EFFECT OF TRANSPORT PROPERTY MODELING ON STABILITY OF BOUNDARY LAYERS IN HYPERSONIC FLOWS

Presented by

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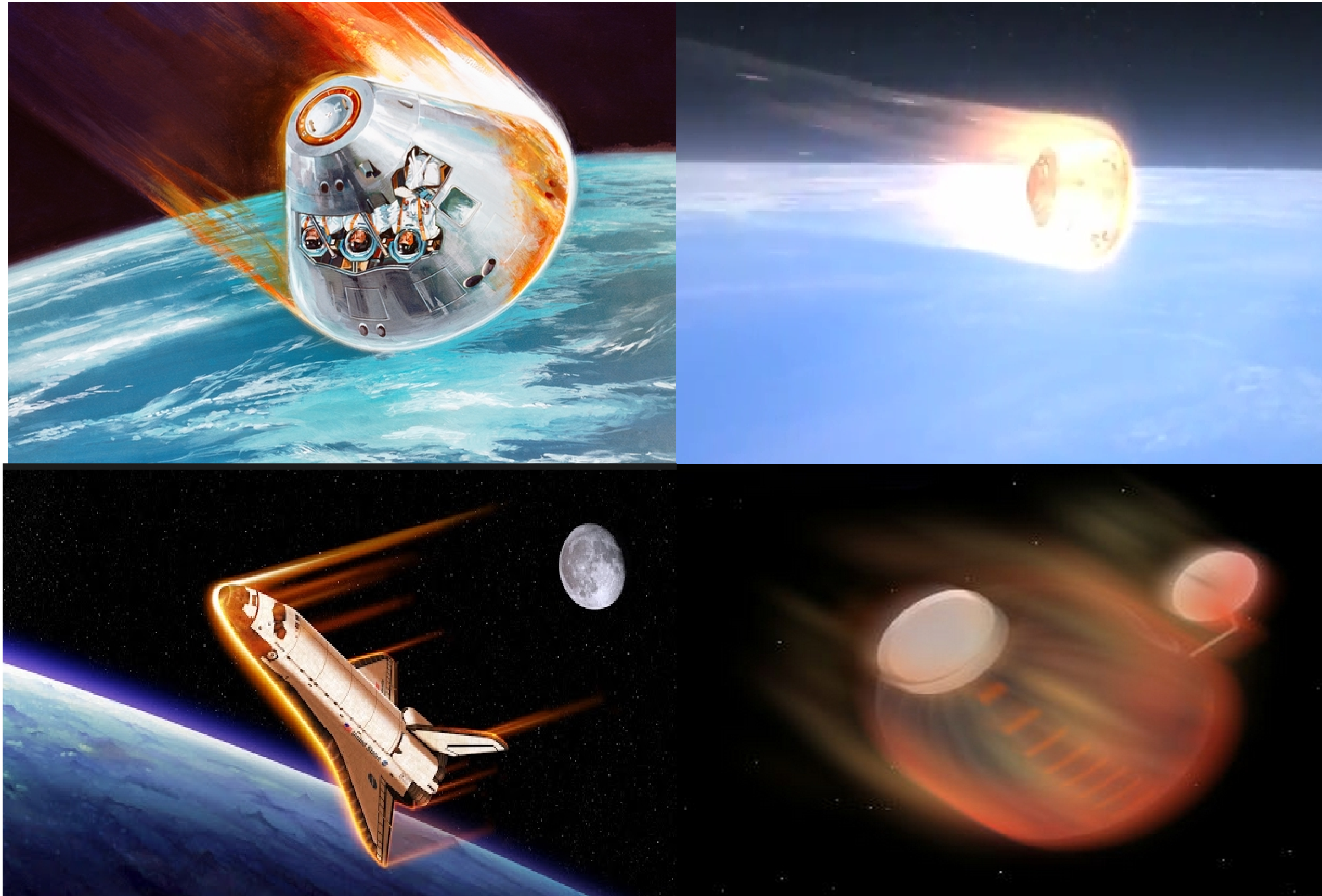
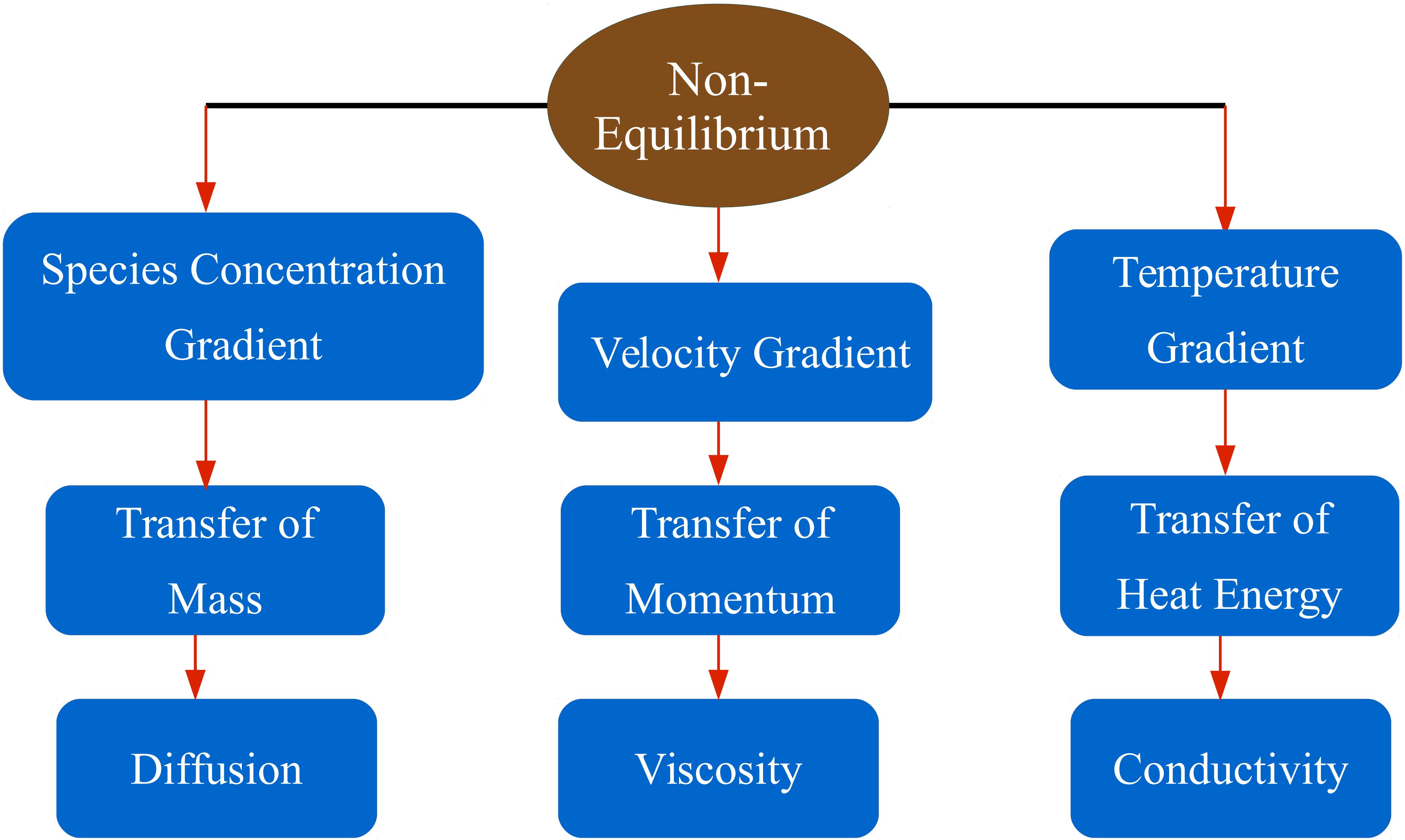
Hypersonic flow



