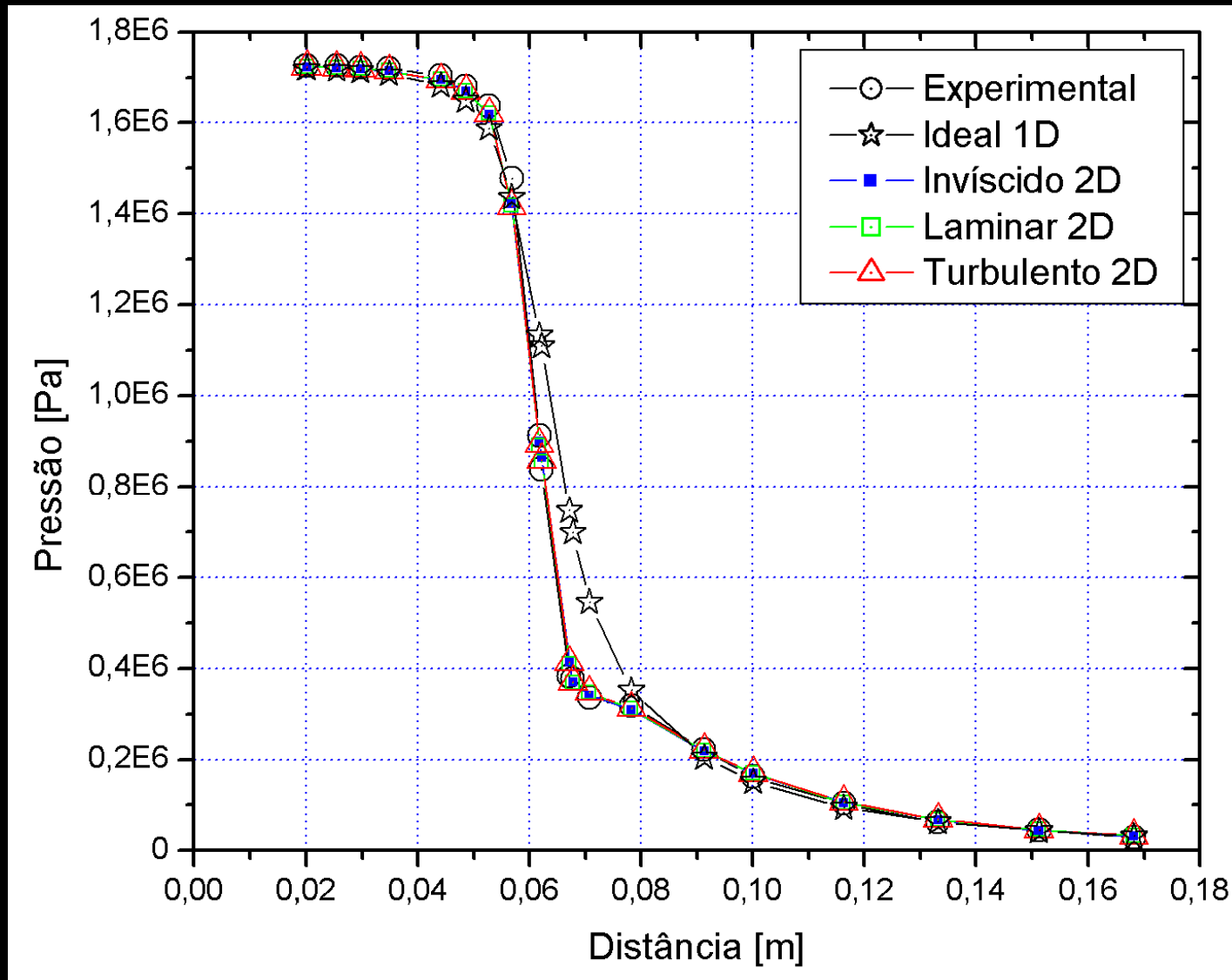
Malha 56x20, Mach2D, invíscido



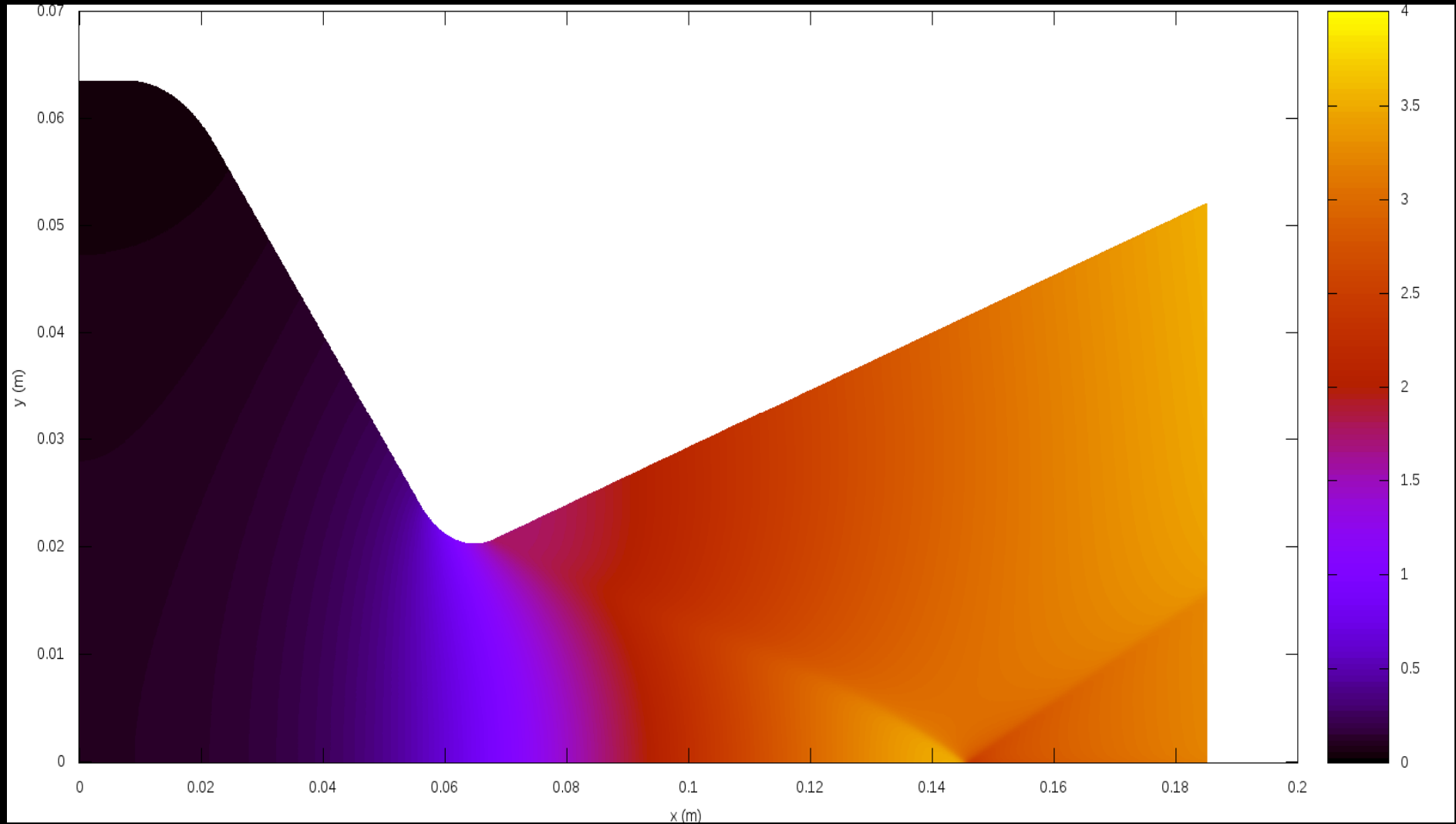
Malha 56x50, Mach2D, laminar



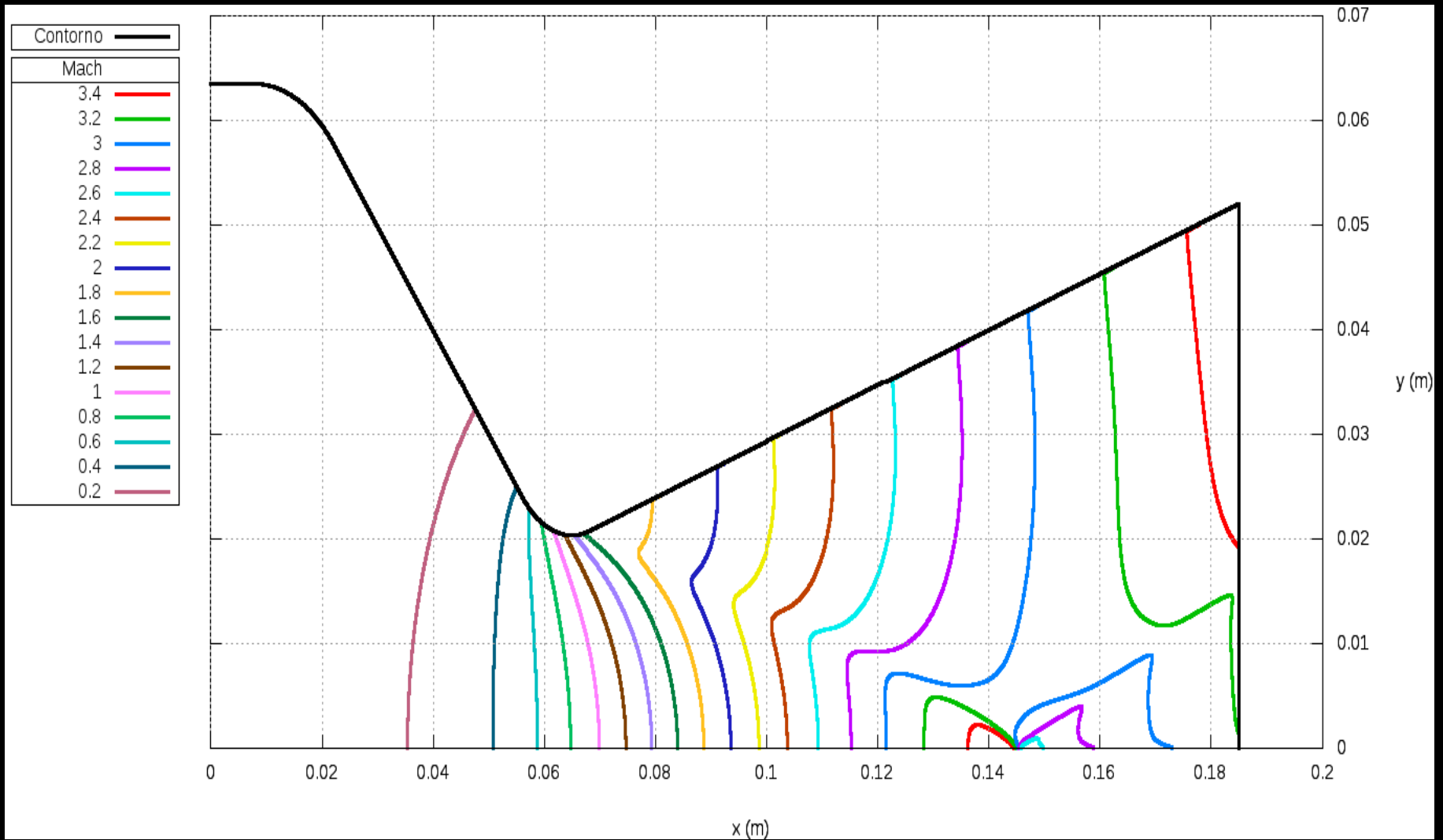
Mach2D, 224x80/200, p parede



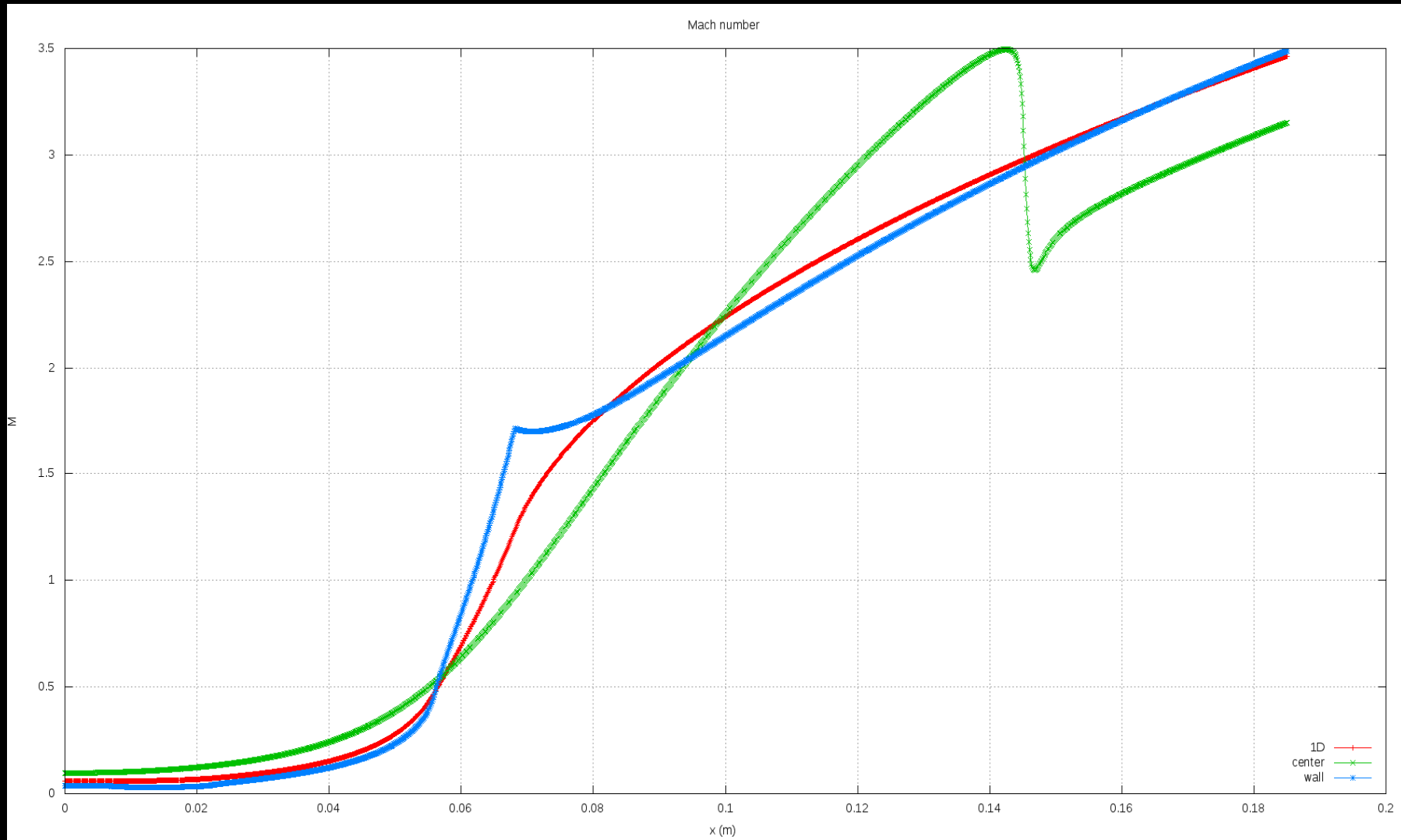
Mach, invíscido, 1792x640, Mach2D



