# Grupo de pesquisa:

# CFD, propulsão e aerodinâmica de foguetes

## (CFD/UFPR) – junho/2002

21 Nov 2019

Laboratórios (100 $m^2$):

Lena 1: alunos

Lena 2: professores

Localização:

salas 7-30 e 7-31 do DEMEC/TC

Equipamentos principais:

23 computadores (192 GB, Xeon, 12 núcleos)

1 impressora laser

# PESQUISADORES atuais (9)

Do DEMEC/TC/UFPR (2):

Prof. Carlos Henrique Marchi (líder)

Prof. Luciano Kiyoshi Araki

De outras instituições (7):

UFPR e outras = 2 (Geovani e Nicholas)

UTFPR = 2 (Guilherme e Cosmo)

UP = 2 (Diego e Alysson)

UNICENTRO = 1 (Martins)

# COLABORAÇÕES
# passadas e atuais: 7

ITA

IAE/DCTA

INPE/CP

UTFPR

UP

UEPG

UNICENTRO

# ORIENTANDOS atuais no DEMEC/TC/UFPR: 22

IC = 2

TG = 2

M = 9

D = 8

PD = 0

estágio = 1

# ORIENTAÇÕES concluídas no DEMEC/TC/UFPR, 2002 →: 101

IC = 27

TG = 35

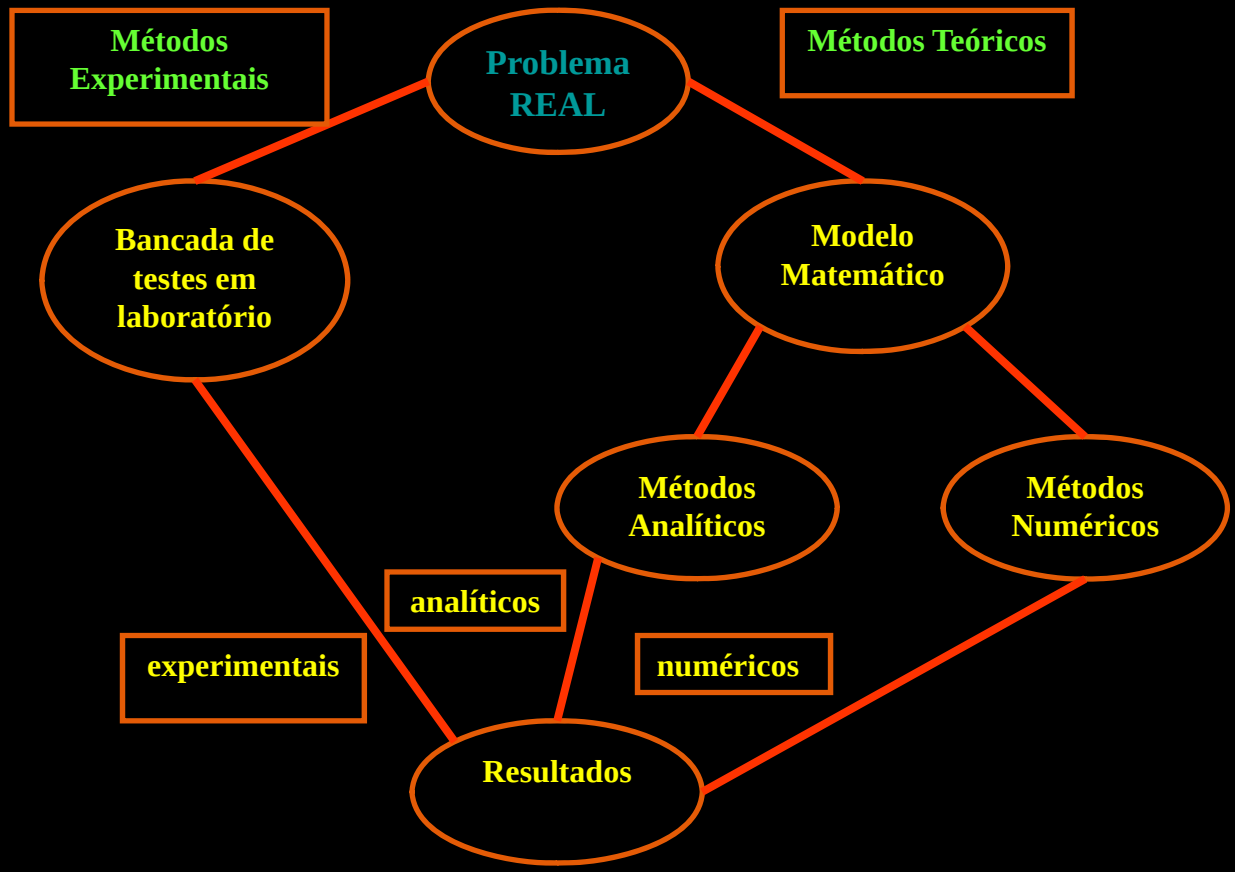
M = 17

D = 21

PD = 1

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

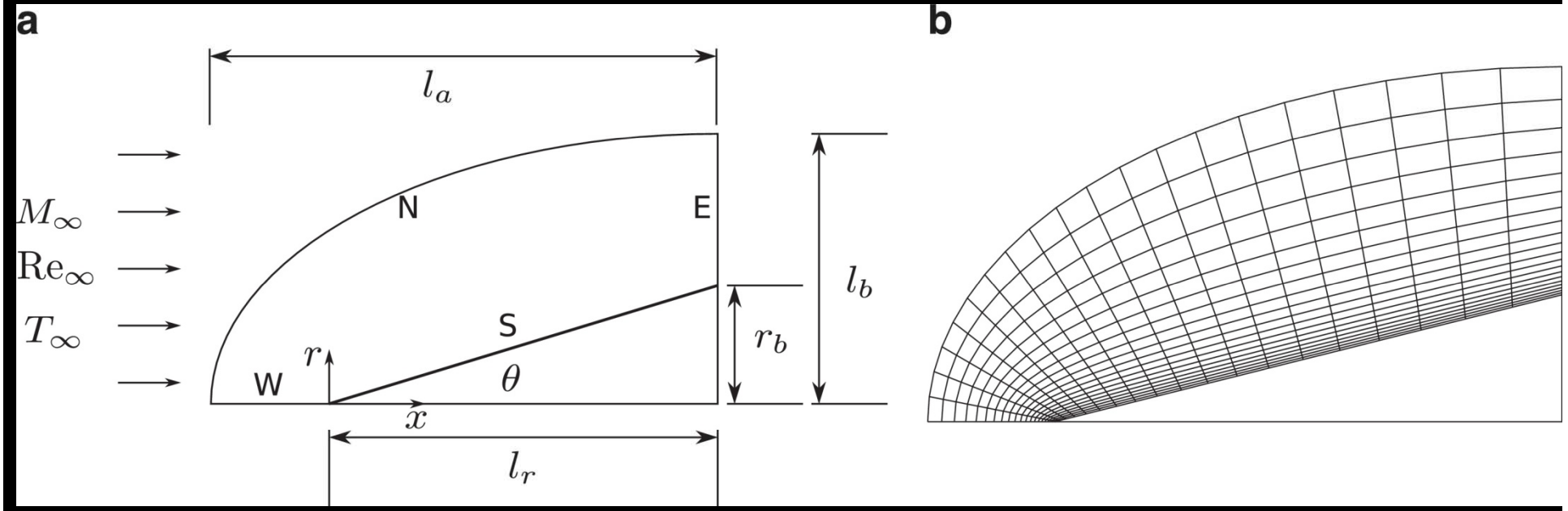
Tipos de malhas:

- Uniformes e não uniformes
- Quadradas e triangulares
- Estruturadas e não estruturadas
- Não ortogonais

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

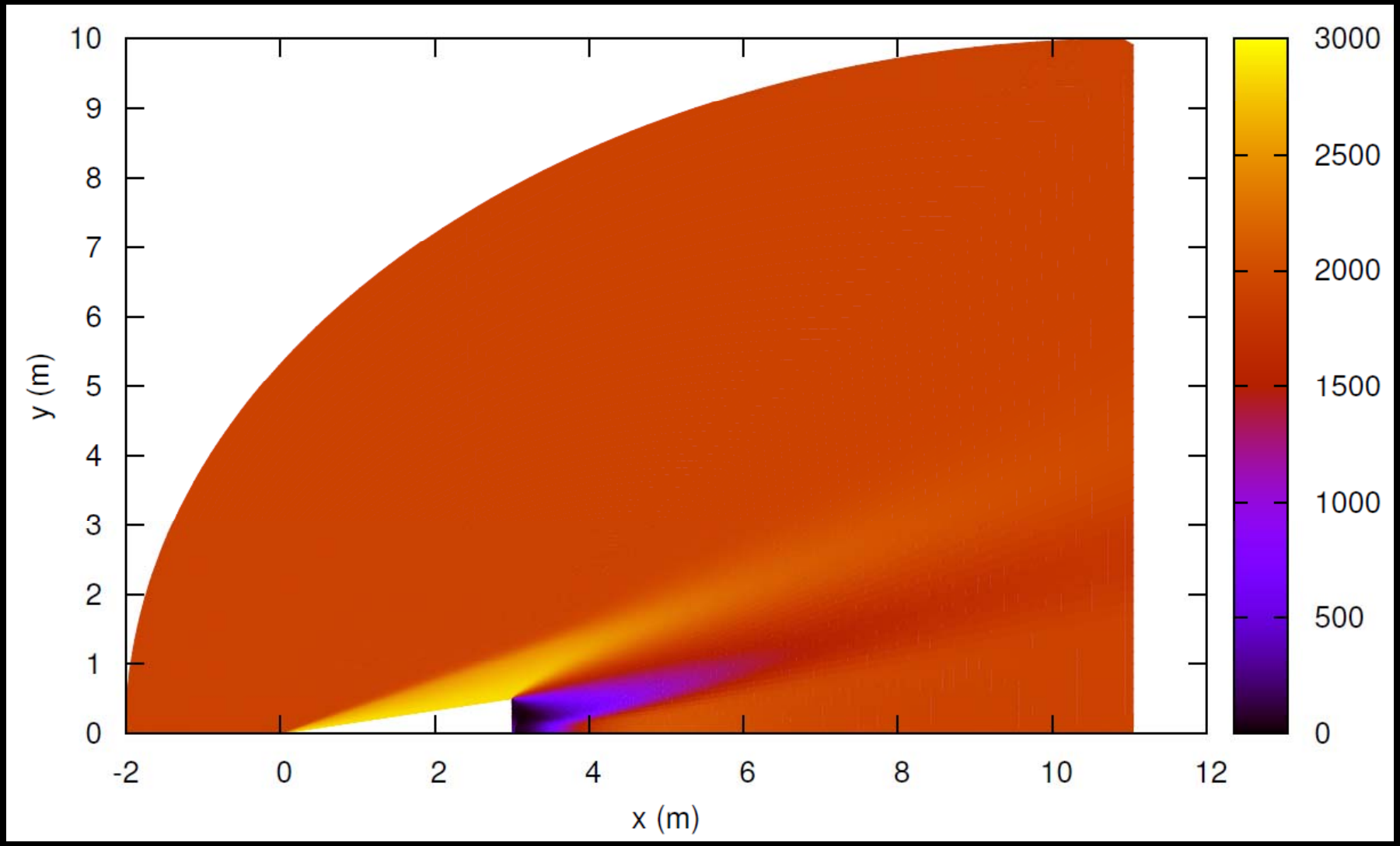
Linguagem de programação: Fortran 90

# Aerodinâmica




**Escoamento supersônico sobre um cone**

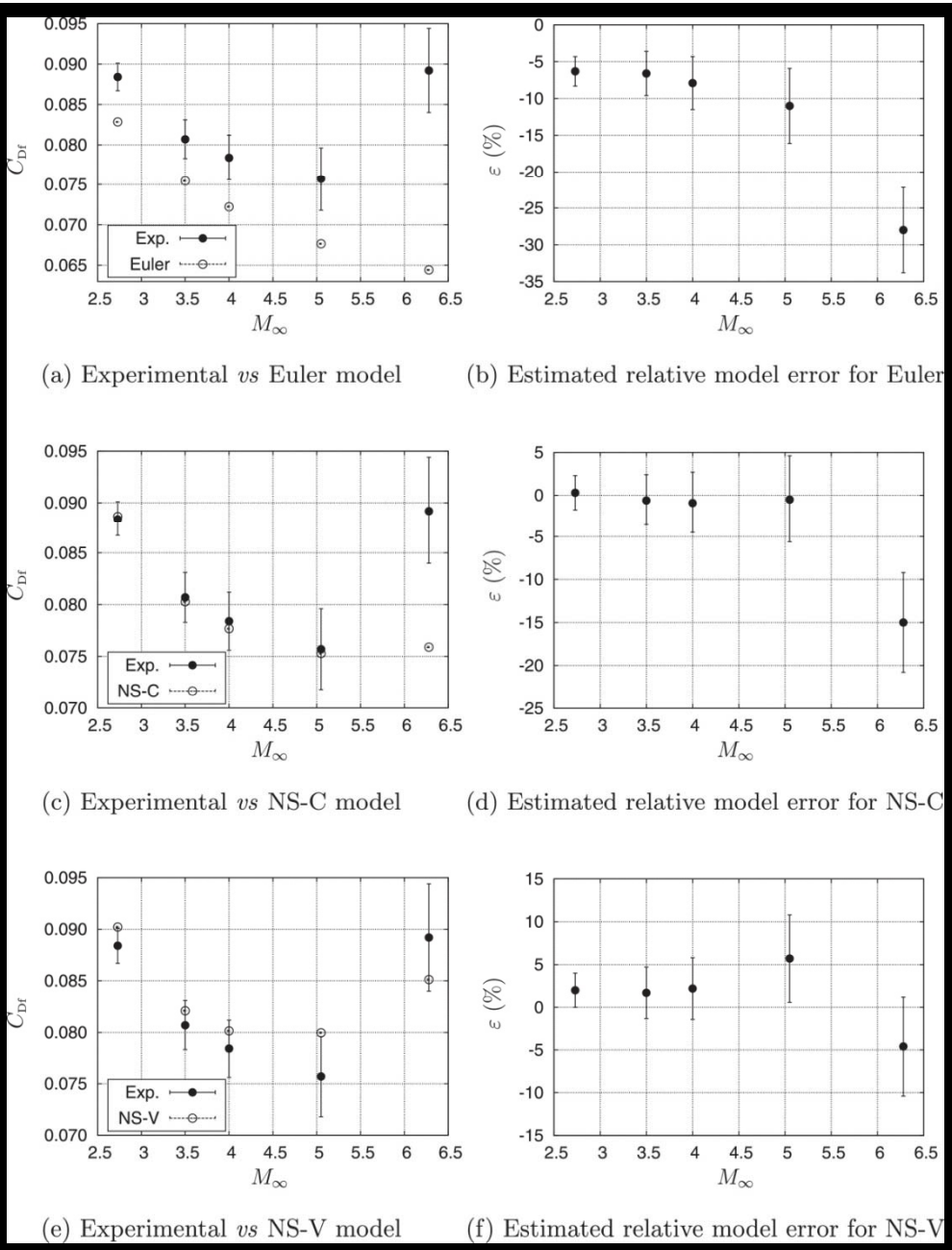
# Ar sobre cone (L/D = 3): campo p



# 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 | $1{,}05 \times 10^6$ | $0{,}076 \pm 0{,}005$ | $0{,}07556 \pm 0{,}00009$ |