What is hypersonic flow??

- Mach number greater than 5
- Very high temperature in the flow-field
- High viscous dissipation in the BL
- Low density environment
- Region of non-equilibrium flow
- Large gradients in the flow properties
- Occurrence of Thermo-chemical phenomena like: vibration or electronic excitation, dissociation, ionization, radiation etc..
- Deviation from perfect gas model, so need to model the transport properties differently.
- Additional transport mechanism of diffusion becomes important

Evolution of transport phenomena



Various viscosity models

- Sutherland's law

$$\mu = 1.458 \times 10^{-6} \frac{T^{\frac{3}{2}}}{T+110.3}$$

Valid for 0 < T < 555 K

- Blottner's formula

$$\mu_s = 0.1\, exp[(A_s ln\, T + B_s) ln\, T + C_s]$$

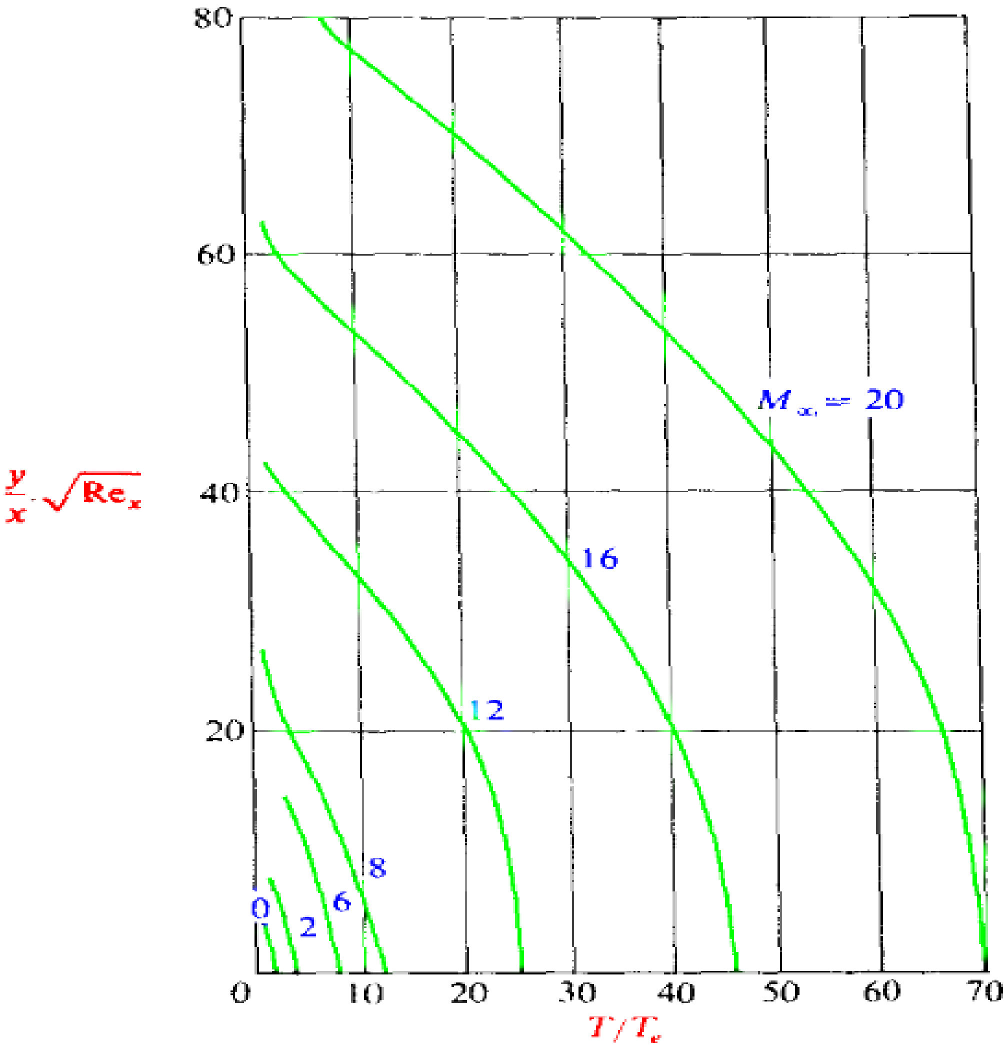
Valid for 10,000K
&
For weak ionization

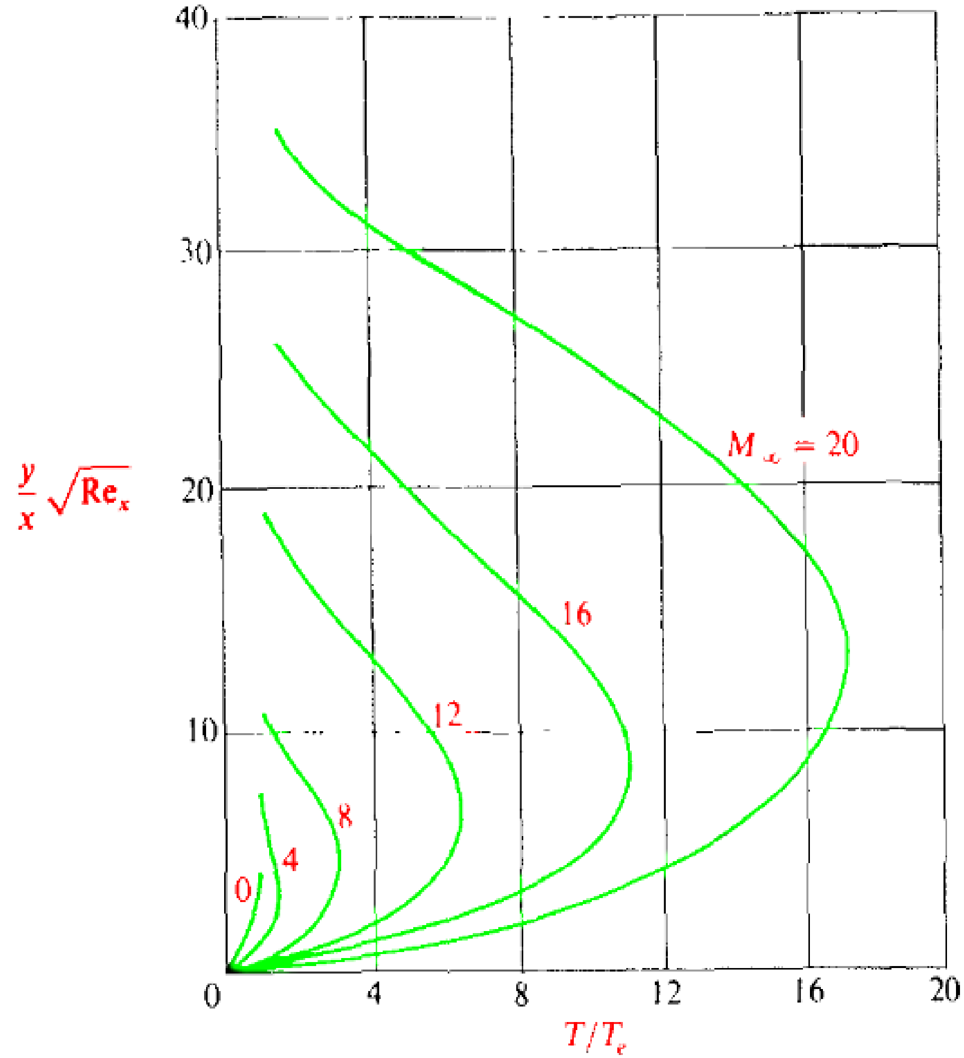