Mach, invíscido, 1792x640, Mach2D



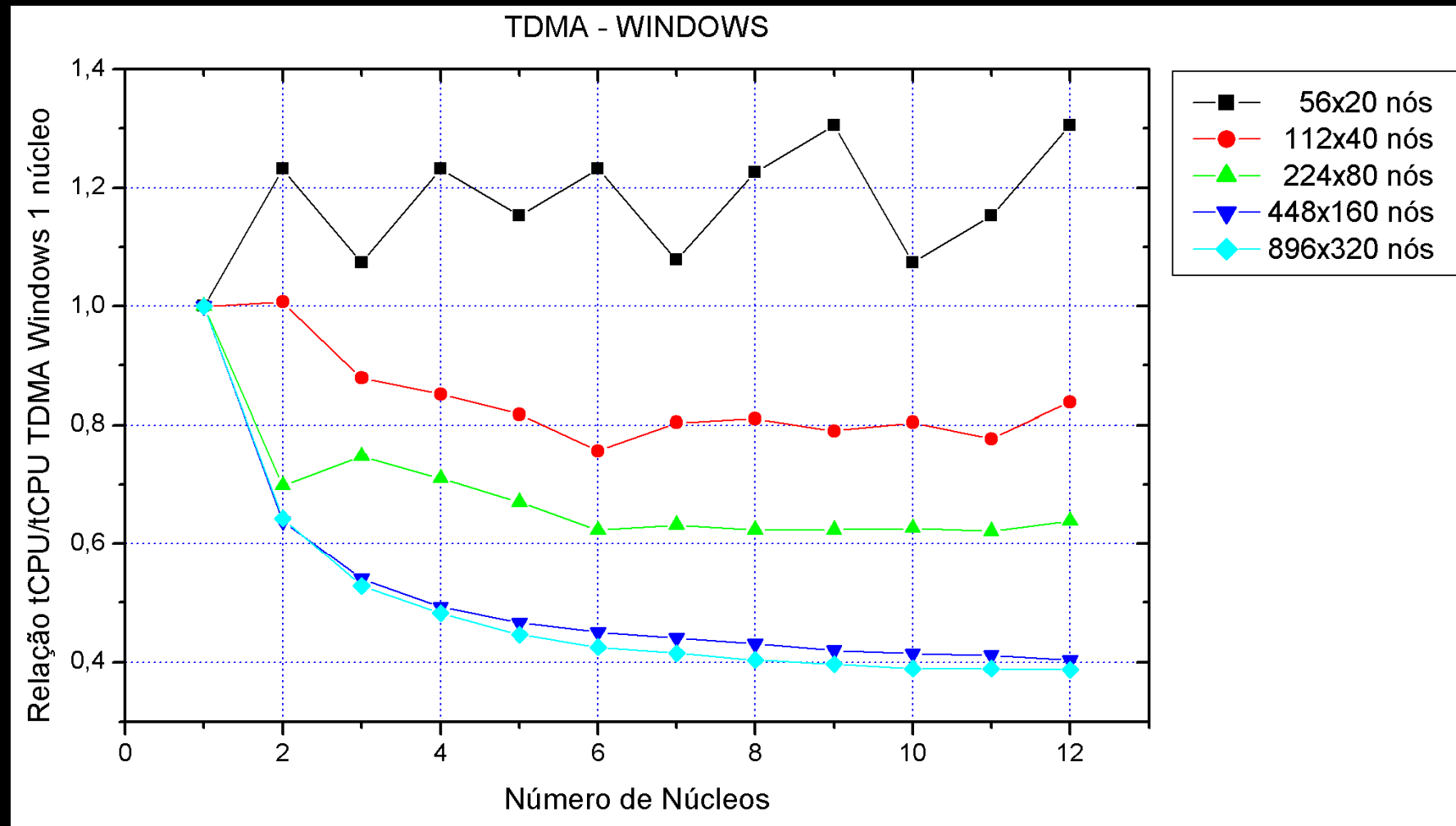
Mach, invíscido, 1792x640, Mach2D



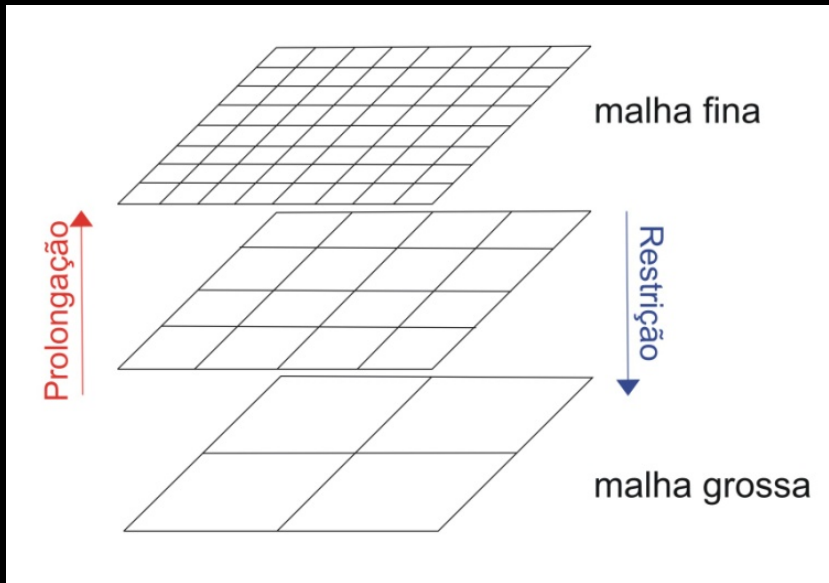
Otimização de métodos numéricos

- Métodos *multigrid* geométricos e algébricos
- Aproximações numéricas
- Multiextrapolação de Richardson
- Programação //, *solvers* etc