# Aerodinâmica




(a) Experimental *vs* Euler model (b) Estimated relative model error for Euler

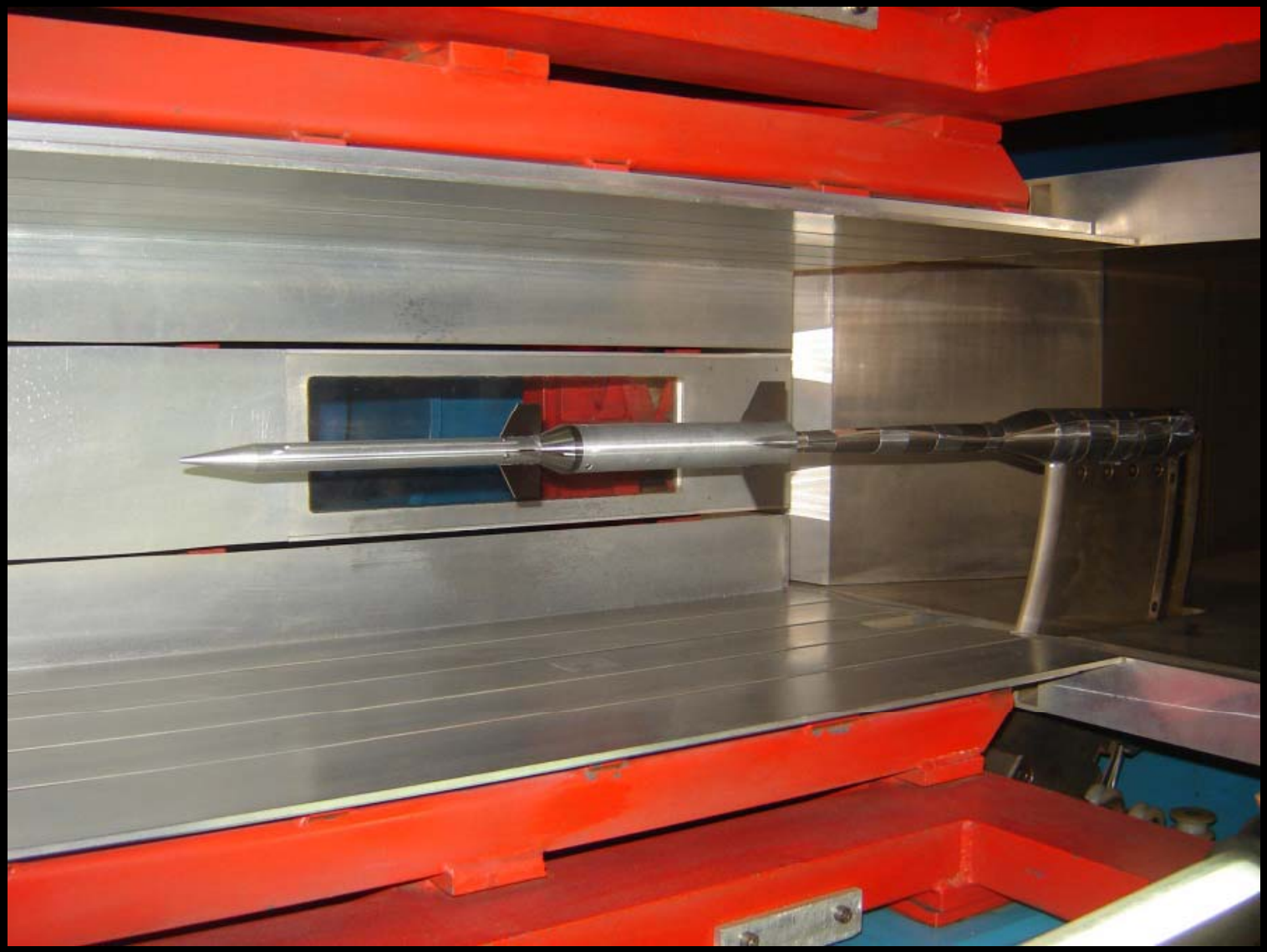
(c) Experimental *vs* NS-C model (d) Estimated relative model error for NS-C

(e) Experimental *vs* NS-V model (f) Estimated relative model error for NS-V

**Escoamento supersônico sobre um cone**


# O foguete brasileiro VLS

# Foguete VS-30 (IAE) em túnel de vento



# Ar sobre o foguete VLS

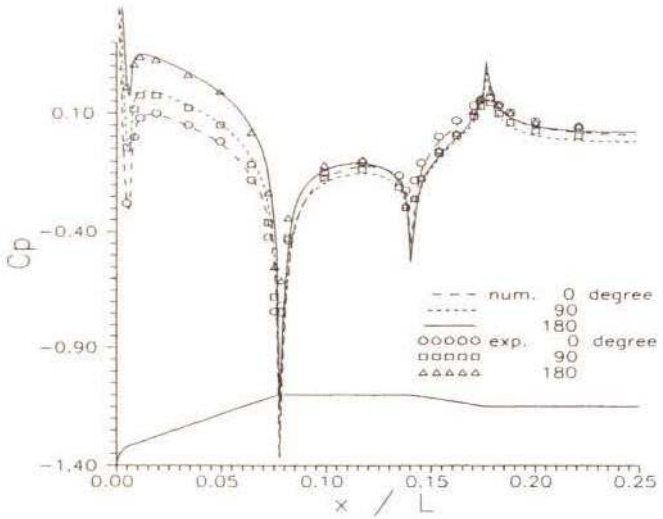



Figure 3. Cp for $M_\infty = 0.50$ and $\alpha = 6.0^0$.

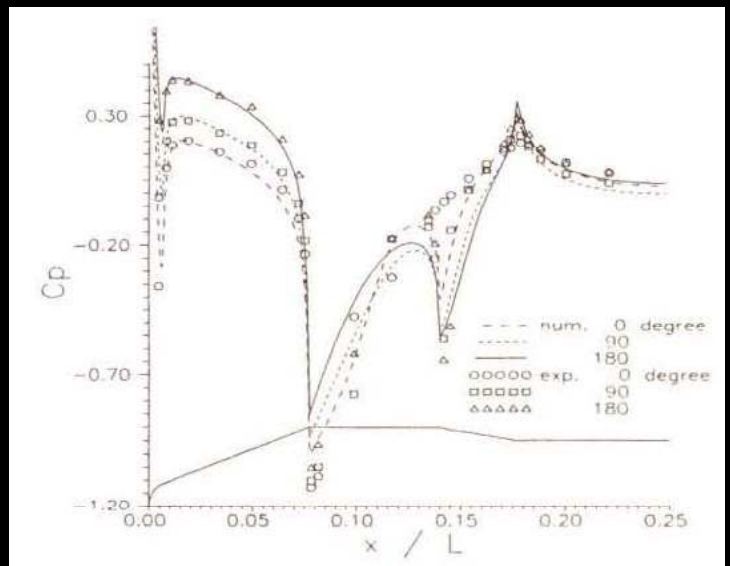



Figure 4. Cp for $M_\infty = 0.90$ and $\alpha = 6.0^0$.

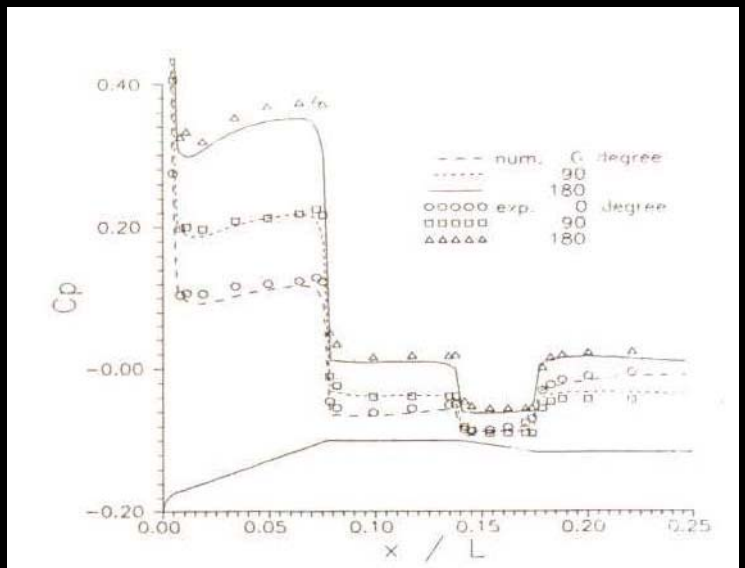
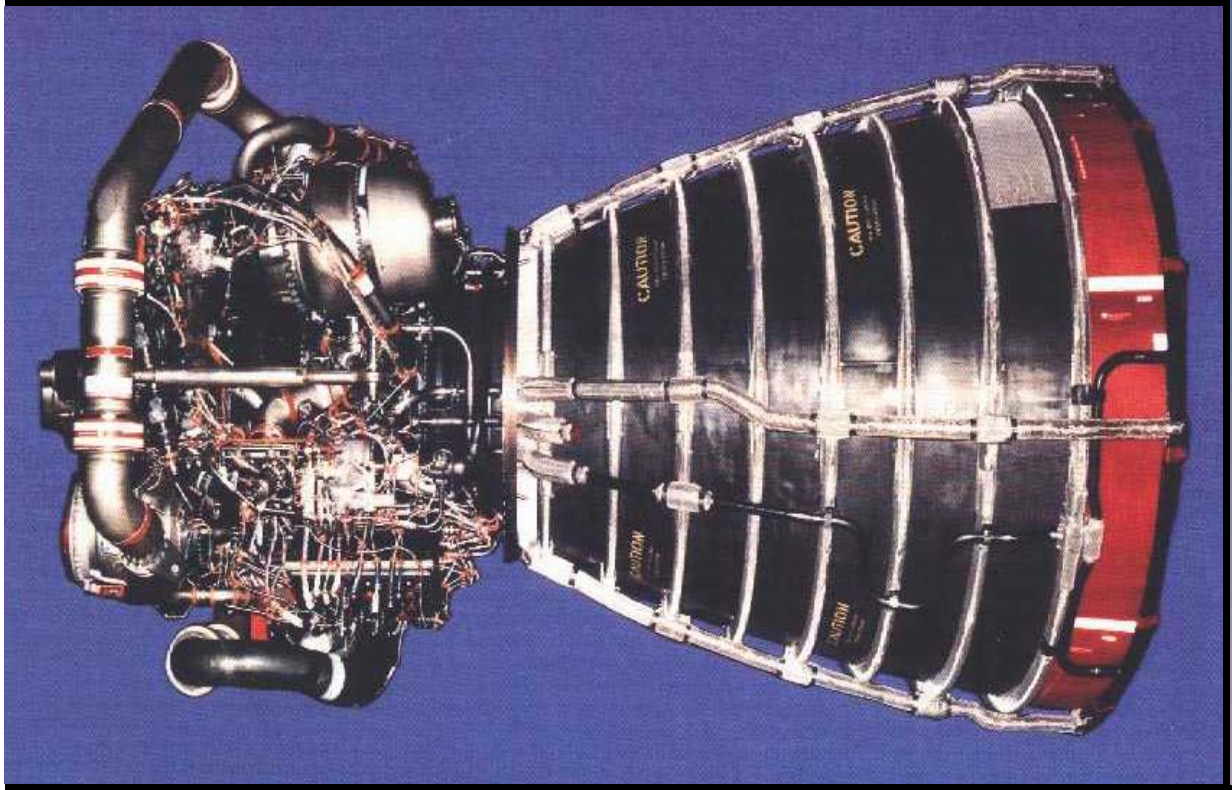
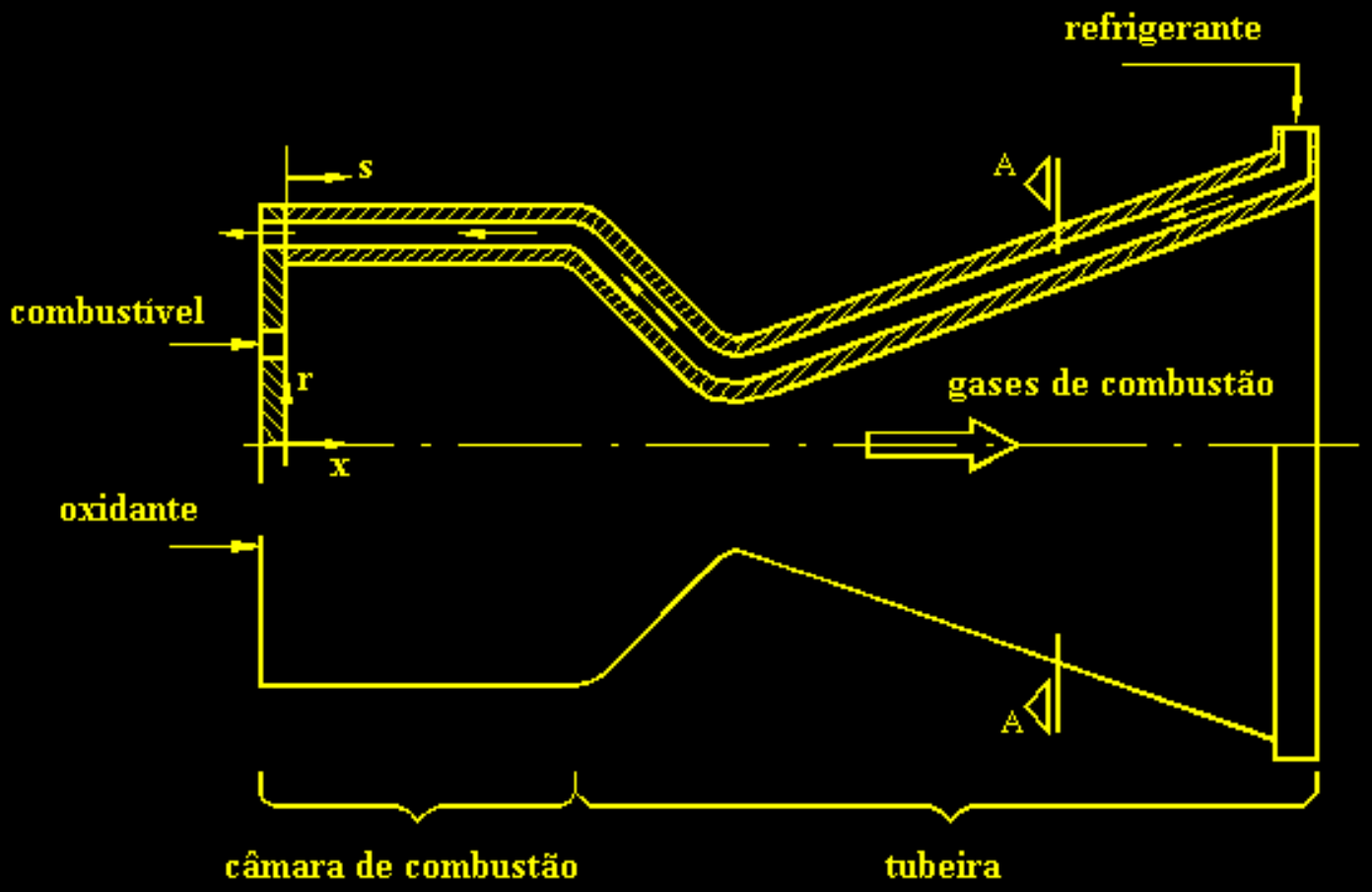


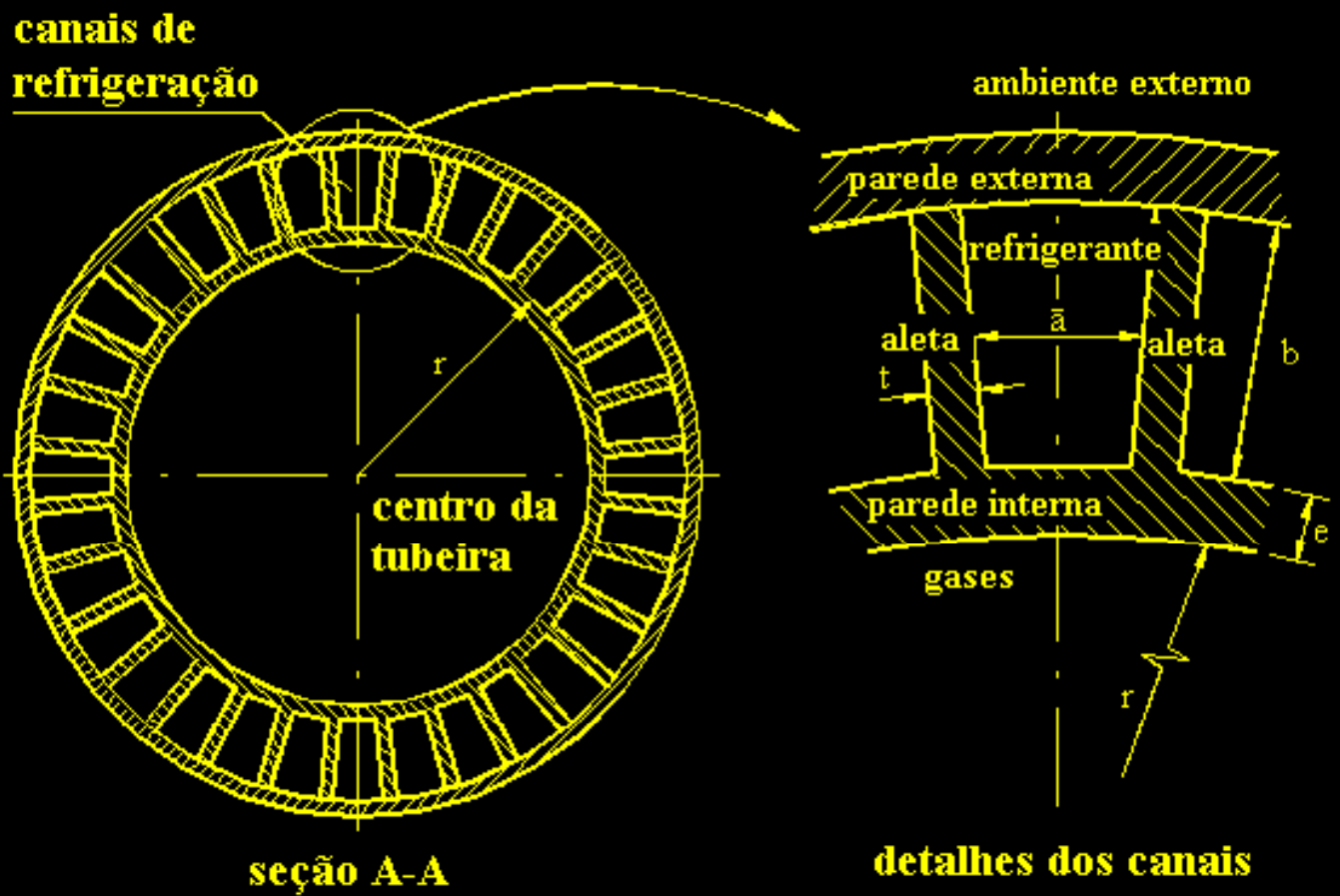

Figure 5. Cp for $M_\infty = 3.0$ and $\alpha = 6.1^0$.