- Collision Integral data

For T > 10000 K

Effect of different visocity models on the stability of hypersonic flows

Thermal boundary layer profile depending on wall boundary condition



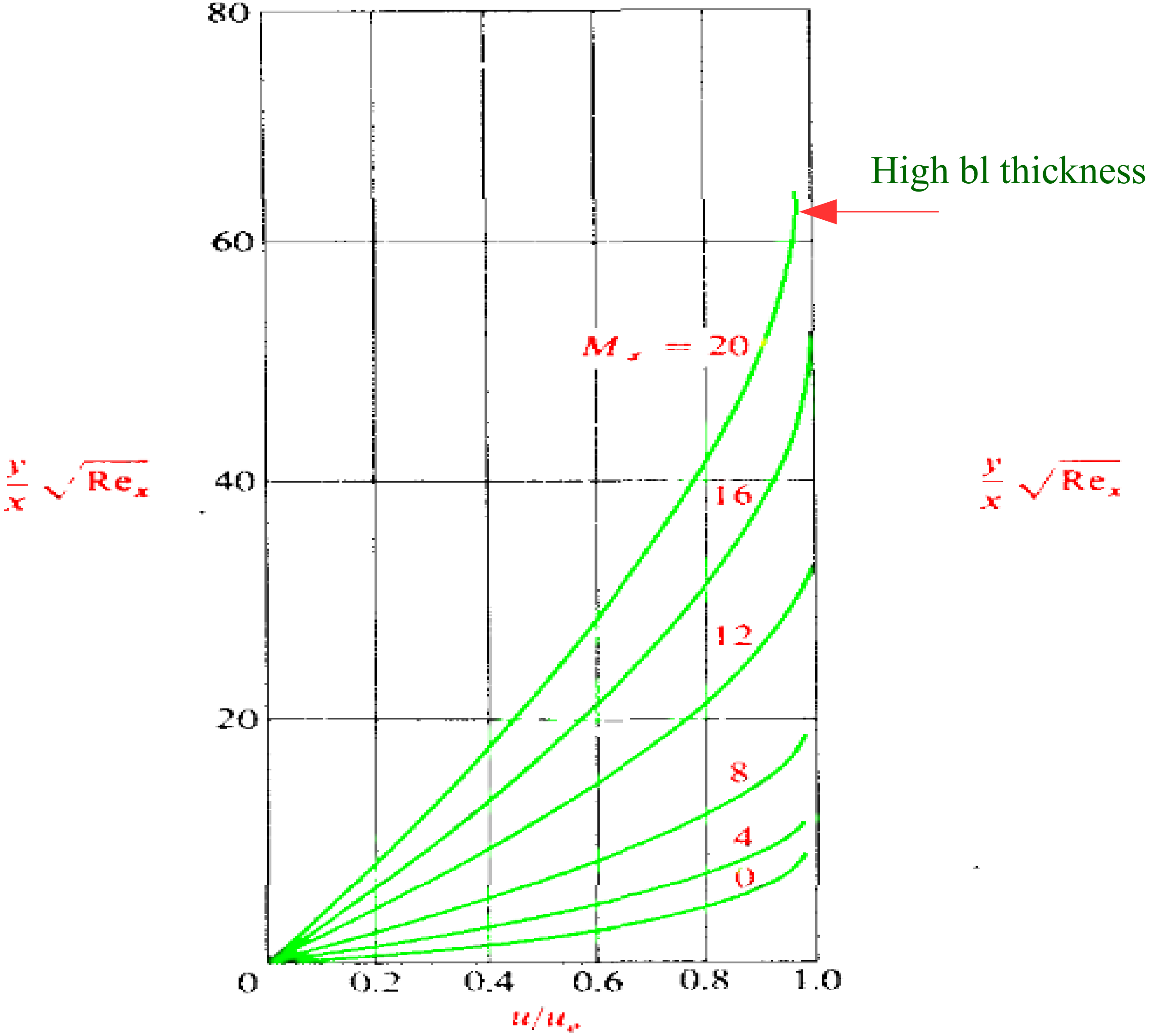


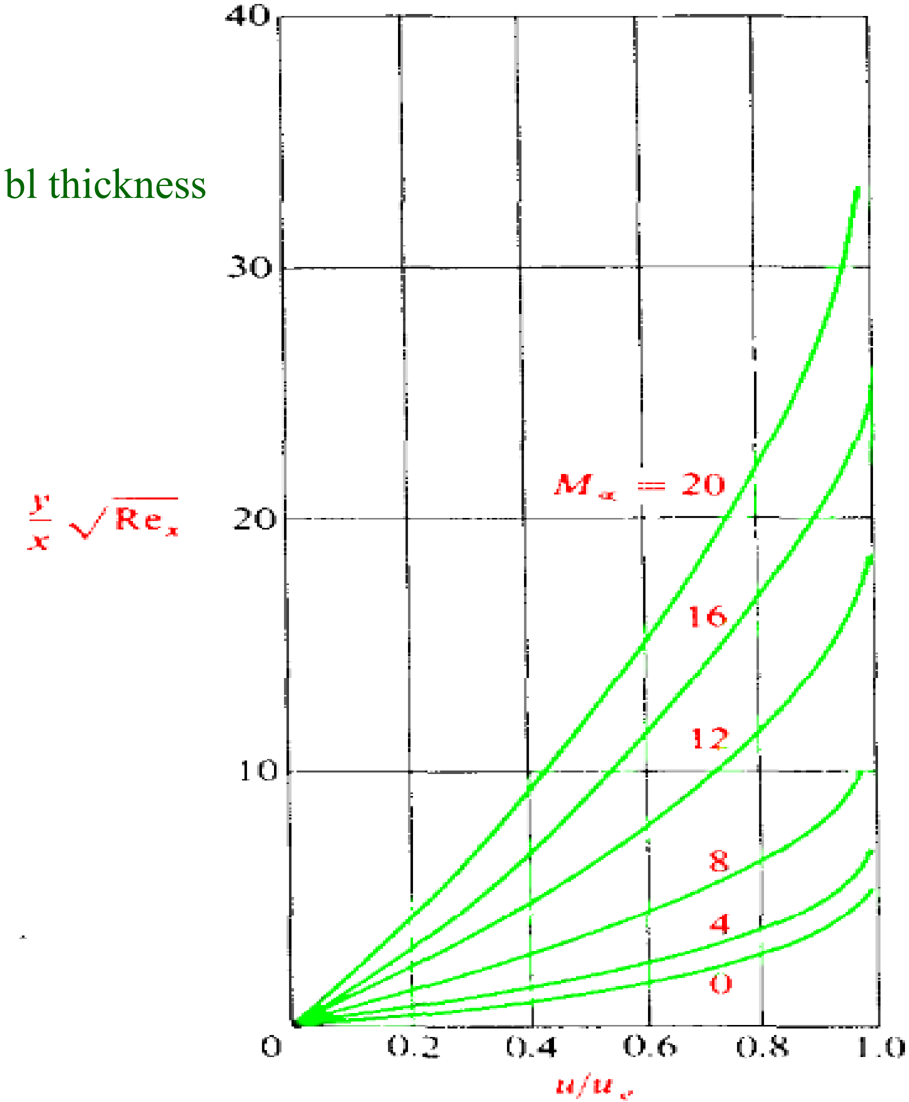
Adiabatic wall

From Ref 5

Cold wall
$T_w < T_{aw}$

Corresponding Velocity boundary layer profile





Adiabatic wall

From Ref 5

Cold wall $T_w < T_{aw}$