Otimização do Mach2D com //

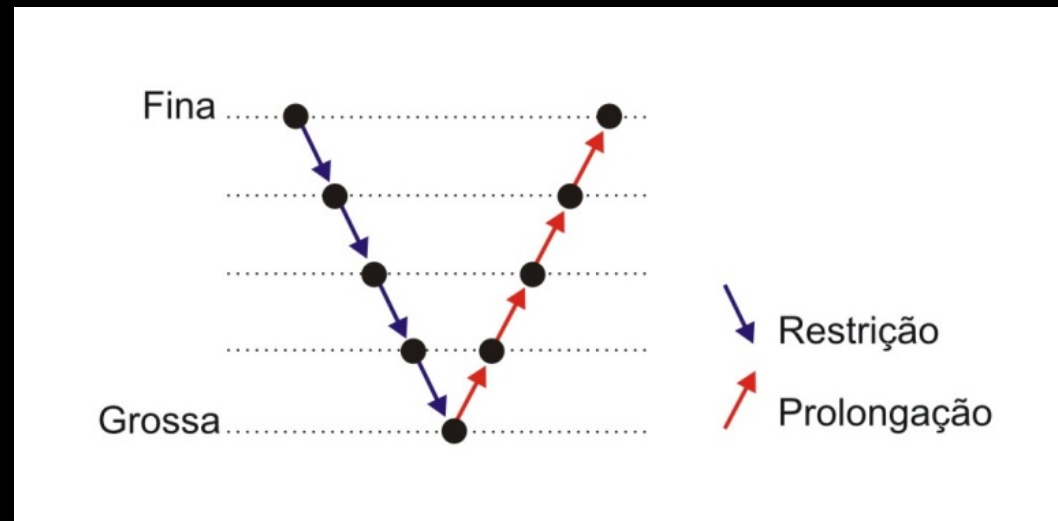


Multigrid

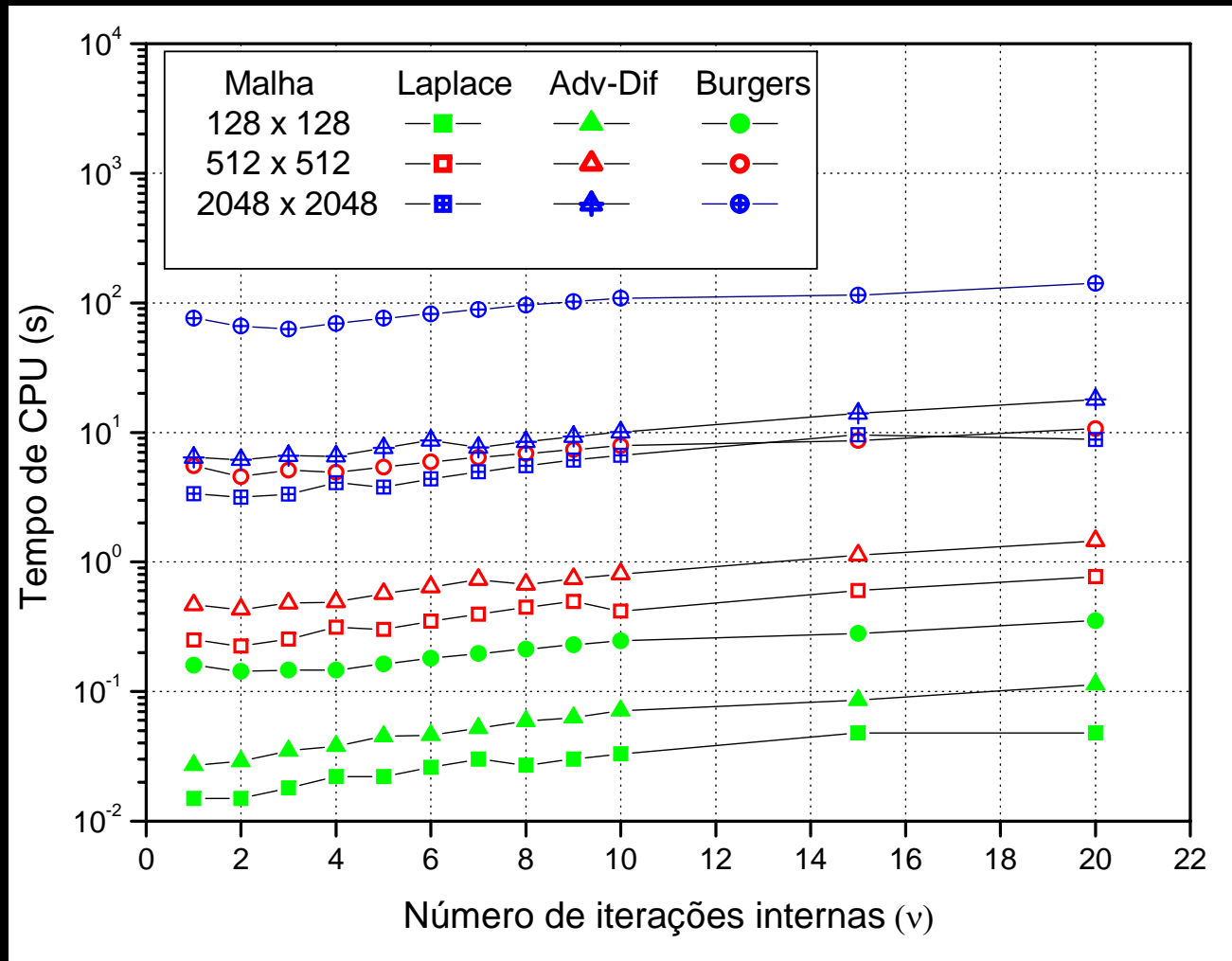


- v, L, N
- *Solver*
- Operadores de transferência

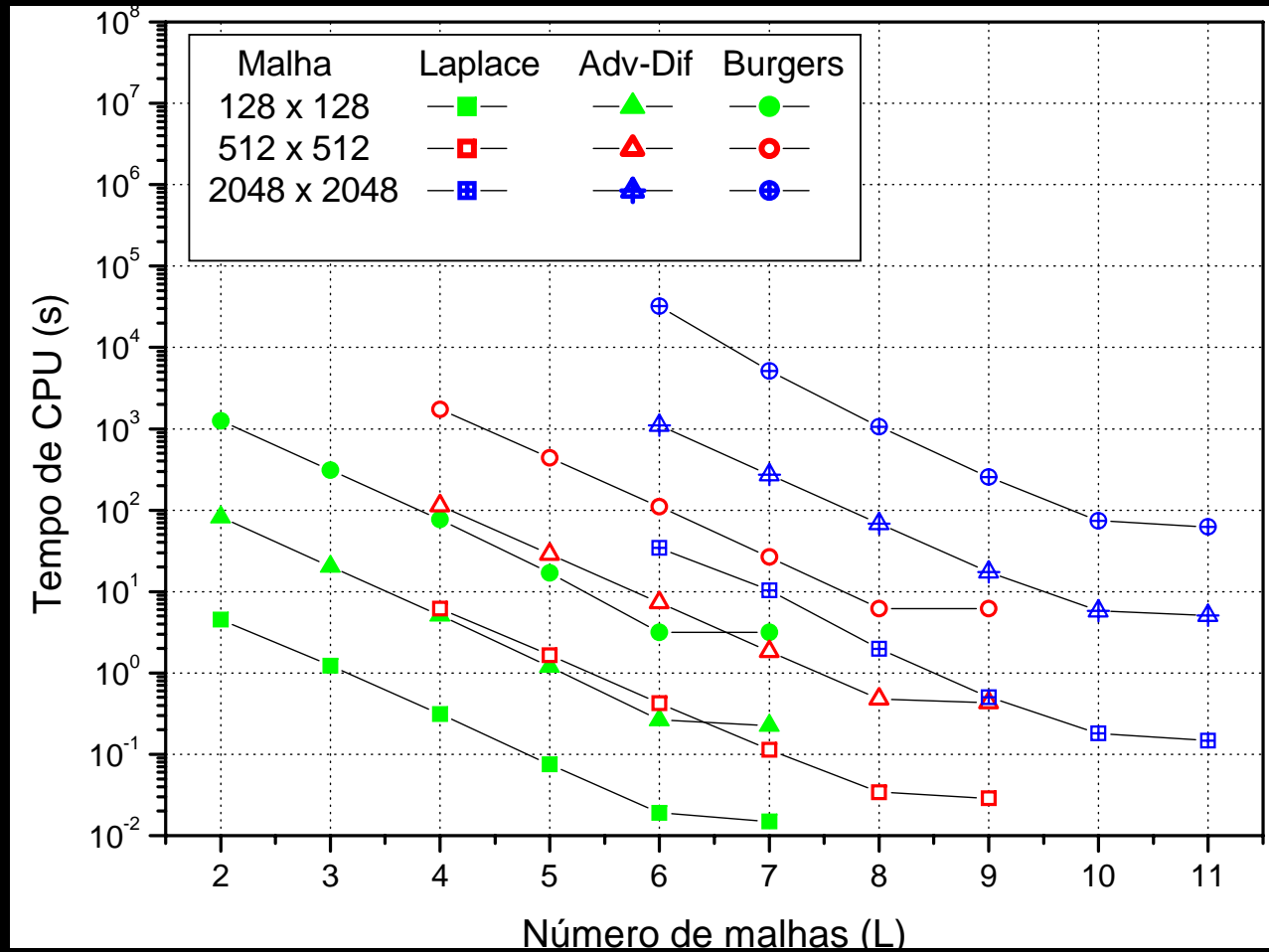
- Ciclos
- FAS x CS
- GMG x AMG
- MG x FMG