# Motor-foguete SSME e Space Shuttle

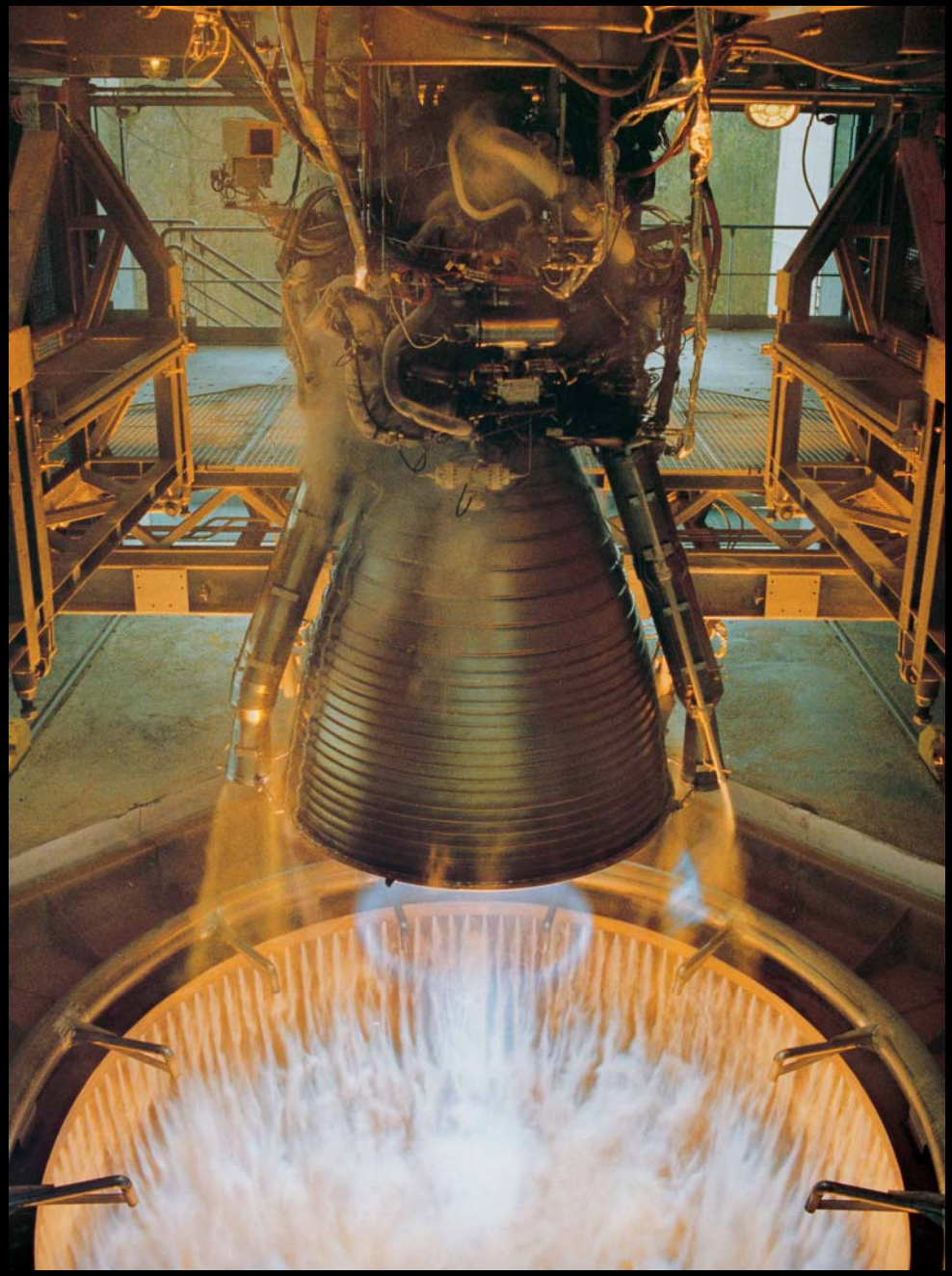



**Esquema de motor-foguete bipropelente com refrigeração regenerativa**




**Detalhes dos canais de refrigeração**



Motor-foguete

Vulcain do

Ariane V

# Motor Vulcain (Ariane V)

- F (nível do mar) = 103 tf
- Tw-max = 750 K
- To = 3.500 K
- Po = 100 atm
- q”max = 60 $MW/m^2$
- 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 reativo 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 | $\phi$ | $C^{\phi}$ | $\Gamma^{\phi}$ | $P^{\phi}$ | $S^{\phi}$ |
|---|---|---|---|---|---|
| Massa | 1 | 1 | 0 | 0 | 0 |
| QML-x | $u$ | 1 | $\mu$ | $-\frac{\partial p}{\partial x}$ | $\frac{1}{3}\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial x}\right)-\frac{2}{3}\frac{\partial}{\partial x}\left[\frac{\mu}{r}\frac{\partial}{\partial y}(rv)\right]$ |
| QML-y | $v$ | 1 | $\mu$ | $-\frac{\partial p}{\partial y}$ | $\frac{1}{3r}\frac{\partial}{\partial y}\left(r\mu\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial y}\right)-\frac{2}{3}\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)-\frac{4}{3}f\frac{u}{r^2}v-\frac{2}{3r}fv\frac{\partial\mu}{\partial y}$ |
| Energia | $T$ | $c_p$ | $k$ | $\frac{\partial p}{\partial t}-uP^{u}-vP^{v}$ | $2\mu\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2+f\left(\frac{v}{r}\right)^2\right]+\mu\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)^2-\frac{2}{3}\mu\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+f\frac{v}{r}\right)^2+S_{eq/tf}$ |
| Espécies | $Y_i$ | 1 | 0 | 0 | $\dot{w}_i$ |