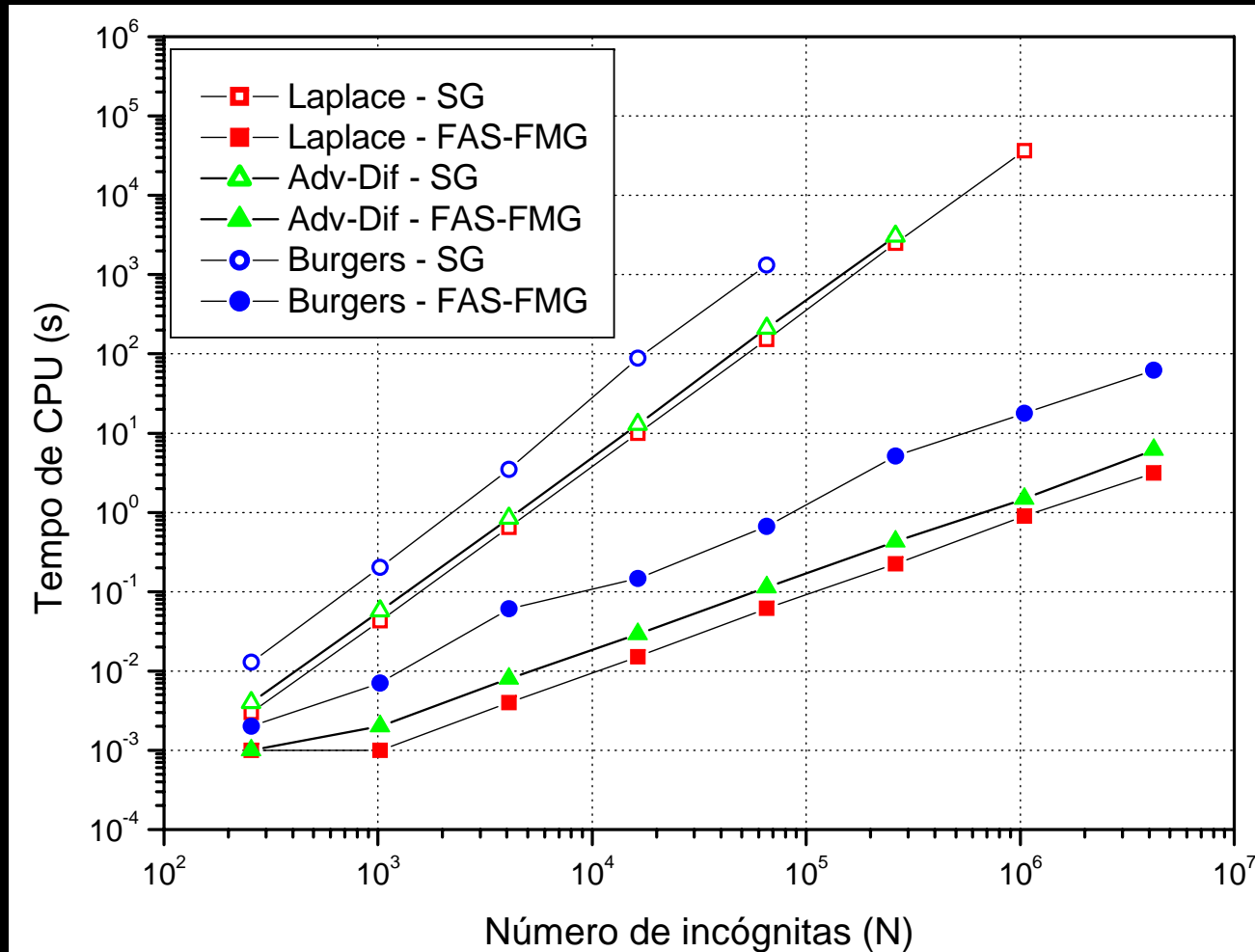
Efeito de ν sobre o tempo de CPU FAS-FMG e *solver* GS-Lex em VF



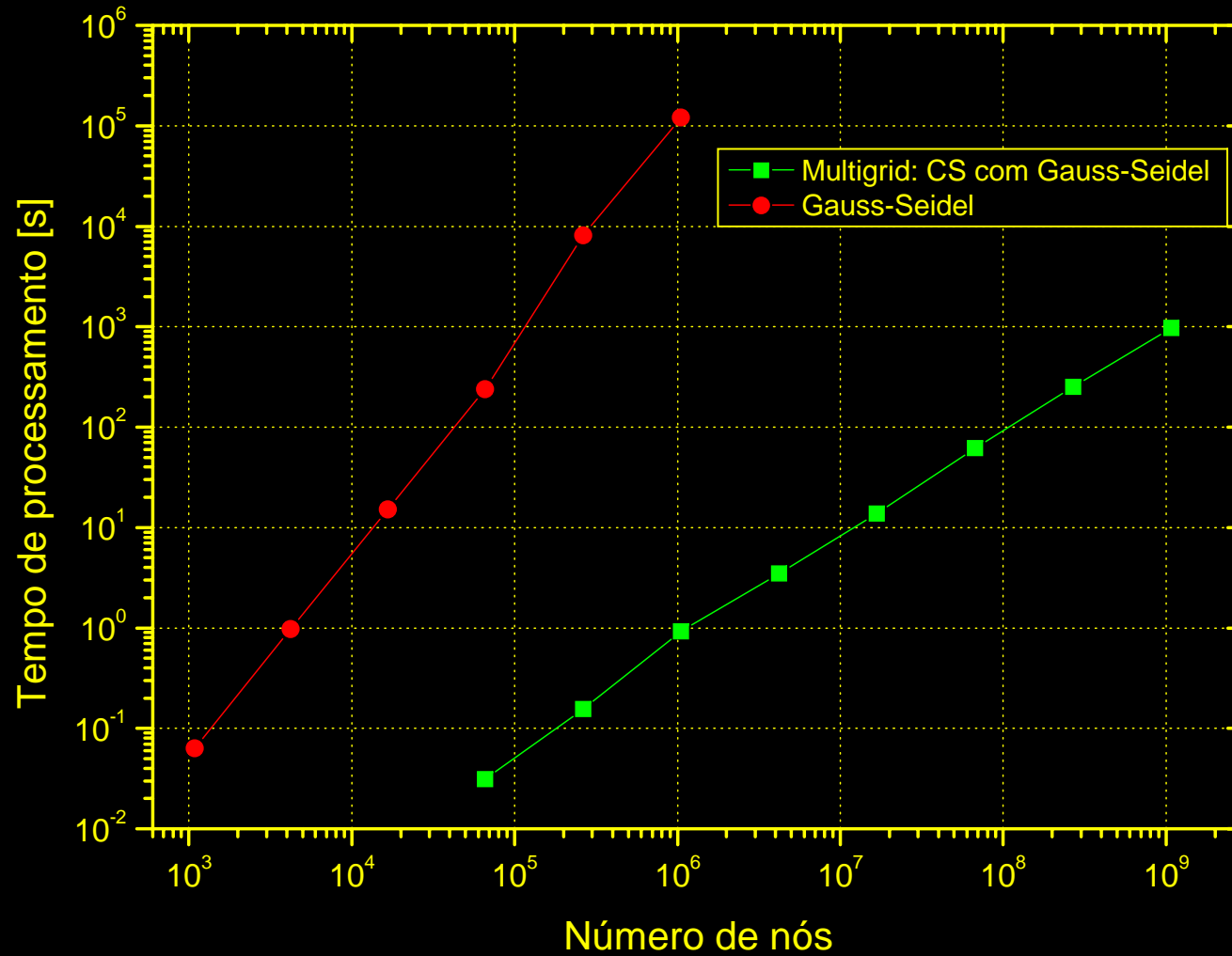
Efeito de L sobre o tempo de CPU FAS-FMG e *solver* GS-Lex em VF



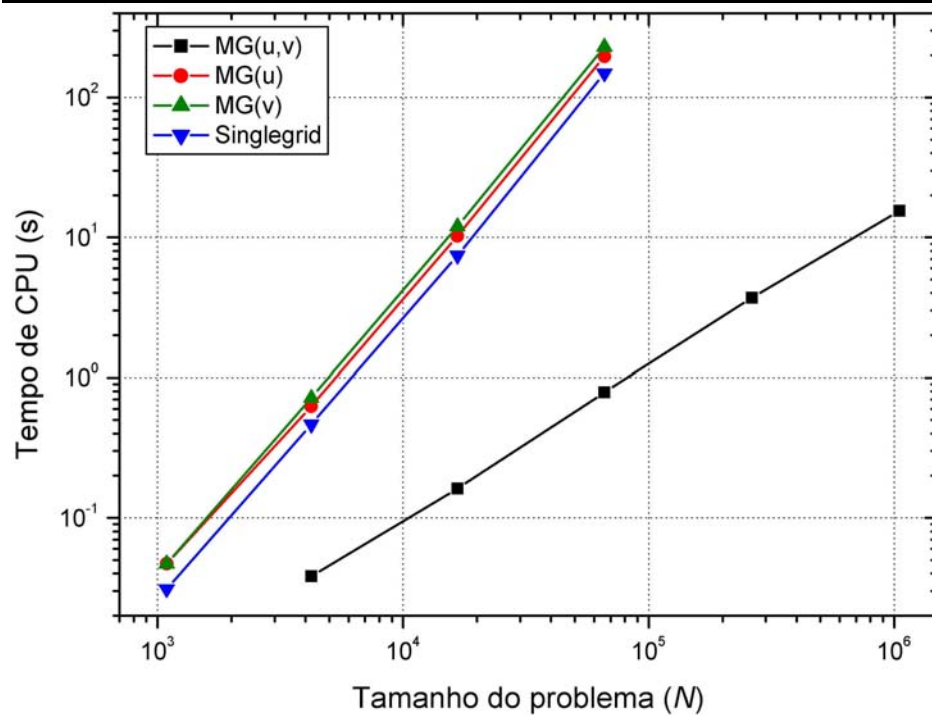
Efeito de N sobre o tempo de CPU FAS-FMG e *solver* GS-Lex em VF