# Escoamento reativo 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:

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

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

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

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

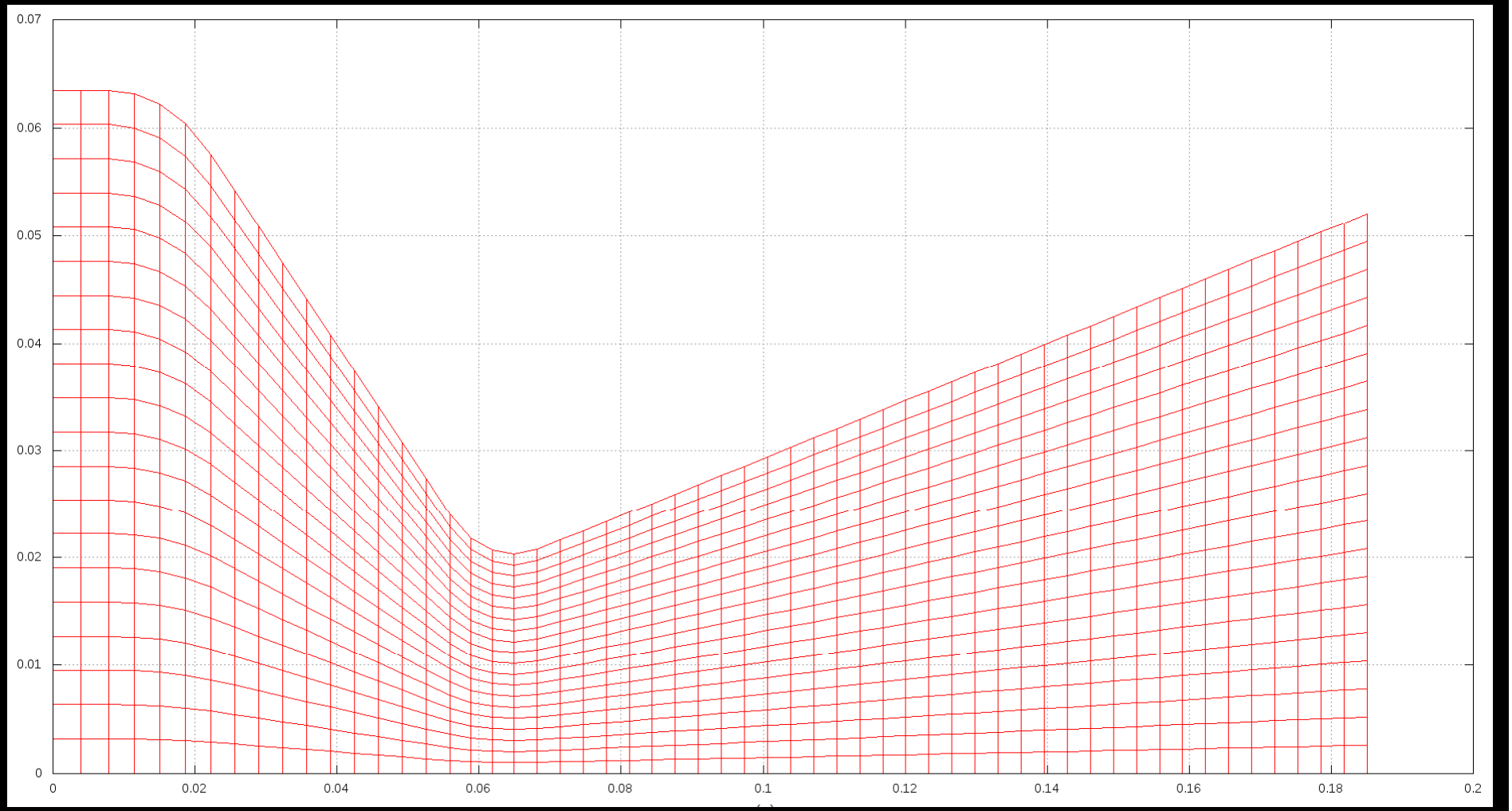
$$p = \rho R T$$

# Modelos químicos para $H_2/O_2$

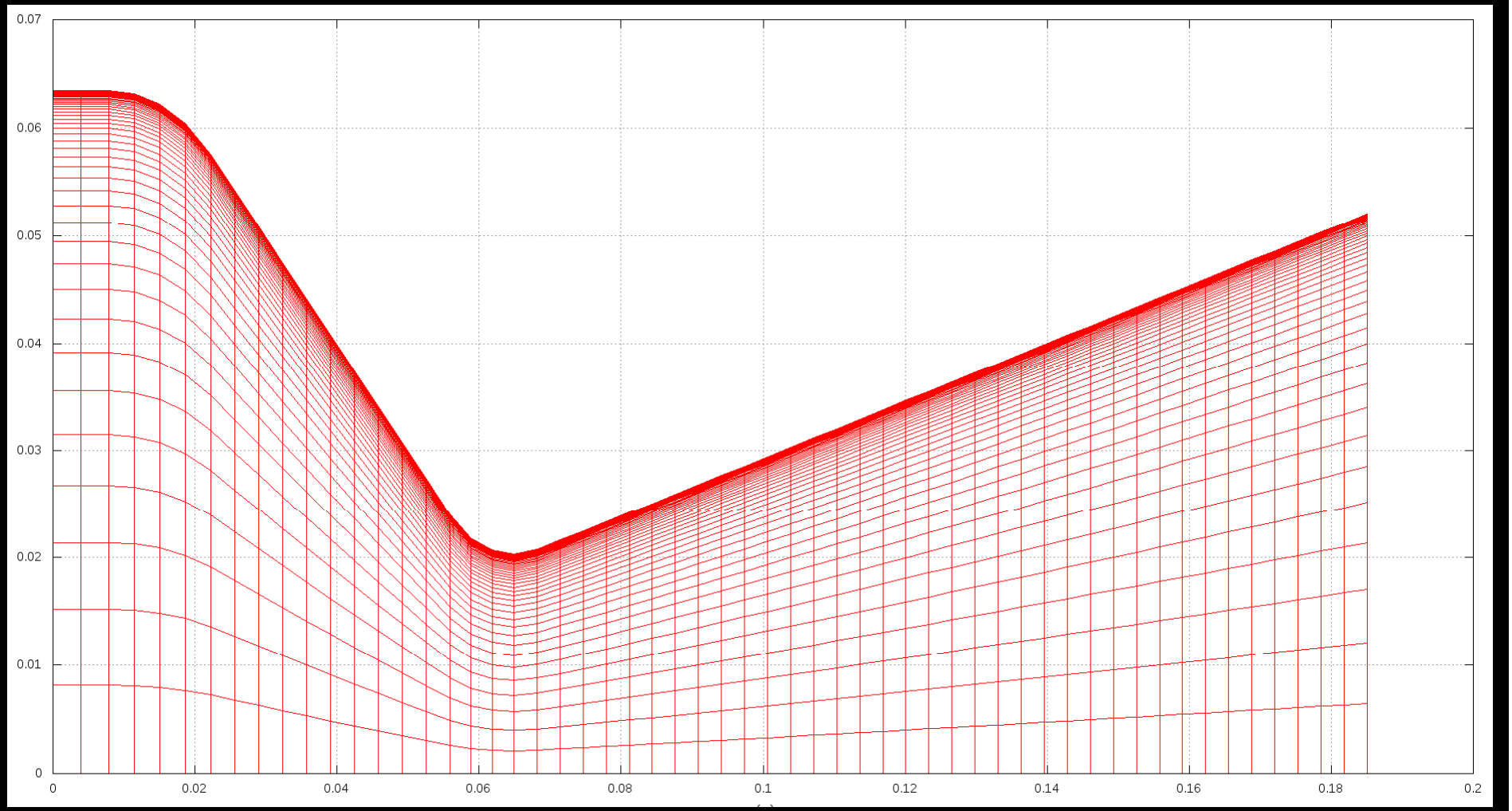
## 9 equilíbrio e 6 taxa finita

| 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, $HO_2$, $H_2O_2$ |

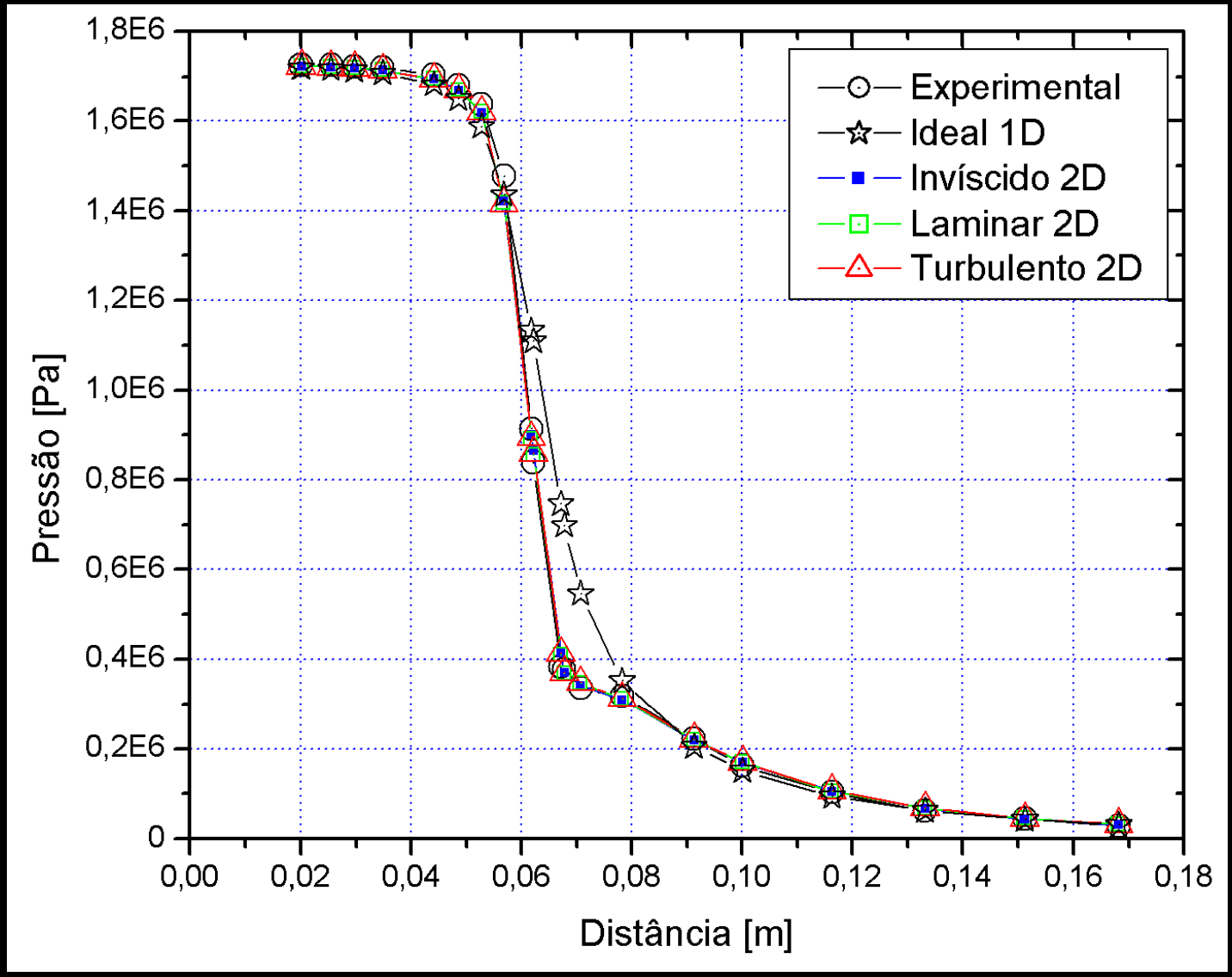
# Malha 56x20, Mach2D, invíscido



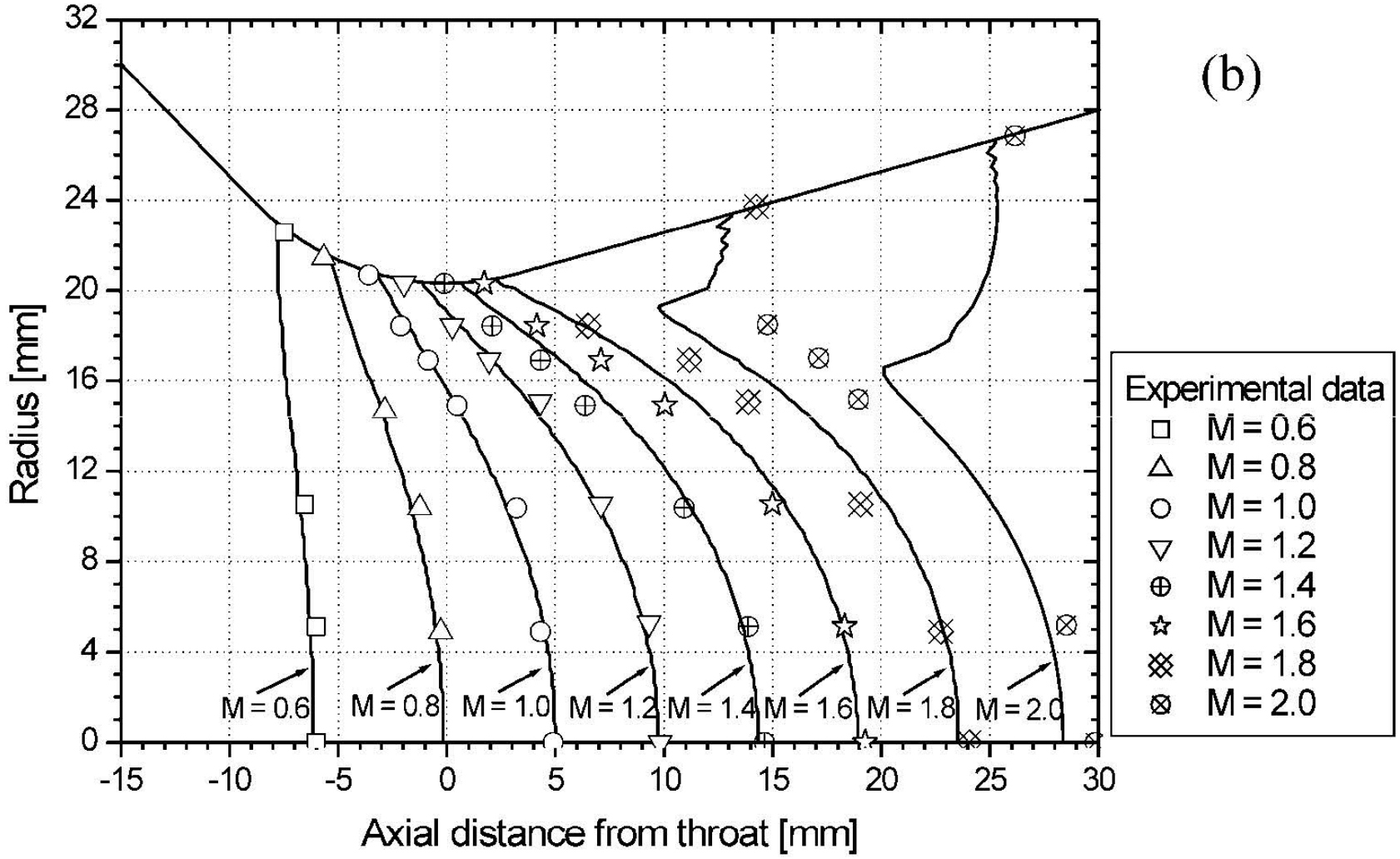
# Malha 56x50, Mach2D, laminar



# Mach2D, 224x80/200, p parede

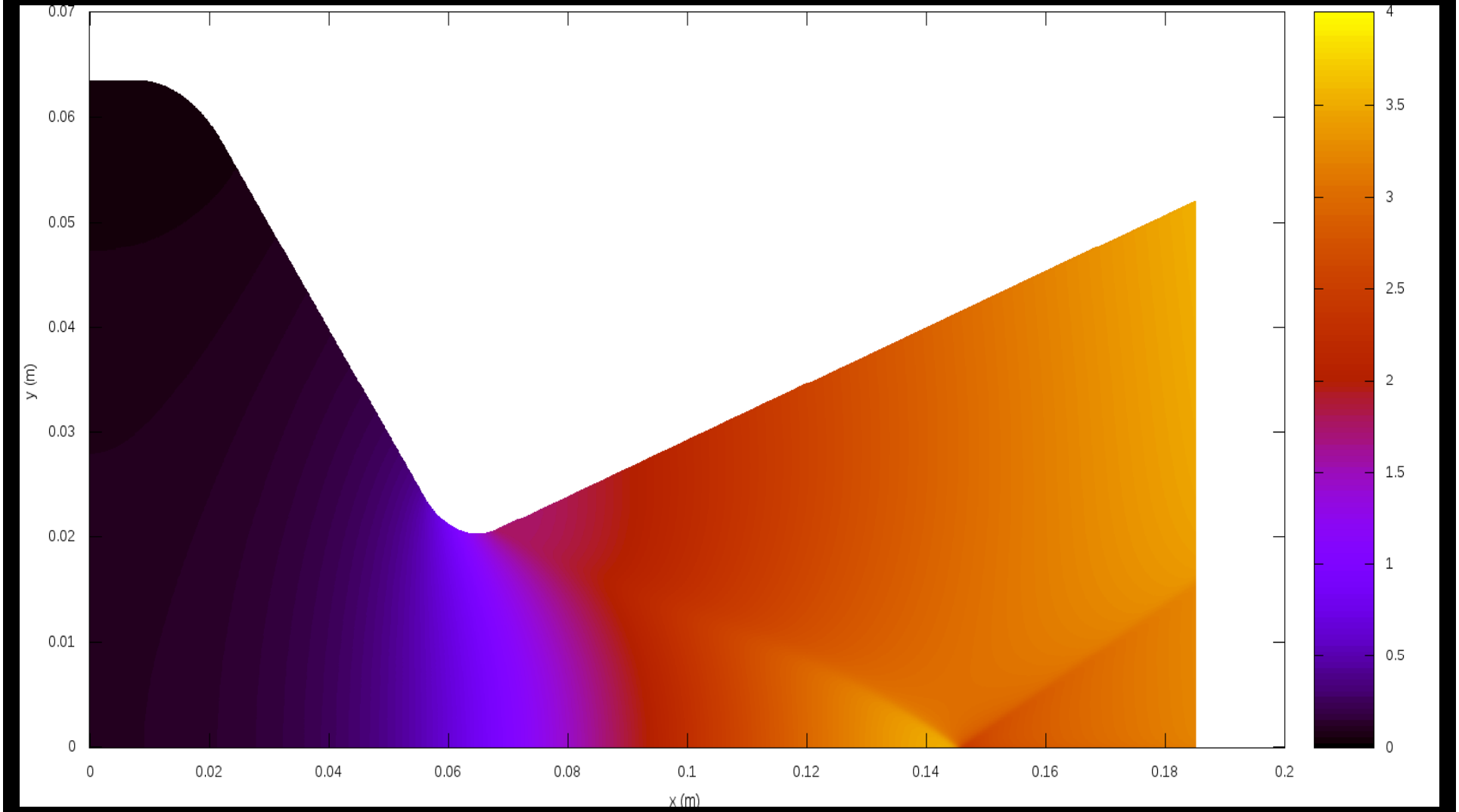


# Propulsão

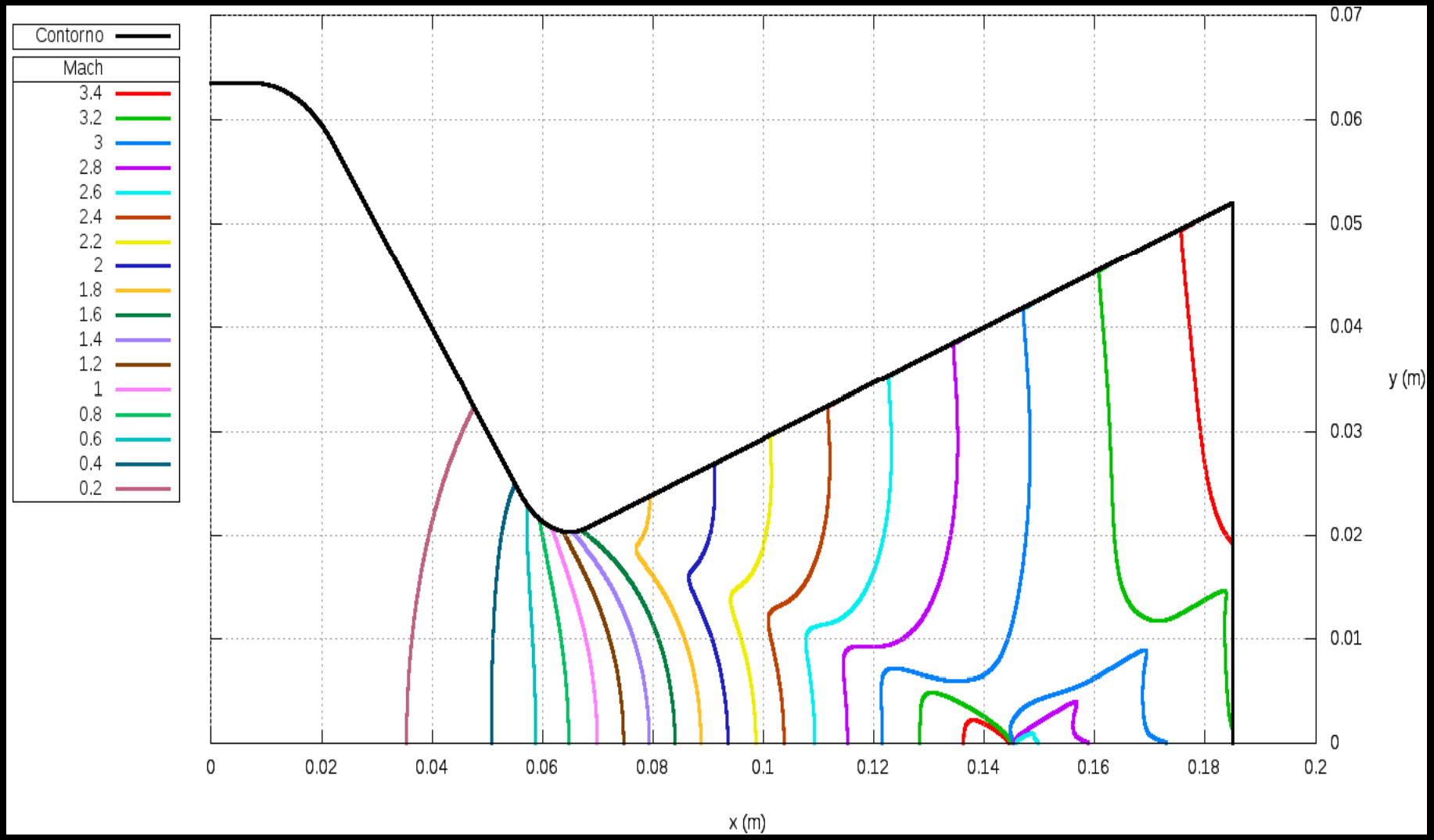



Mach, invíscido, 720x80, CDS-2, Mach2D

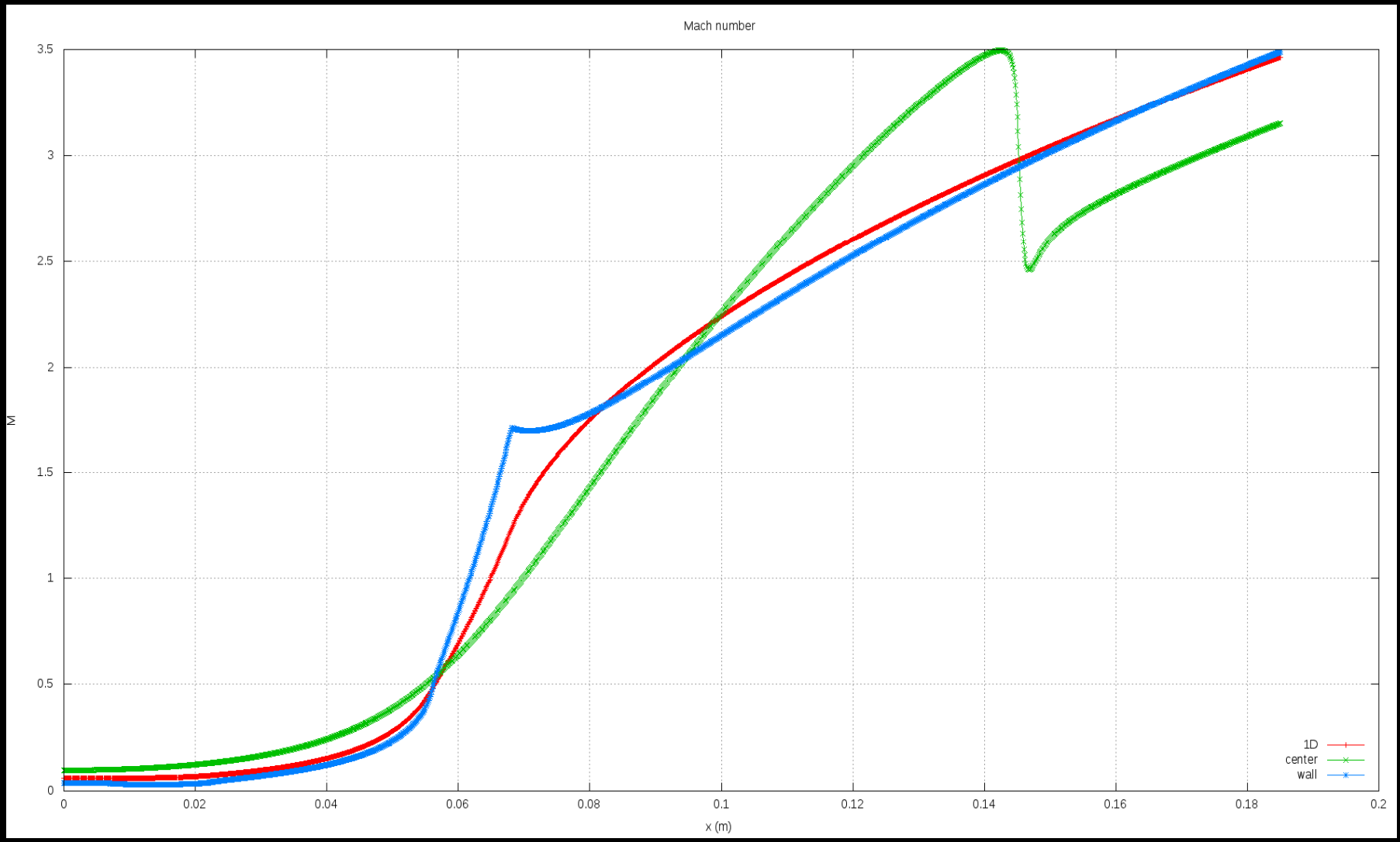
# Mach, invíscido, 1792x640, Mach2D



# Mach, invíscido, 1792x640, Mach2D



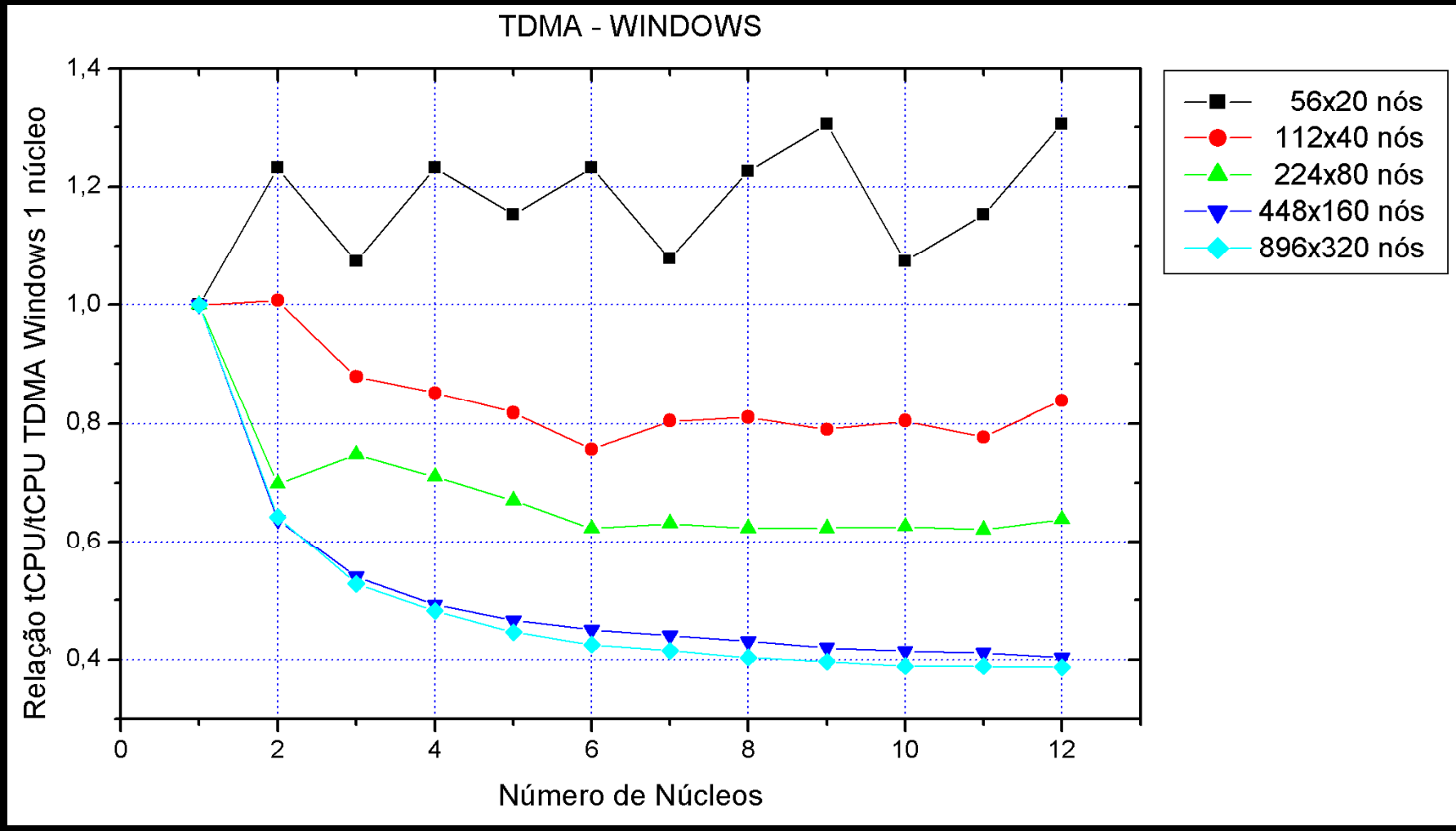
# Mach, invíscido, 1792x640, Mach2D

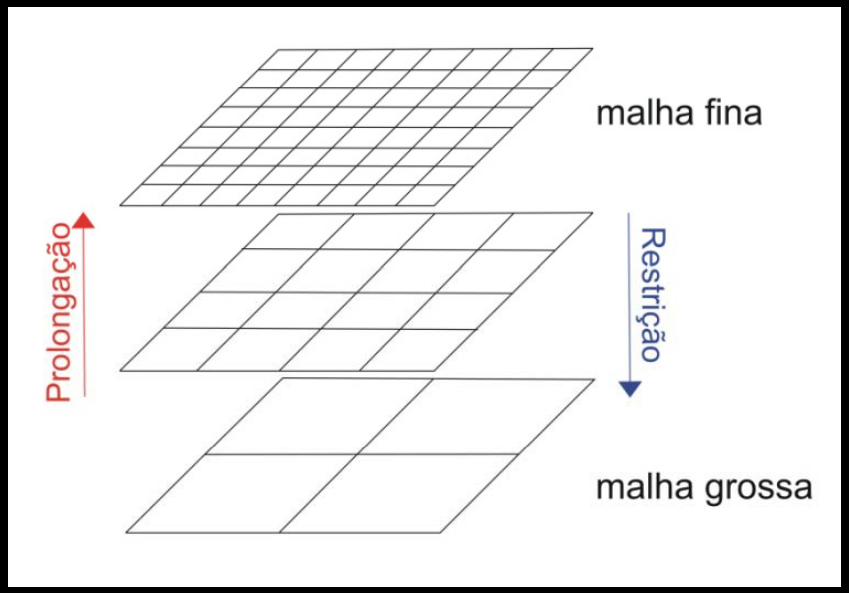


# Otimização de métodos numéricos

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

# Otimização do Mach2D com //

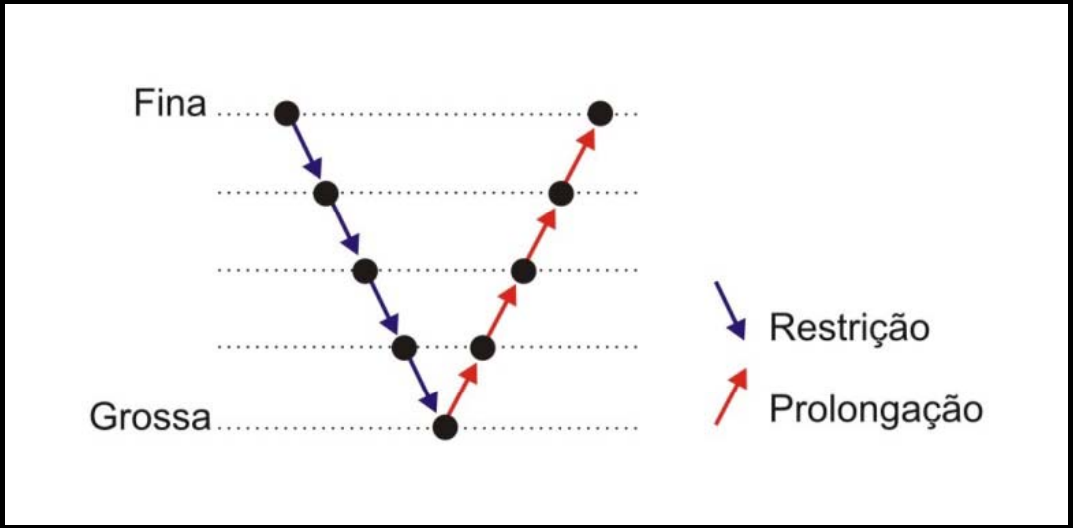




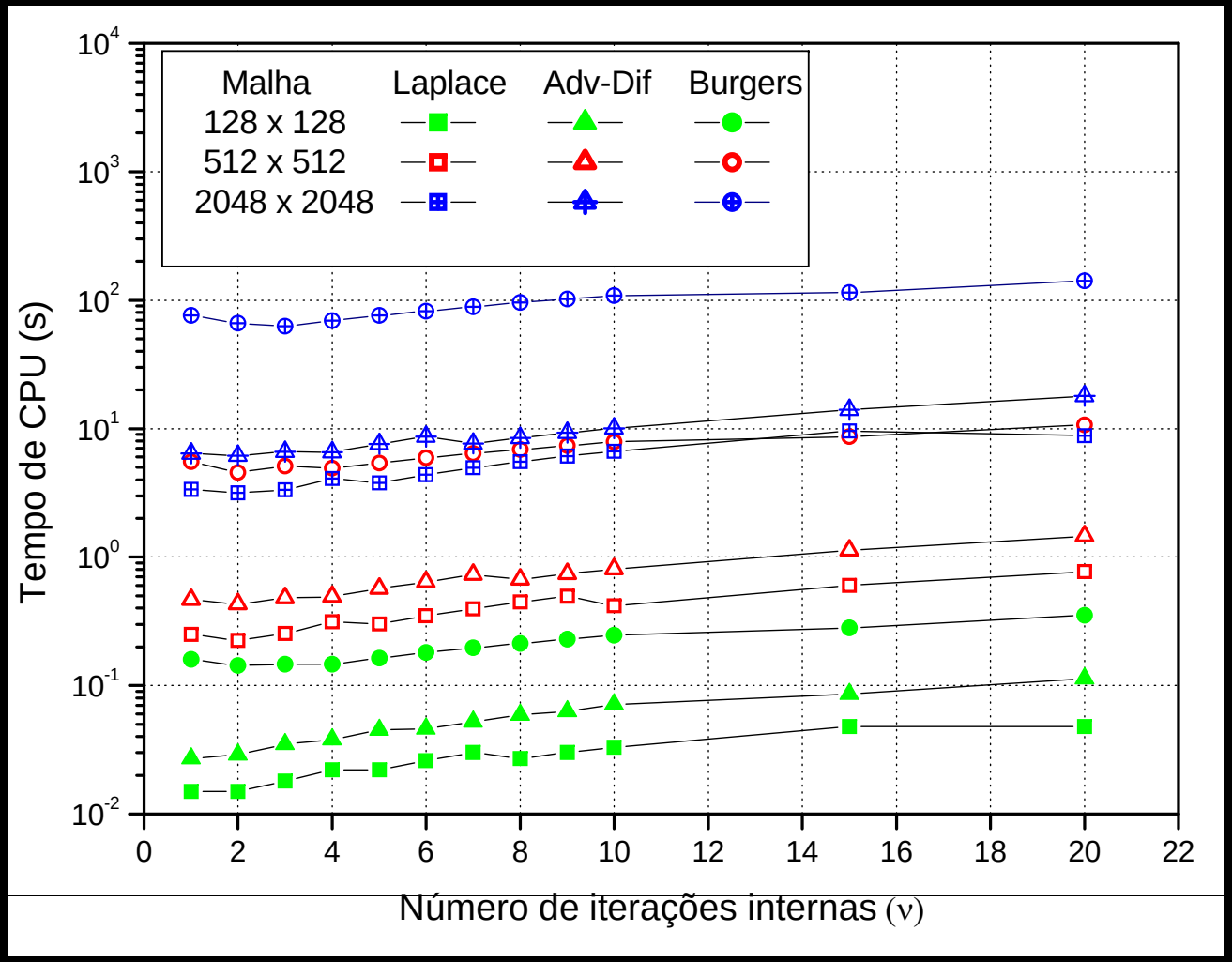

# *Multigrid*

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

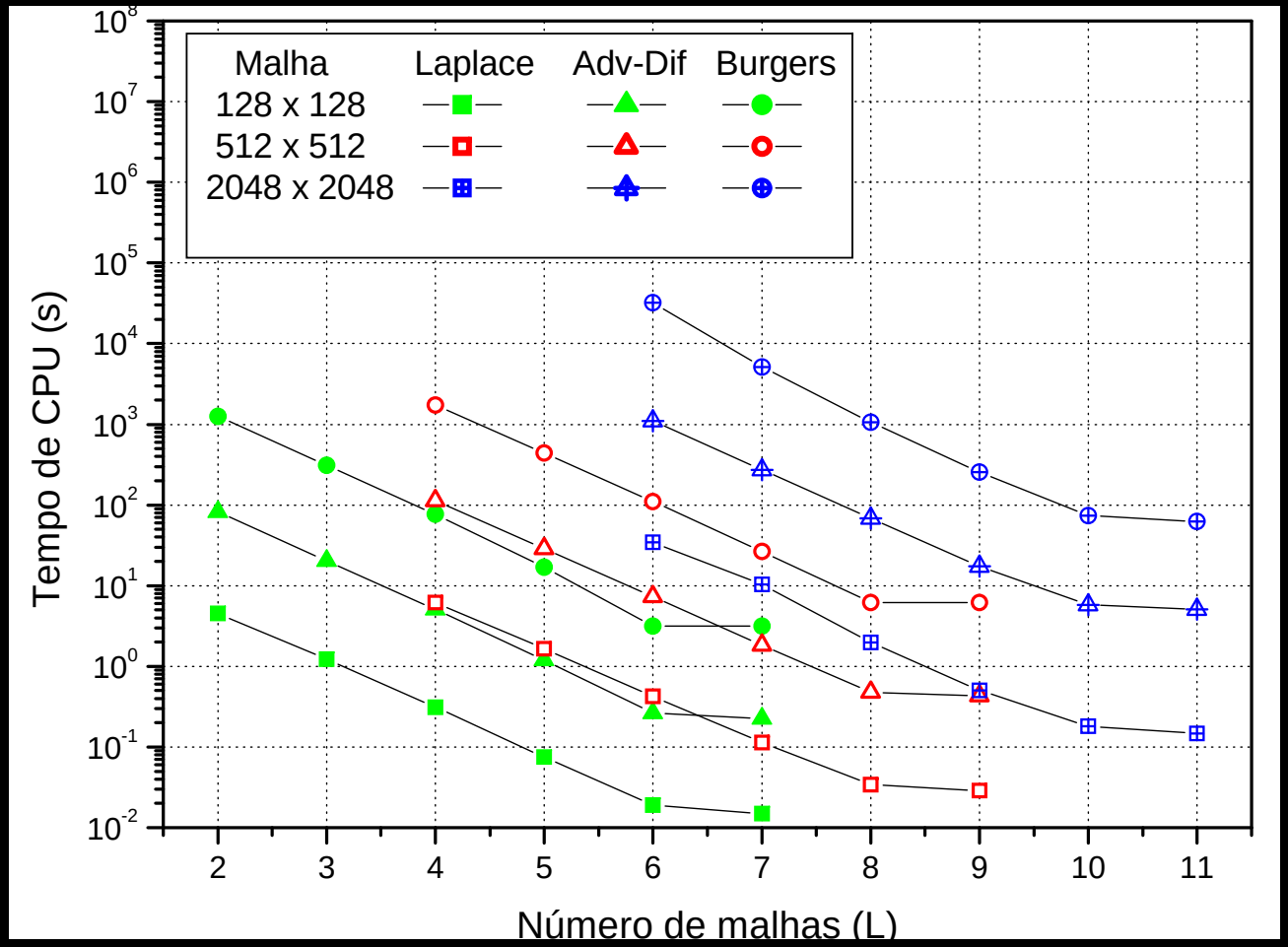
- Ciclos
- FAS x CS
- GMG x AMG
- MG x FMG