Laplace 2D em DF com CDS-2

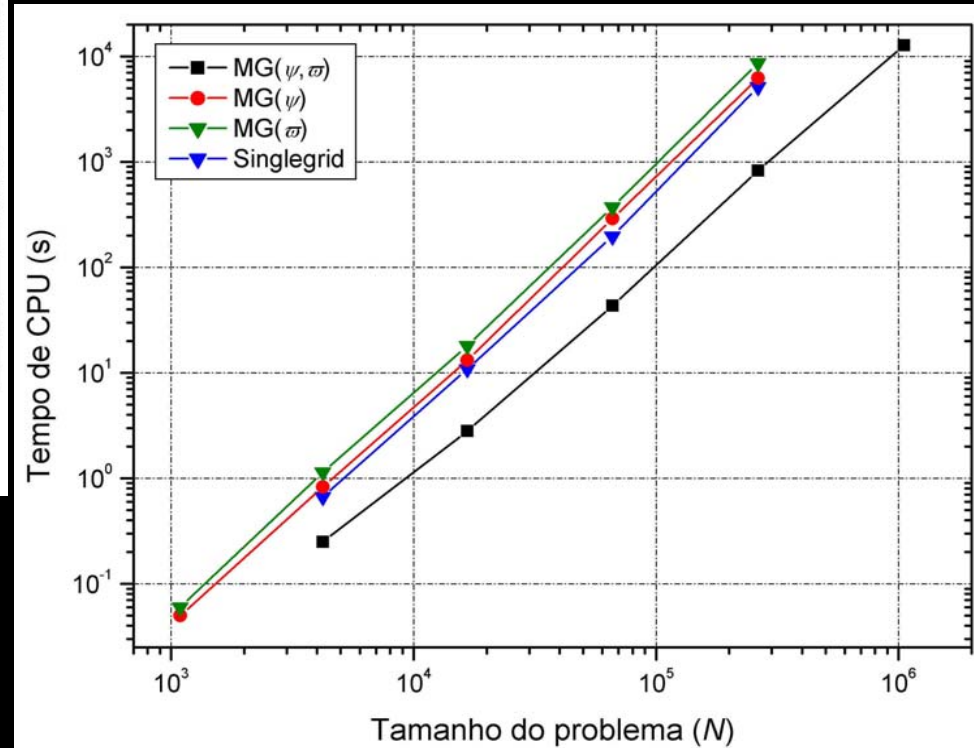


Multigrid em 1 ou 2 equações

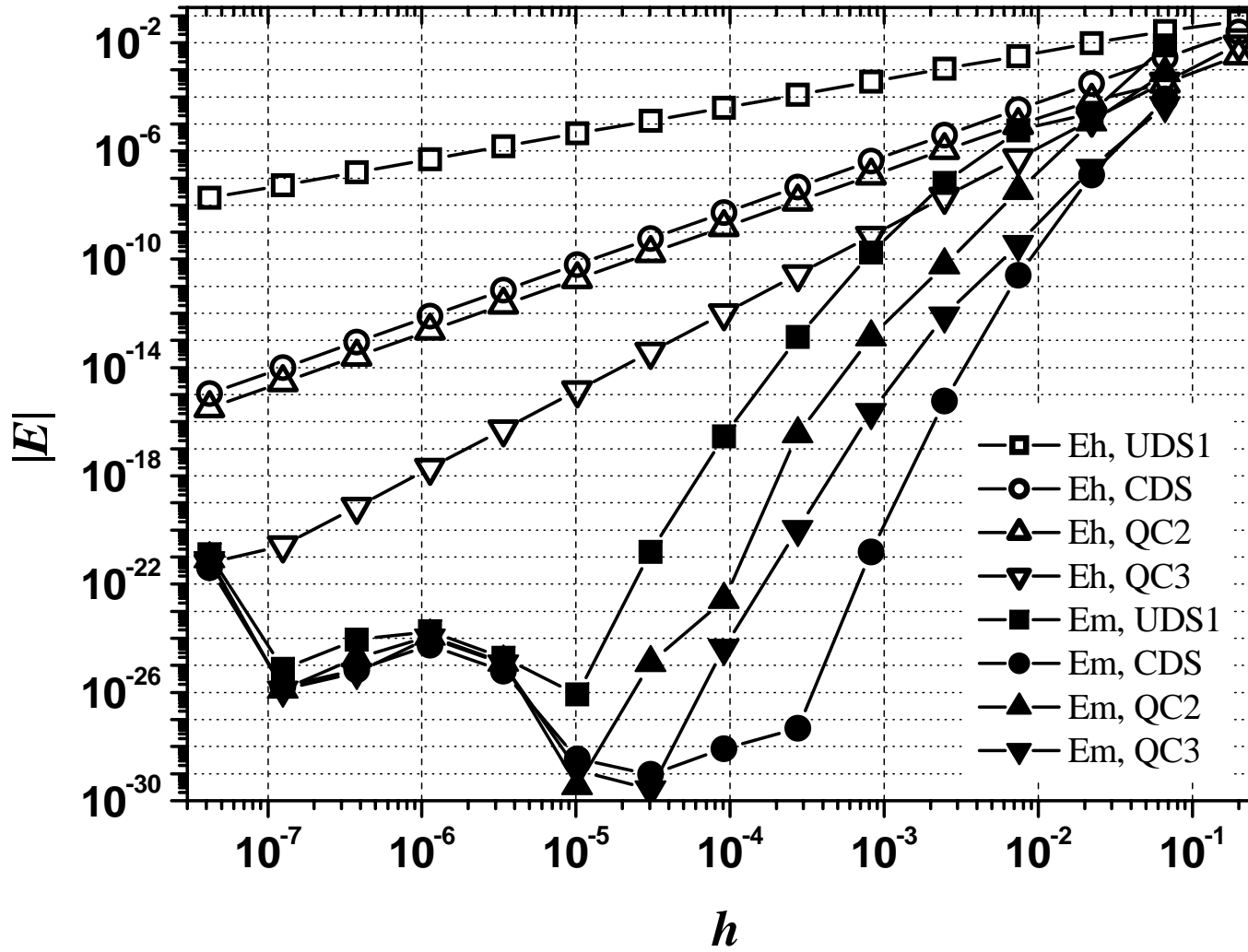


Burgers 2D, DF

Navier-Stokes 2D, ψ - ω , DF



MER em Tc, Advecção-difusão 1D, VF



MER

$$E(\phi) = \Phi - \phi$$

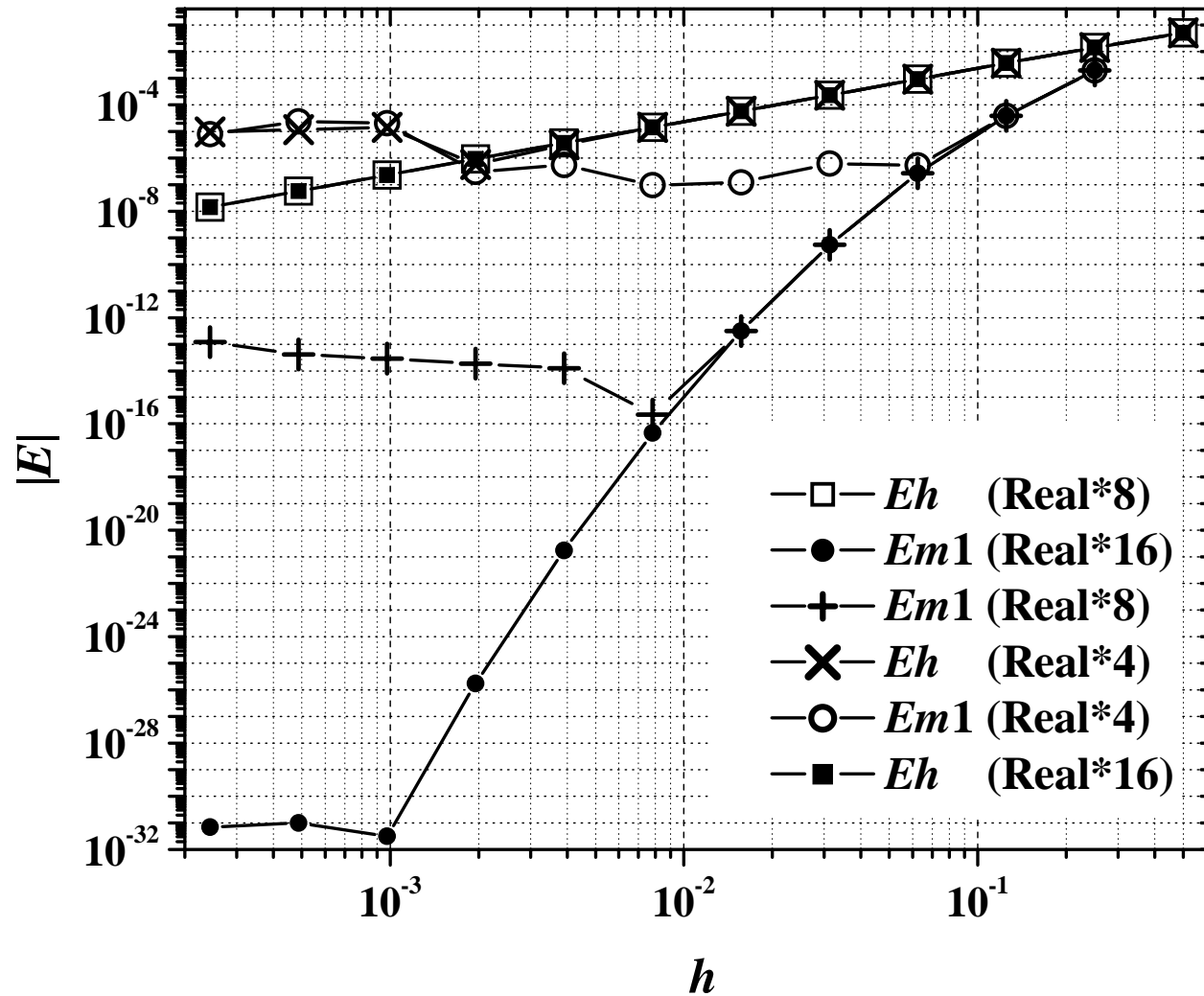
$$E(\phi) = C_0 h^{p_0} + C_1 h^{p_1} + C_2 h^{p_2} + \dots = \sum_{m=0}^{\infty} C_m h^{p_m}$$

$$\phi_{g,m} = \phi_{g,m-1} + \frac{\phi_{g,m-1} - \phi_{g-1,m-1}}{r^{p_{m-1}} - 1}$$

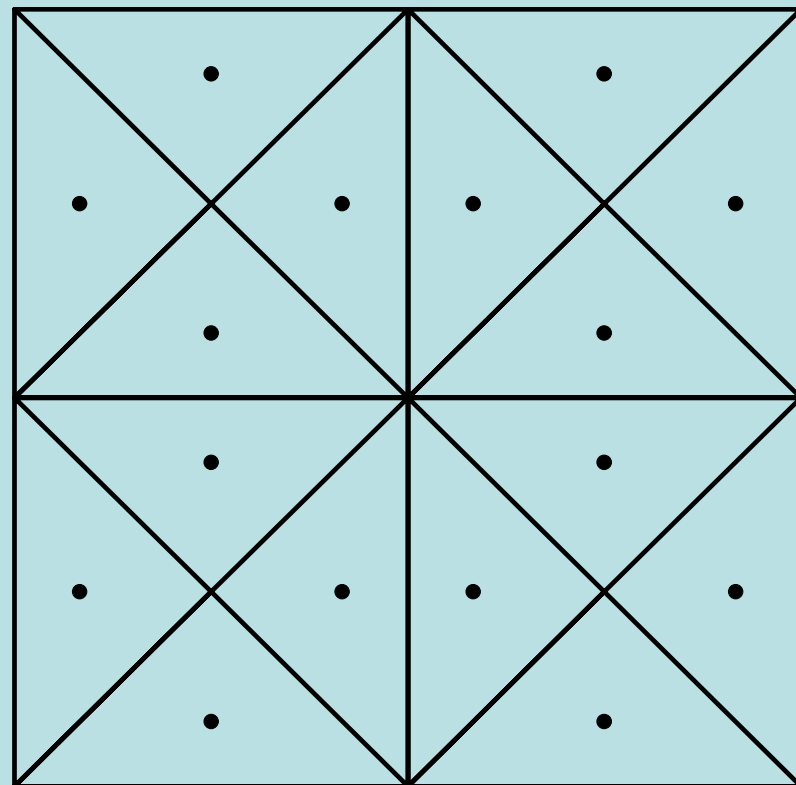
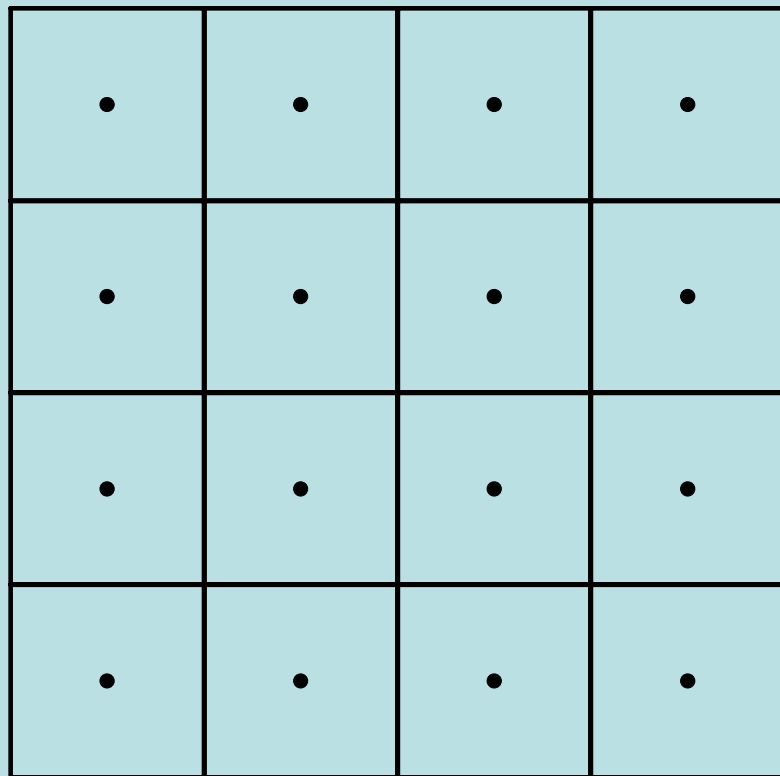
Tabela de MER

g \ m	0	1	2	3	4
1	1,0				
2	2,0	2,1			
3	3,0	3,1	3,2		
4	4,0	4,1	4,2	4,3	
5	5,0	5,1	5,2	5,3	5,4

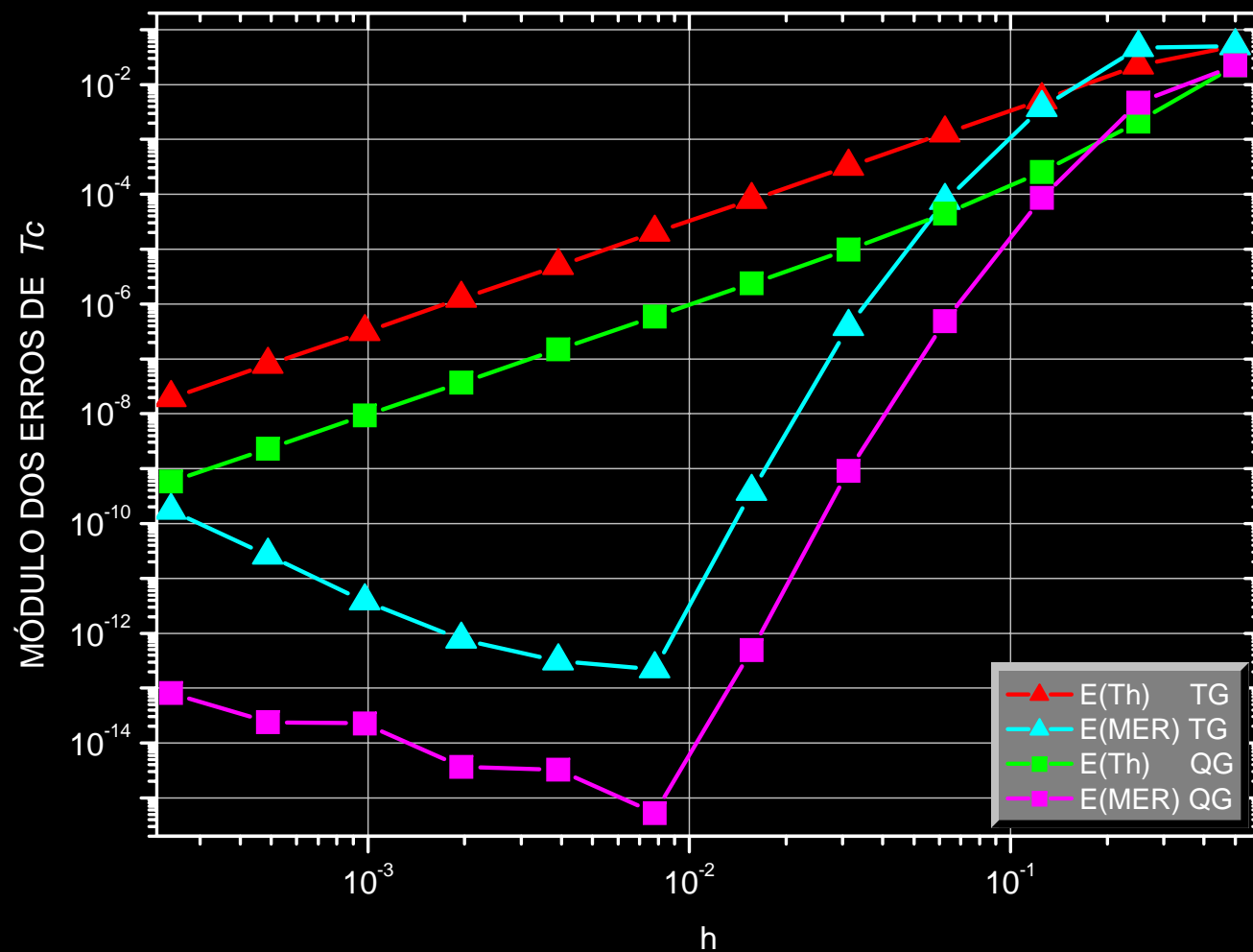
MER em Tc, Laplace 2D, DF



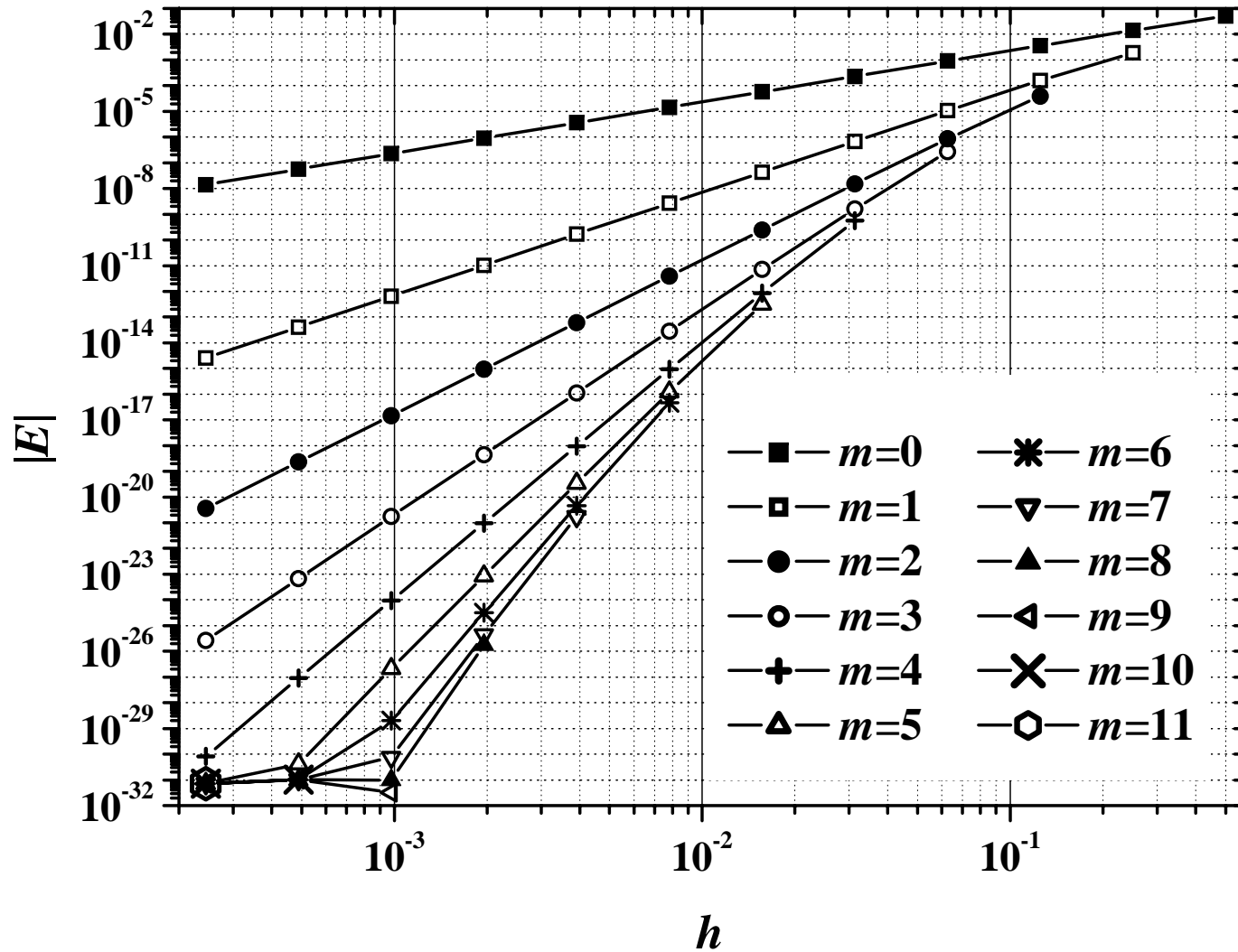
Malhas quadradas e triangulares



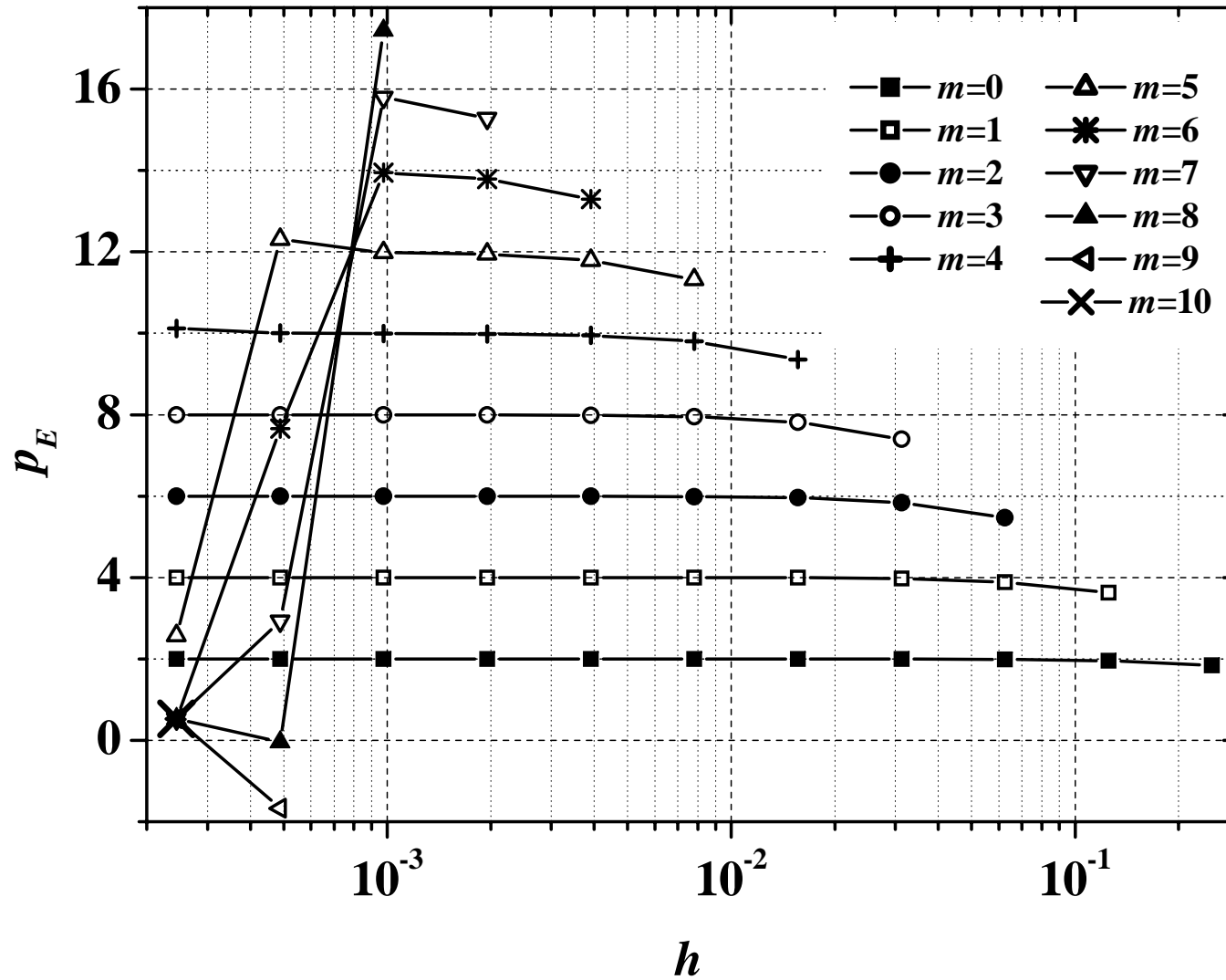
MER em Tc, Laplace 2D, VF



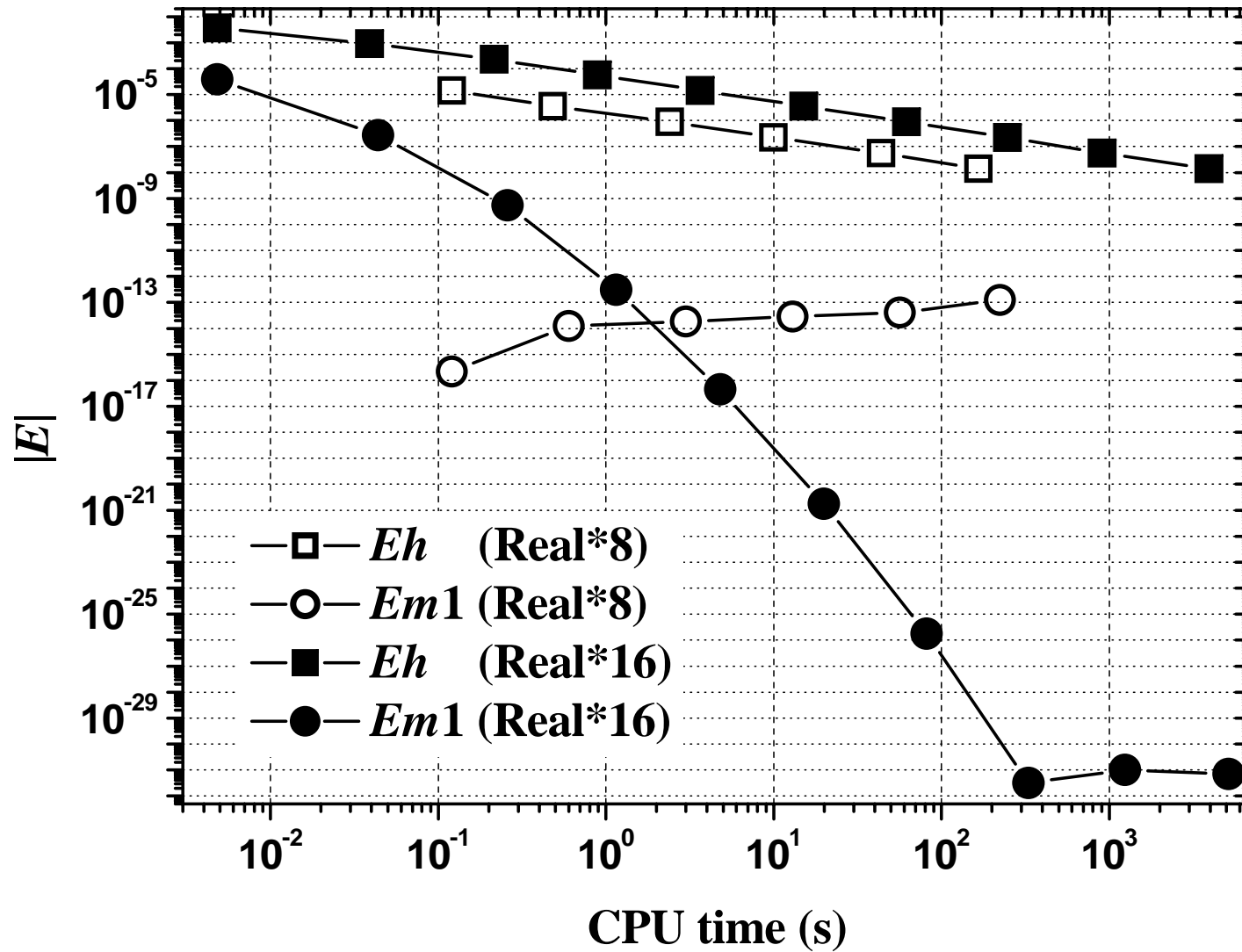
MER em Tc, Laplace 2D, DF



MER em Tc, Laplace 2D, DF



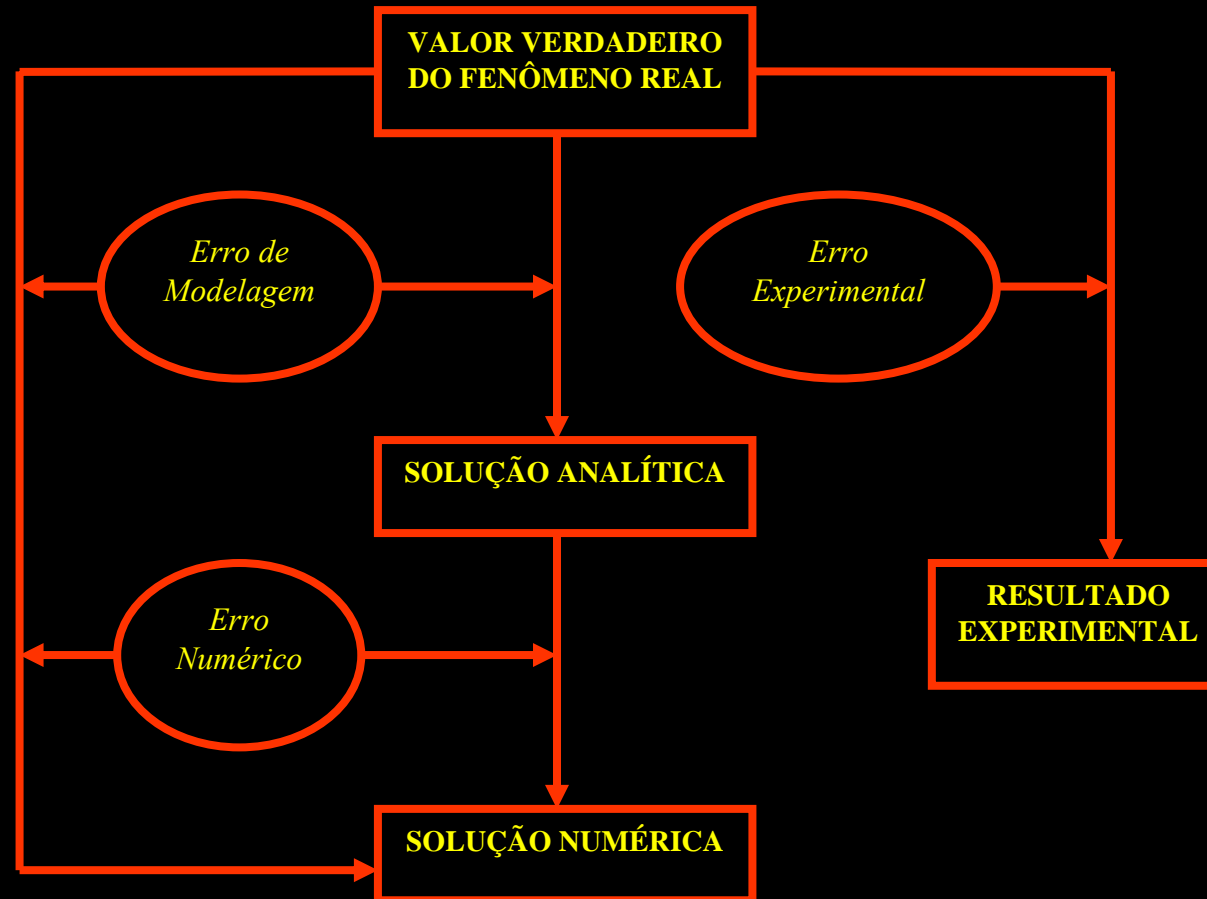
MER em Tc, Laplace 2D, DF



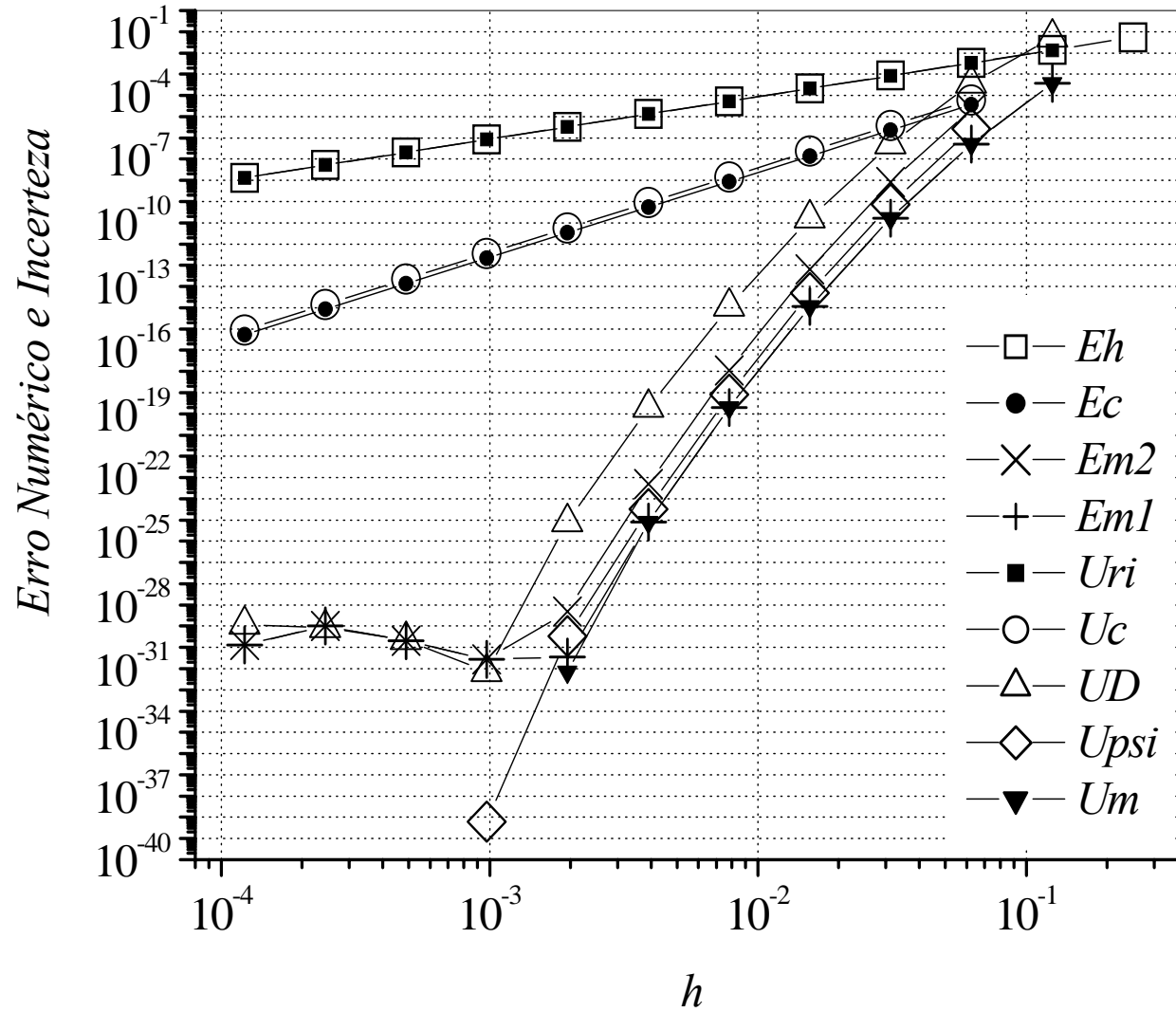
Verificação e validação de soluções numéricas

- Verificar códigos e soluções numéricas
- Validar soluções numéricas
- Avaliar e desenvolver estimadores de erros numéricos
- Gerar resultados numéricos de referência
- Incerteza dos dados da simulação

Tipos de erros



V & V: estimador de erro para MER



Poisson 1D, DF, T(3/4) nodal, CDS-2

Benchmark da cavidade 2D