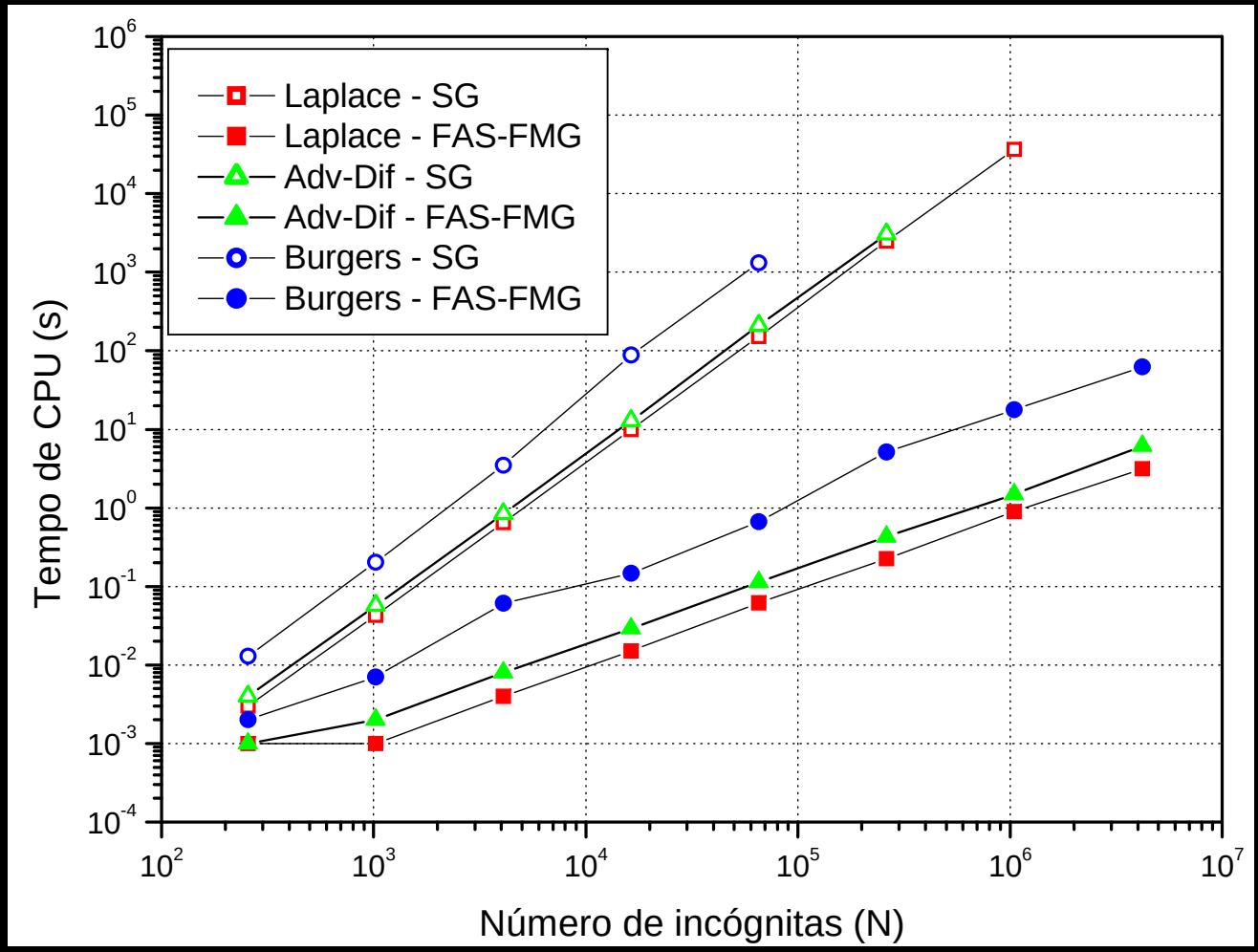
# Efeito de *v* sobre o tempo de CPU FAS-FMG e *solver* GS-Lex em VF



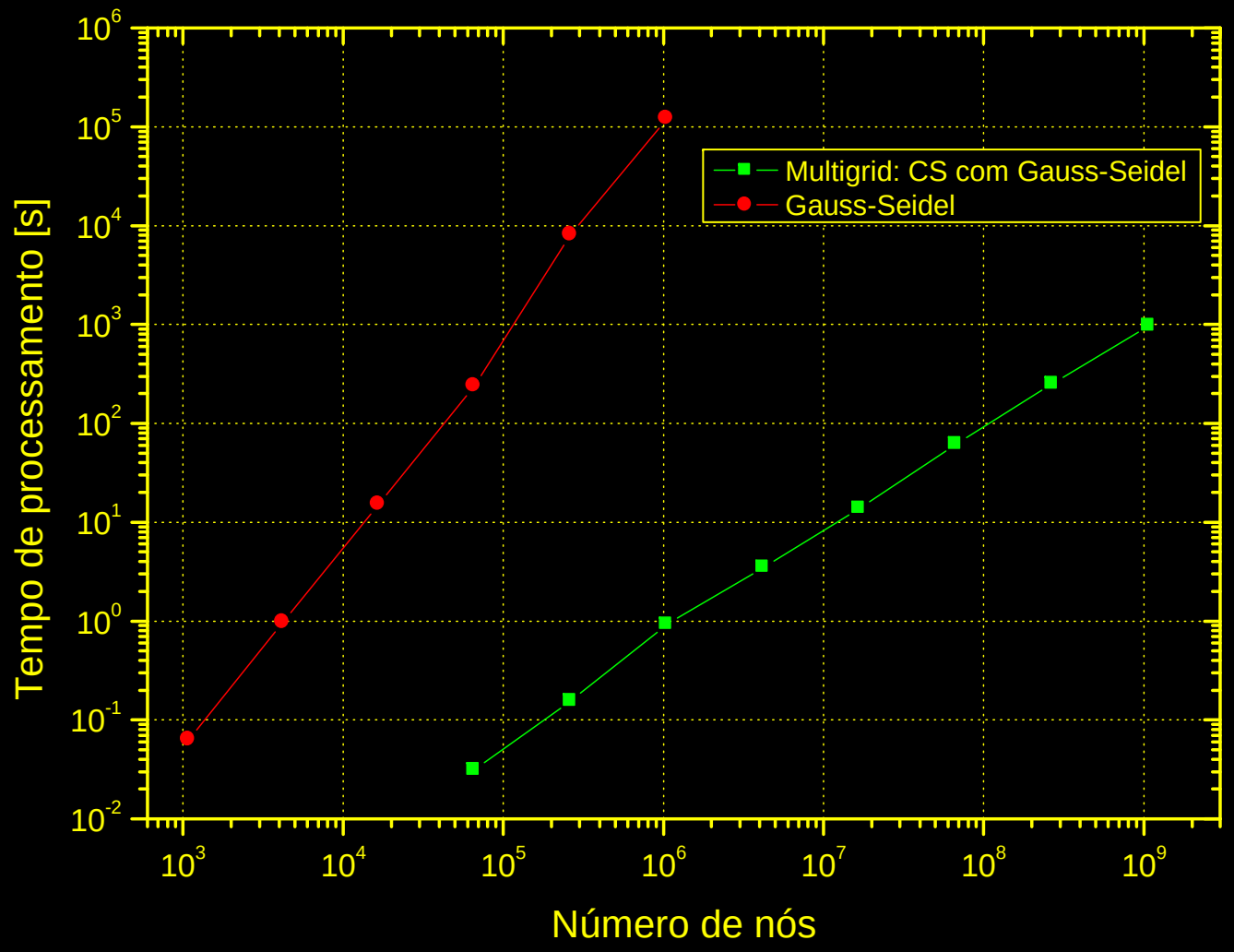
# Efeito de *L* sobre o tempo de CPU FAS-FMG e *solver* GS-Lex em VF



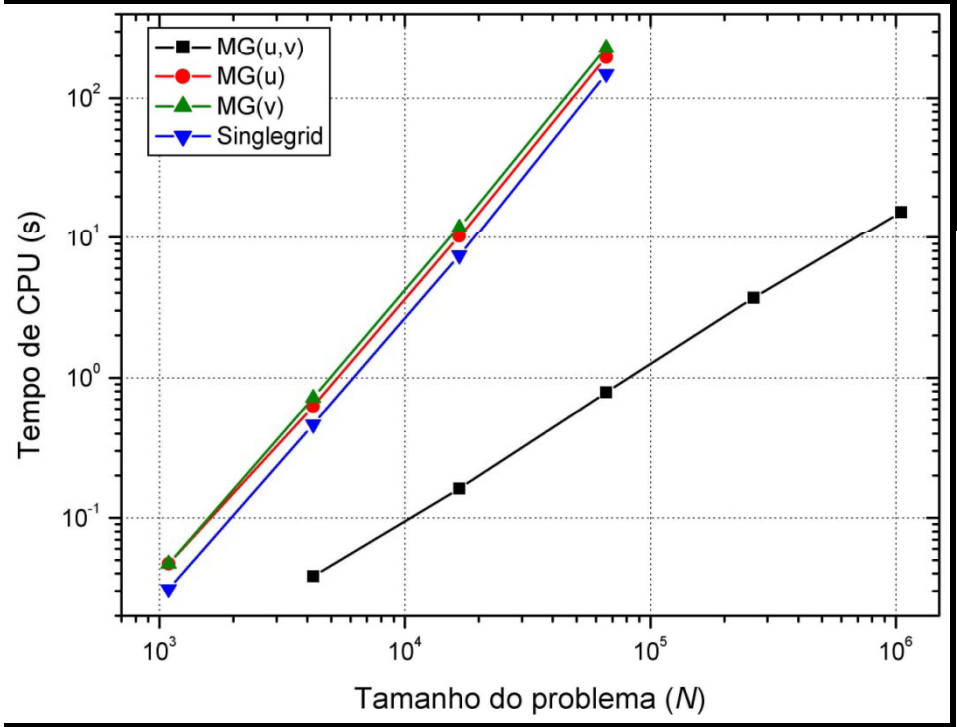
# Efeito de N sobre o tempo de CPU FAS-FMG e *solver* GS-Lex em VF



# Laplace 2D em DF com CDS-2

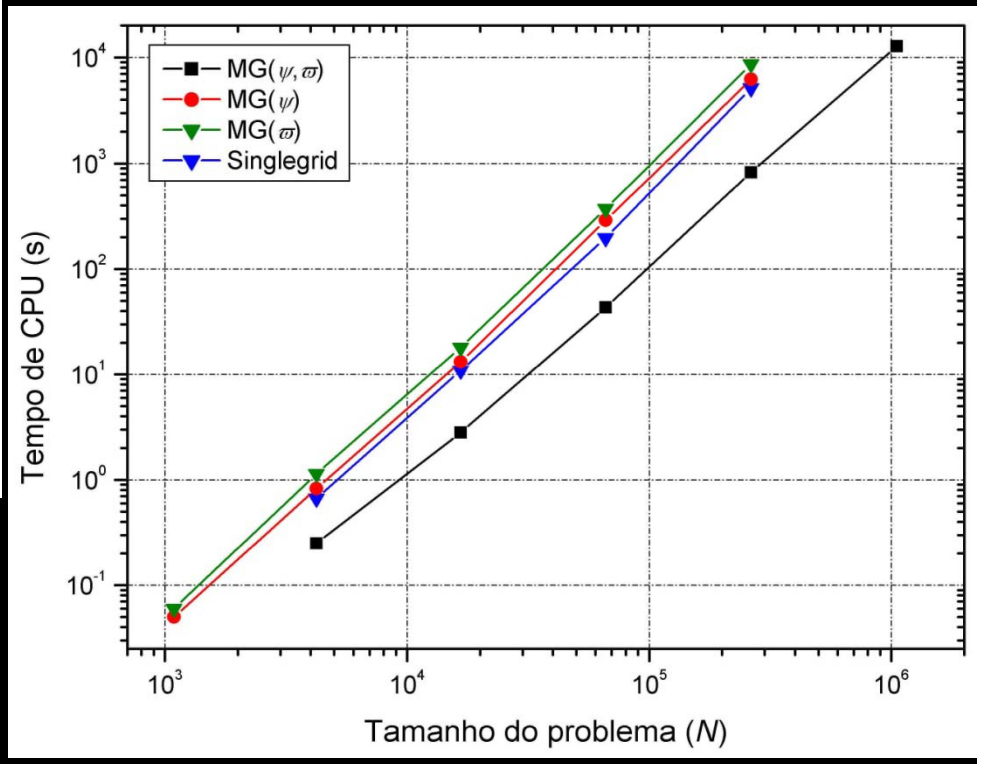


# *Multigrid* em 1 ou 2 equações

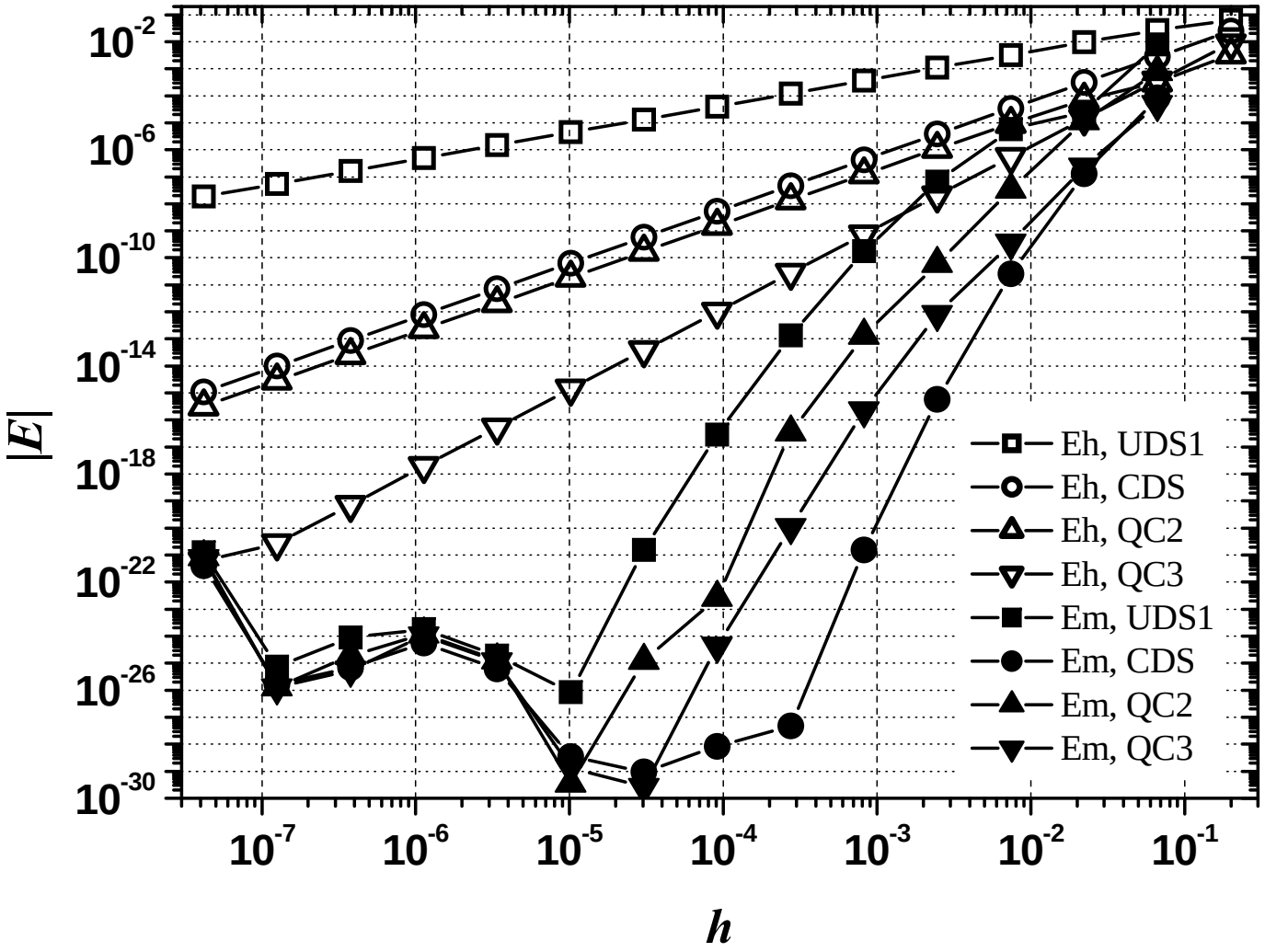



Burgers 2D, DF

Navier-Stokes 2D, ψ-ω, DF



# MER em Tc, Advecção-difusão 1D, VF



# MER

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

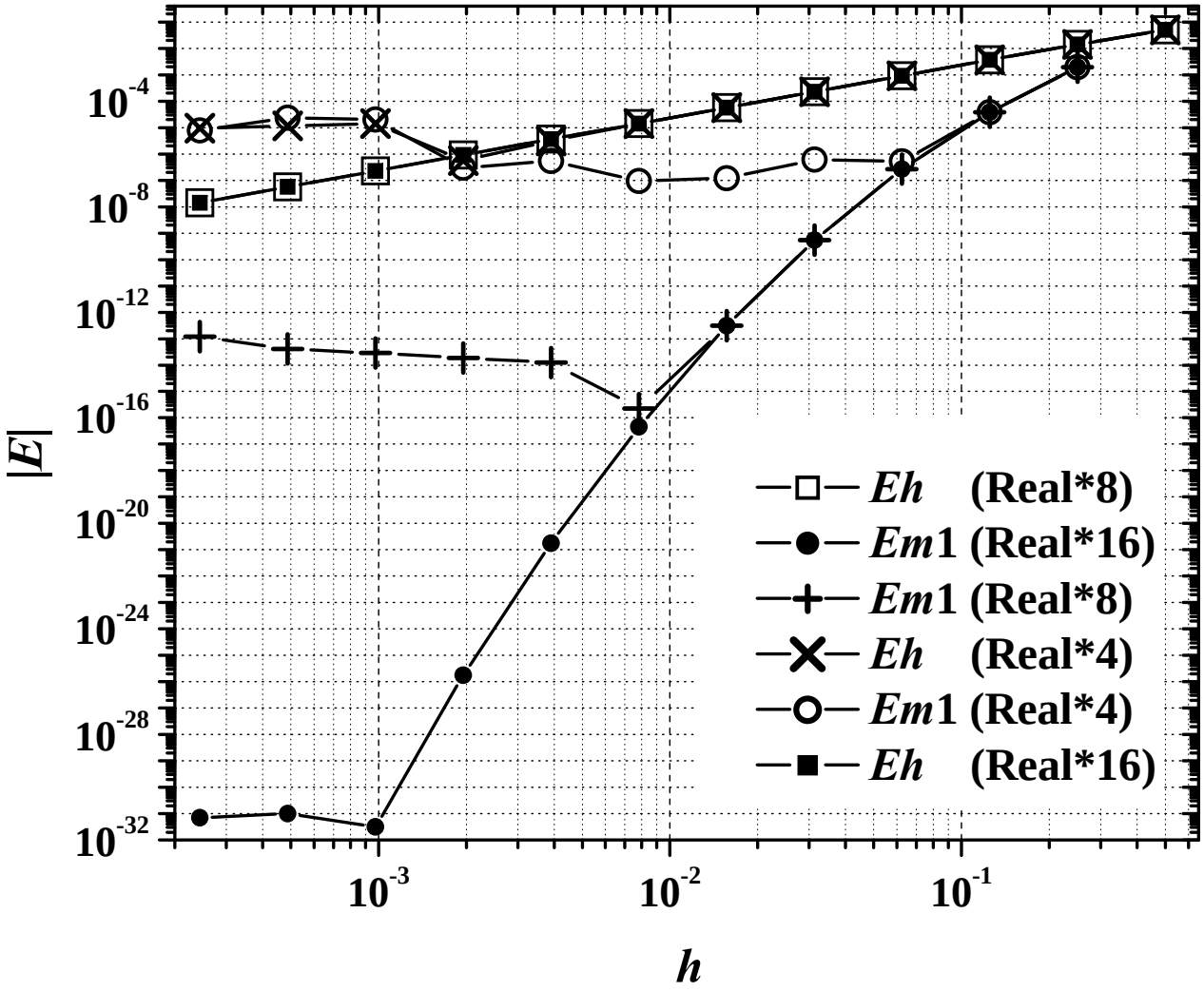
$$E(\phi) = C_0 h^{p_0} + C_1 h^{p_1} + C_2 h^{p_2} + \ldots = \sum_{m=0}^{\infty} C_m h^{p_m}$$

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

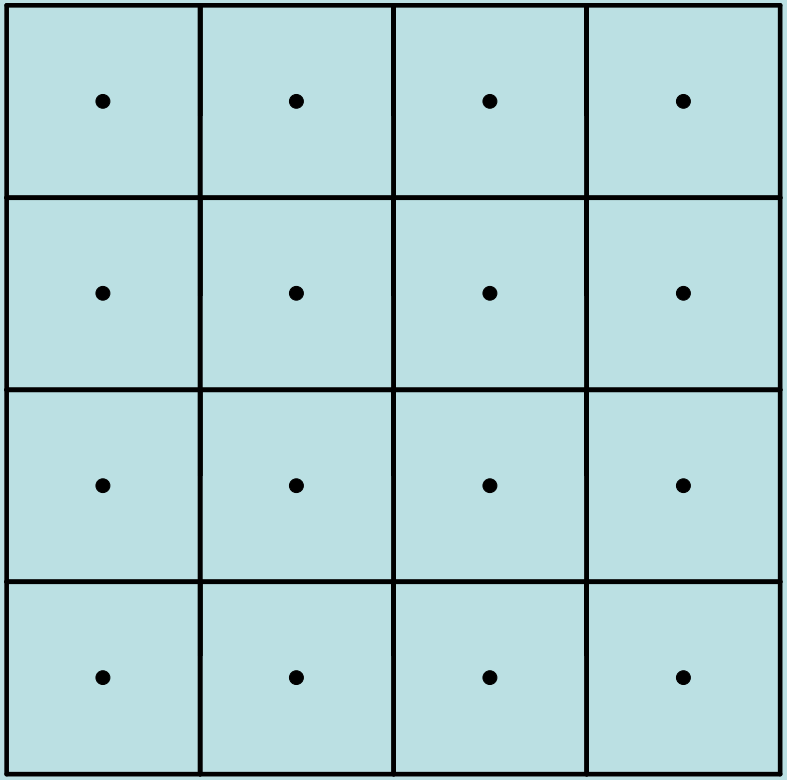
# Tabela de MER

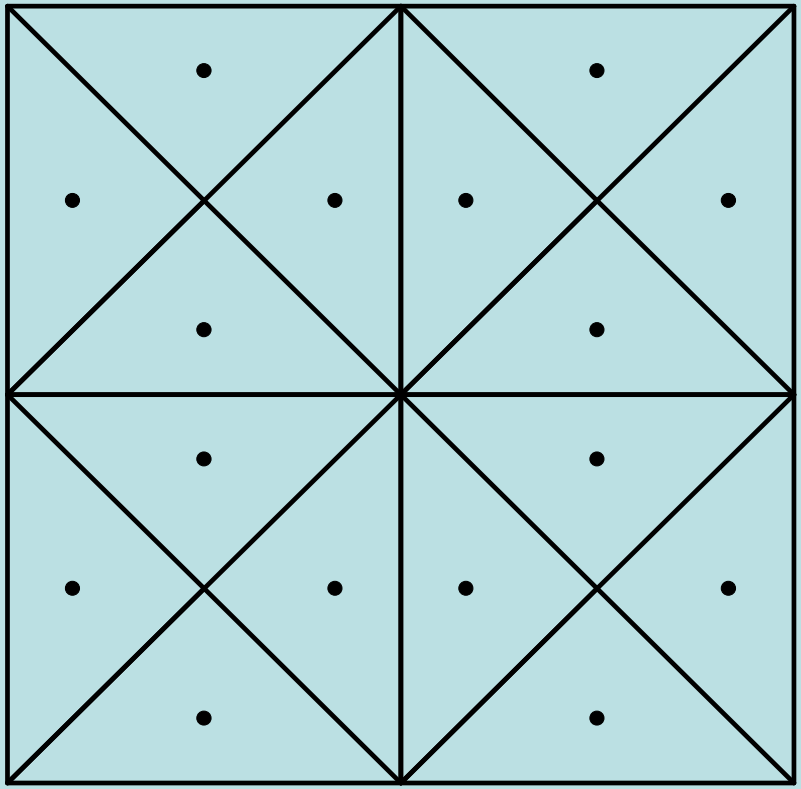
| g \ m | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| 1 | 1,0 | | | | |
| 2 | 2,0 | 2,1 | | | |
| 3 | 3,0 | 3,1 | 3,2 | | |
| 4 | 4,0 | 4,1 | 4,2 | 4,3 | |
| 5 | 5,0 | 5,1 | 5,2 | 5,3 | 5,4 |