Ref.	----- Re = 100 -----			----- Re = 400 -----			----- Re = 1000 -----		
	$-\Psi_{min}$	x	y	$-\Psi_{min}$	x	y	$-\Psi_{min}$	x	y
2	0.1022			0.1017					
3	0.1034						0.114		
4							0.1193		
5	0.103423	0.6172	0.7344	0.113909	0.5547	0.6055	0.117929	0.5313	0.5625
6	0.10330	0.61667	0.74167	0.11399	0.55714	0.60714	0.11894	0.52857	0.56429
7	0.1034	0.6188	0.7375	0.1136	0.5563	0.6000	0.1173	0.5438	0.5625
9	0.103506	0.6094	0.7344				0.119004	0.5313	0.5625
10	0.1030	0.6196	0.7373	0.1121	0.5608	0.6078	0.1178	0.5333	0.5647
11	0.103519	0.6157	0.7378				0.118821	0.5308	0.5659
12							0.1157		
13	0.10330			0.11389			0.118930		
14							0.1189366	0.5308	0.5652
15	0.103511	0.617187	0.734375				0.118806	0.531250	0.562500
17	0.103	0.6125	0.7375	0.113	0.5500	0.6125	0.117	0.5250	0.5625
16							0.118942	0.5300	0.5650
18							0.11892	0.53125	0.56543