# MER em Tc, Laplace 2D, DF

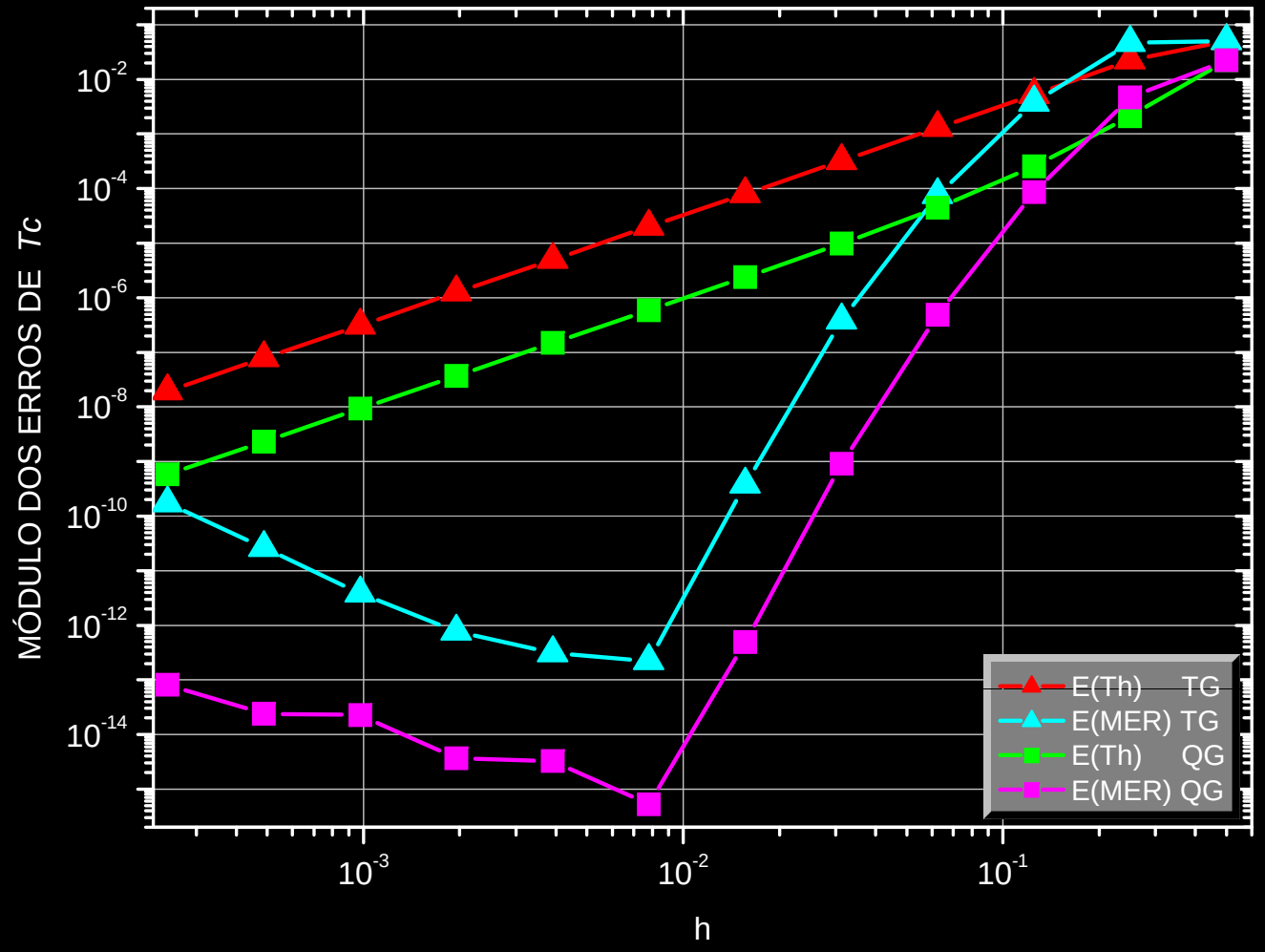


# Malhas quadradas e triangulares

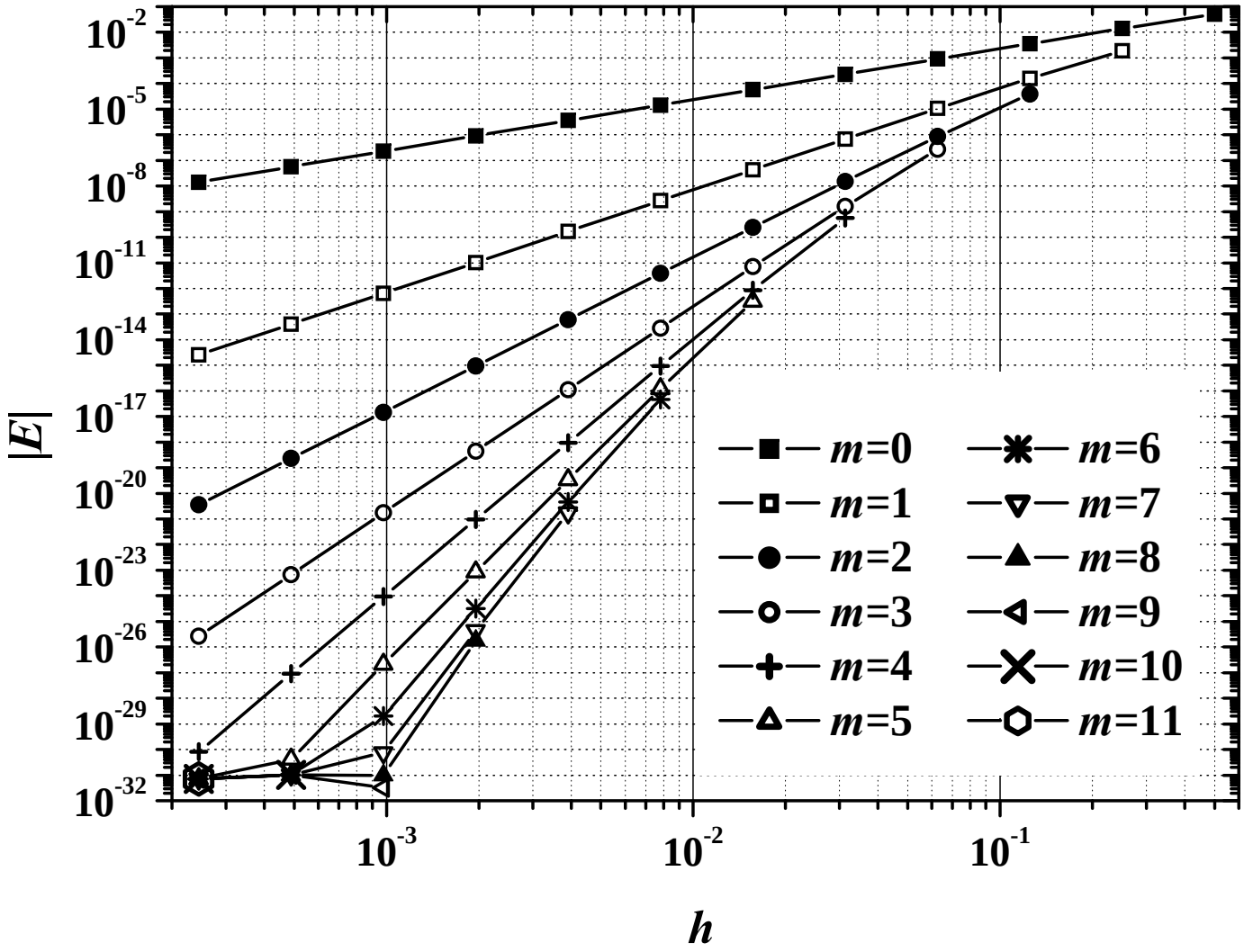




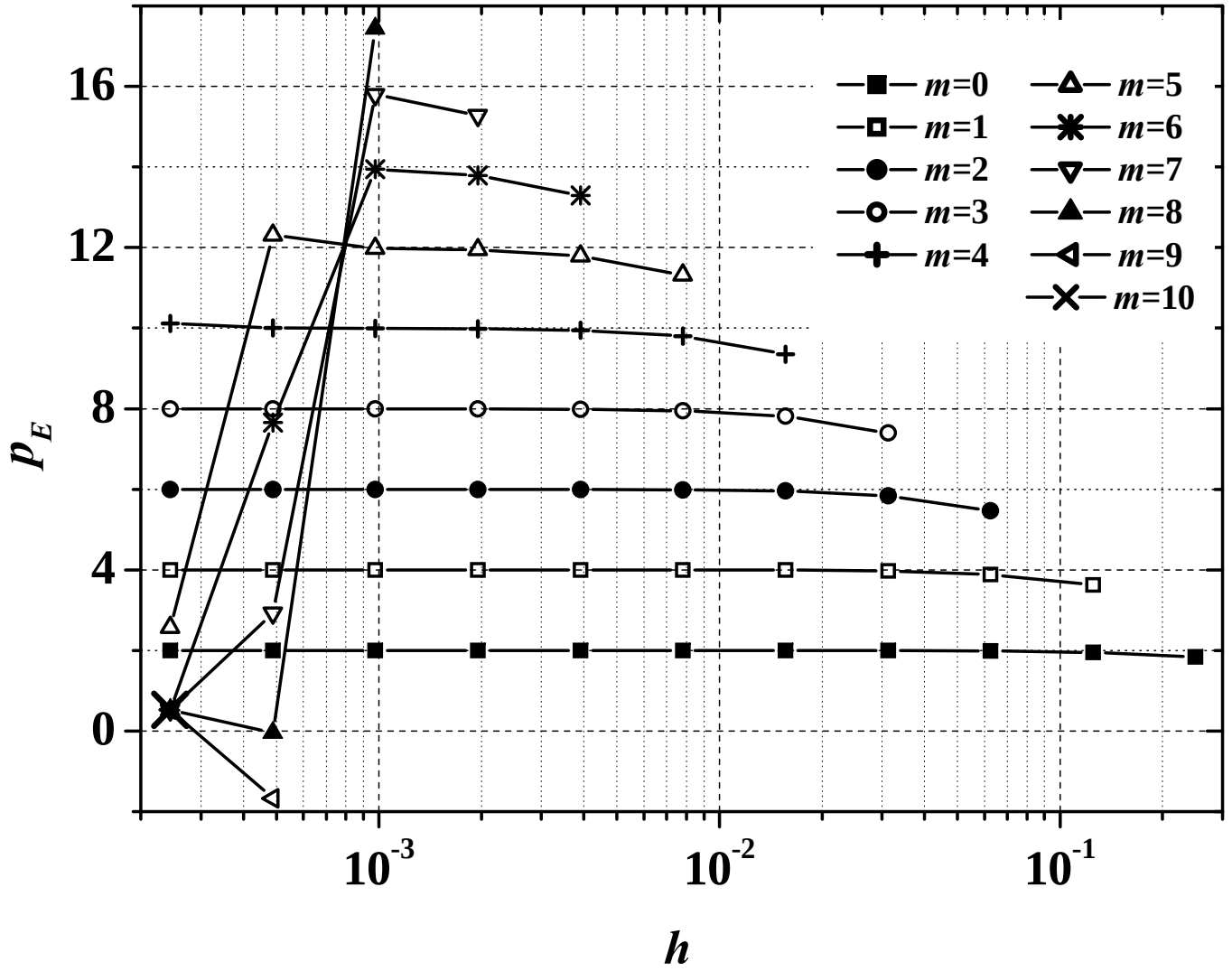
# MER em Tc, Laplace 2D, VF



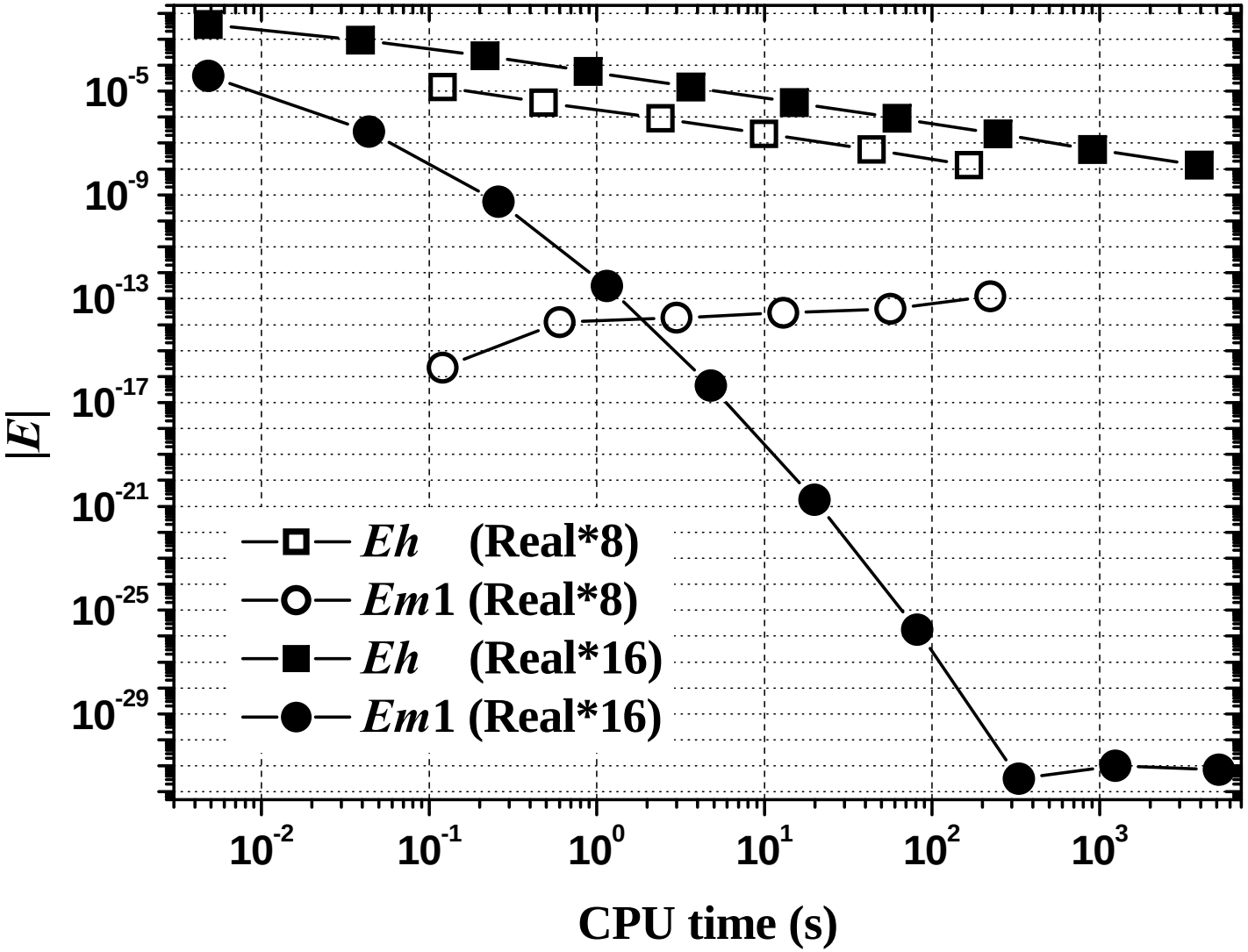
# MER em Tc, Laplace 2D, DF



# MER em Tc, Laplace 2D, DF



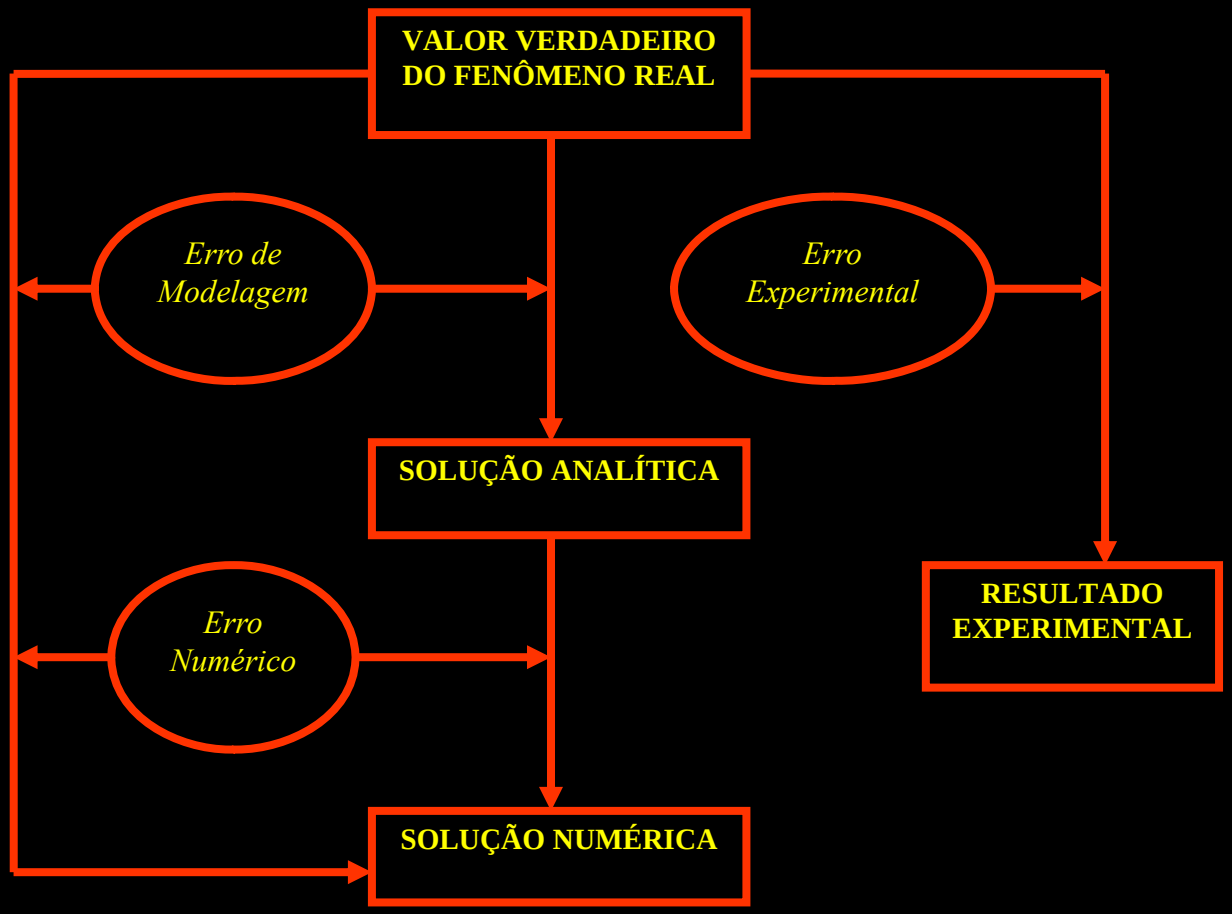
# MER em Tc, Laplace 2D, DF



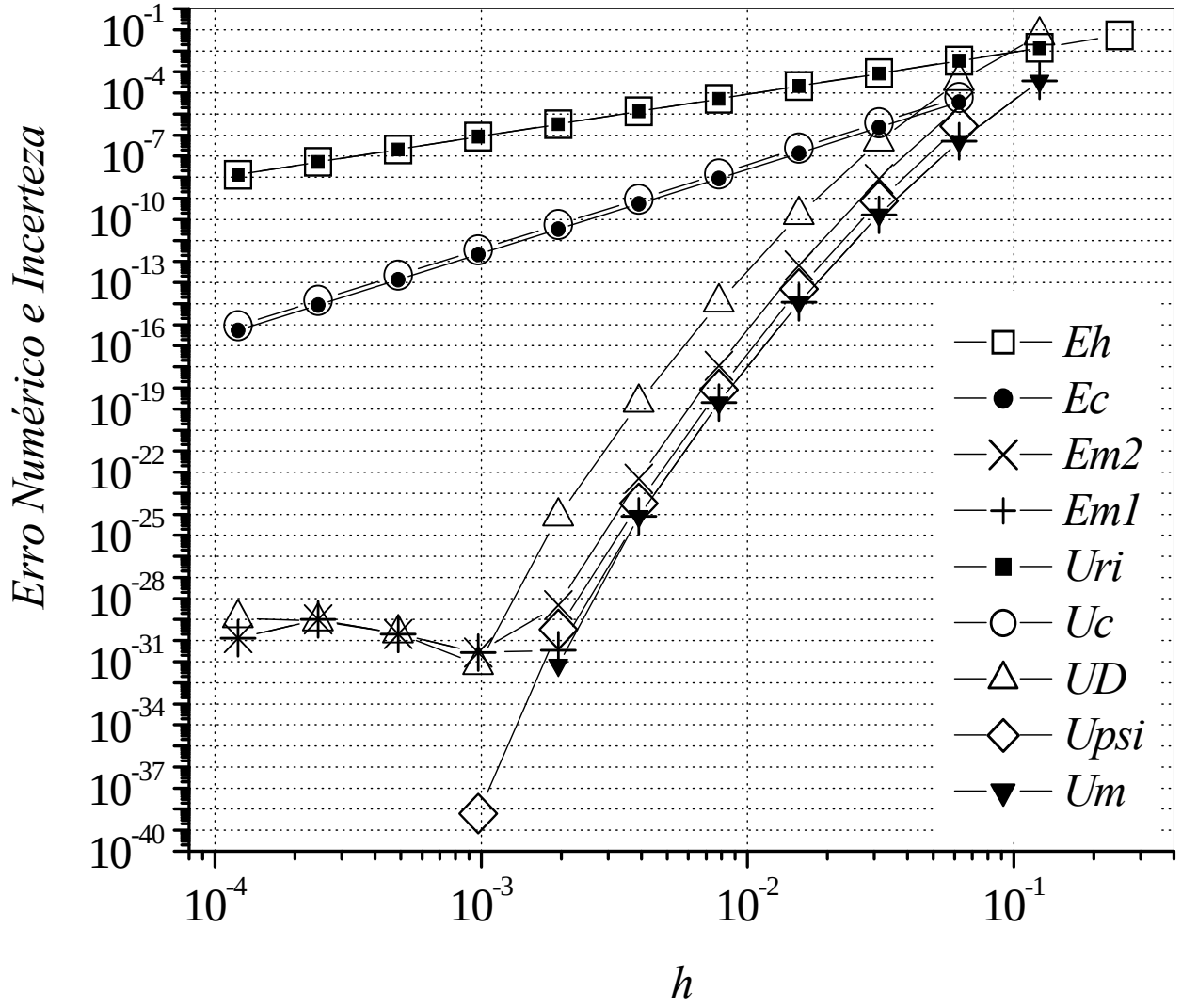
# Verificação e validação de soluções numéricas

- 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 |
| CFD2009 | 0.1035212 | 0.61621 | 0.73730 | 0.11398887 | 0.55371 | 0.60547 | 0.118936708 | 0.53125 | 0.56543 |
| CFD2016 | | | | | | | 0.1189366104 | 0.5307901165 | 0.56524055 |

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

# Otimização de métodos numéricos

Comparisons of *uc* with other authors for the problem 4.

Type II-2D variable, with 2D polynomial interpolation, $p = 1$.

| Reference | *uc* | *U* | $p_U$ |
|---|---|---|---|
| [23] | -0.06080 | | |
| [24] | -0.0620561 | | |
| [6] | -0.0620 | | |
| [25] | -0.06205 | | |
| [7] | -0.0620561 | ±6E-07 | 2.07 |
| Present | -0.062056135194 61 | -3E-14 | 9.41 |

Navier-Stokes 2D, VF, CDS-2 com MER
Problema clássico da cavidade quadrada com tampa móvel

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**Para interessados em**
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