CFD	0.1035212	0.61621	0.73730	0.11398887	0.55371	0.60547	0.118936708	0.53125	0.56543

Re = 10, Ref. 2: $-\psi_{min} = 0.0999$; Present: $-\psi_{min} = 0.1001132$

Classificação de motores de espaçomodelos

Motores B6-4:

$I_t = 2,51$ a $5,00$ Ns

$E_m = 6$ N

$t = 4$ s

Motores C20-0:

$I_t = 5,01$ a $10,00$ Ns

$E_m = 20$ N

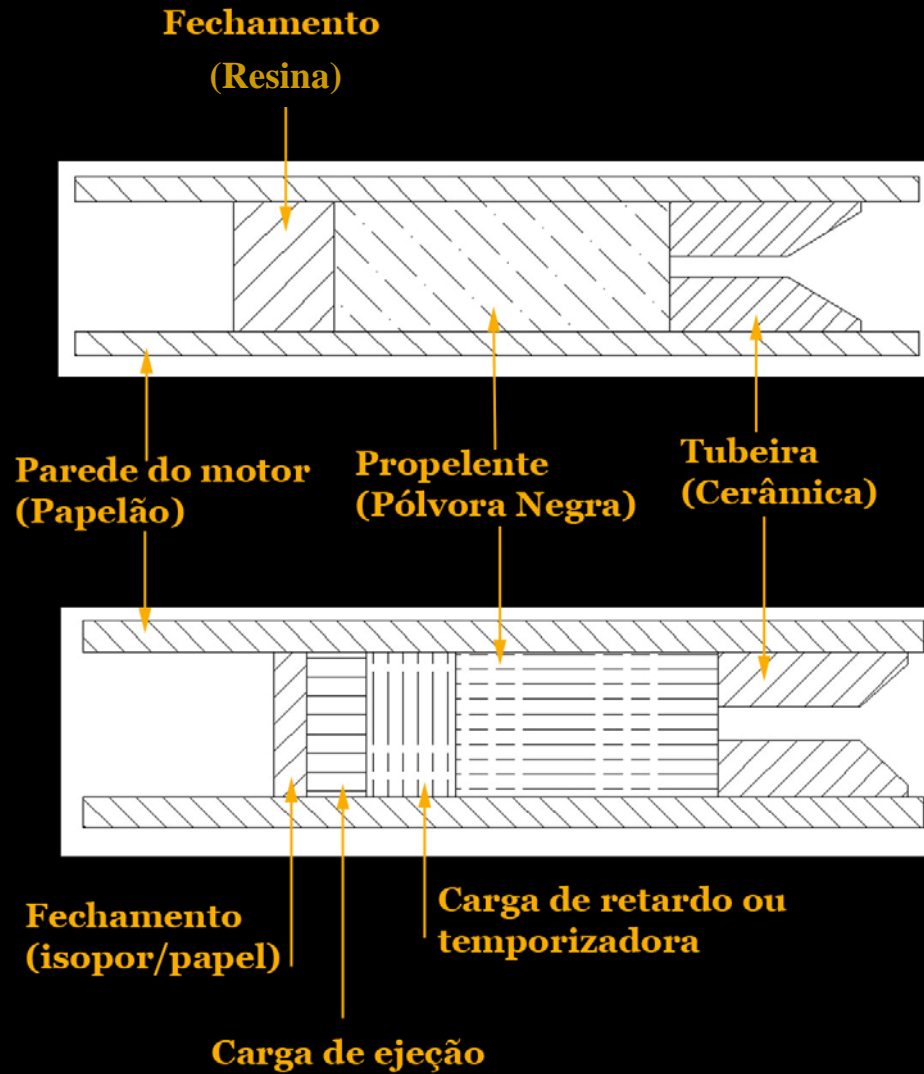
Motores D20-0:

$I_t = 10,01$ Ns a $20,00$ Ns

$E_m = 20$ N



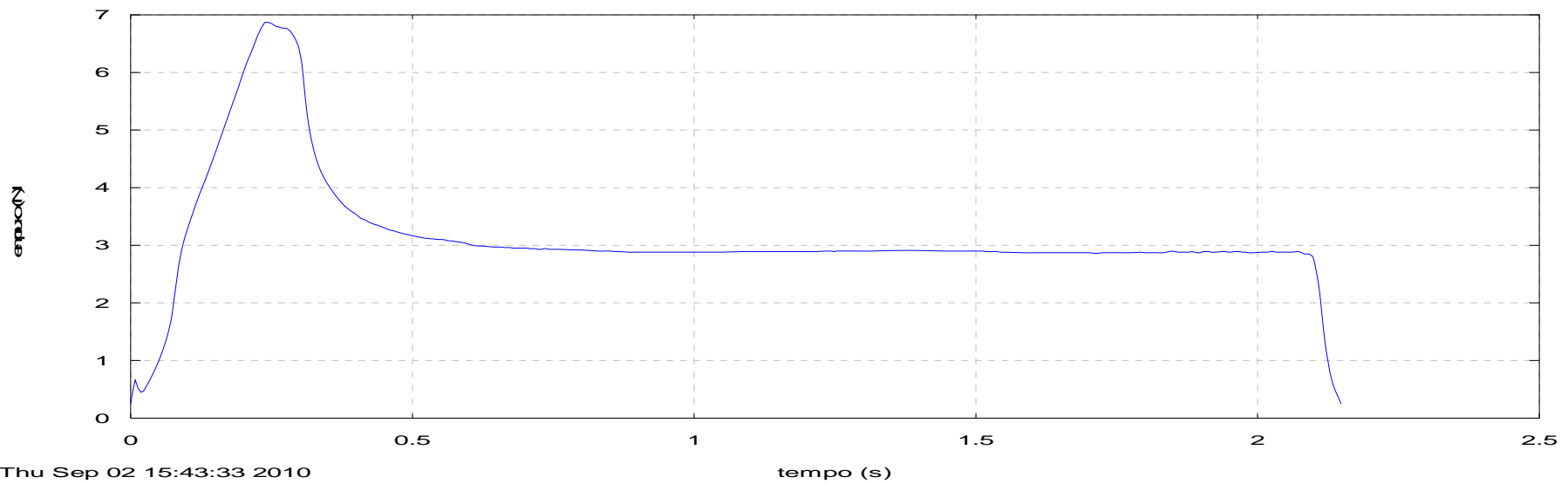
Componentes do motor-foguete



Teste estático de motor de EM



Motor BT-100, TE 27 Jul 2010, Curva_empuxo 1.2



Thu Sep 02 15:43:33 2010

Lançamento EM α -17/C6-5 (23/06/2011)



Agradecimentos (financiadores):

AEB

PG-MEC

CNPq

PPGMNE

CAPES

DEMEC

FA

UFPR

**Para interessados em
IC, TG, M, D, PD, colaborações:**

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