Computational Parameters

Reed & Iyan:

Geometry: Spherically blunted right-circular cone

Cone angle: 21^{o}

AOA: 0^{o}

Altitude: 20km

Free-stream M =13.5

Free-stream Re $=1.25 * 10^4$ (Based on nose radius)

Wall temperature: 500K

BC at wall: No-slip,Non-reacting, Zero pressure gradient

Franko, Lele:

Geometry: Flat Plate

Free-stream M = 10

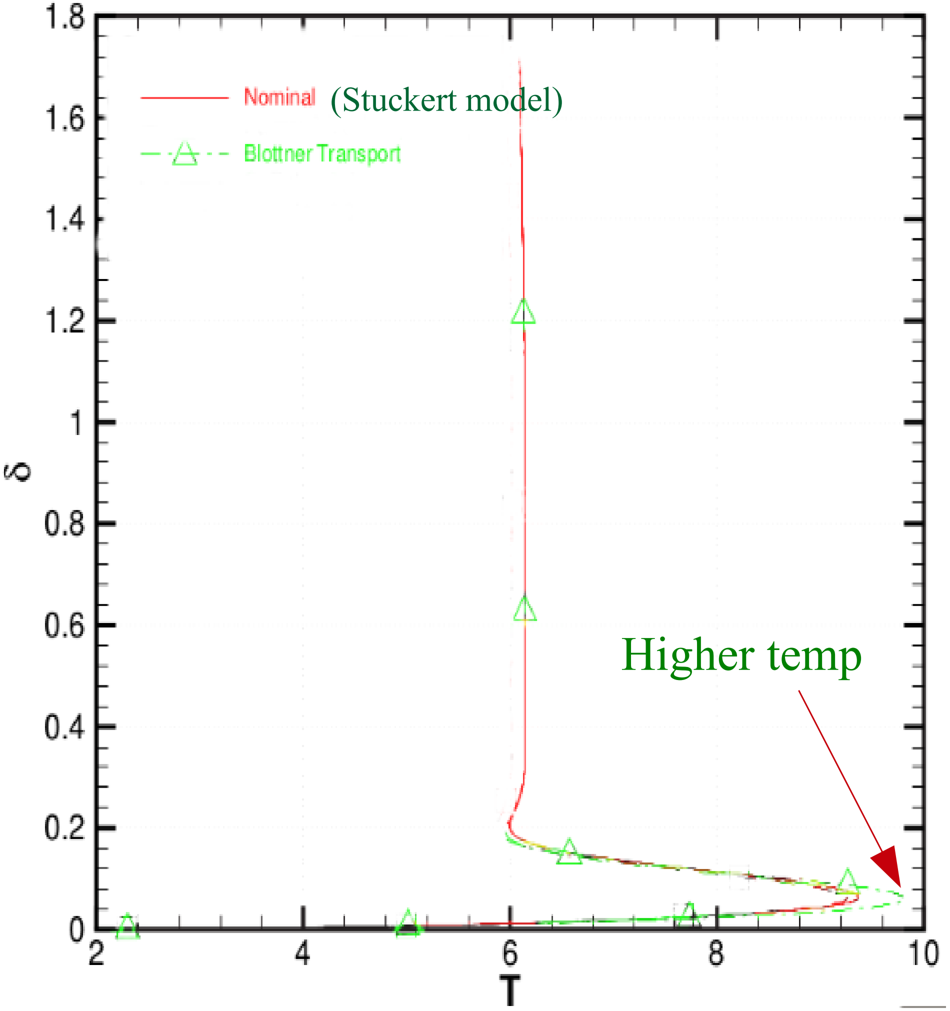
Unit Re $= 9.824 * 10^6\ m^{-1}$

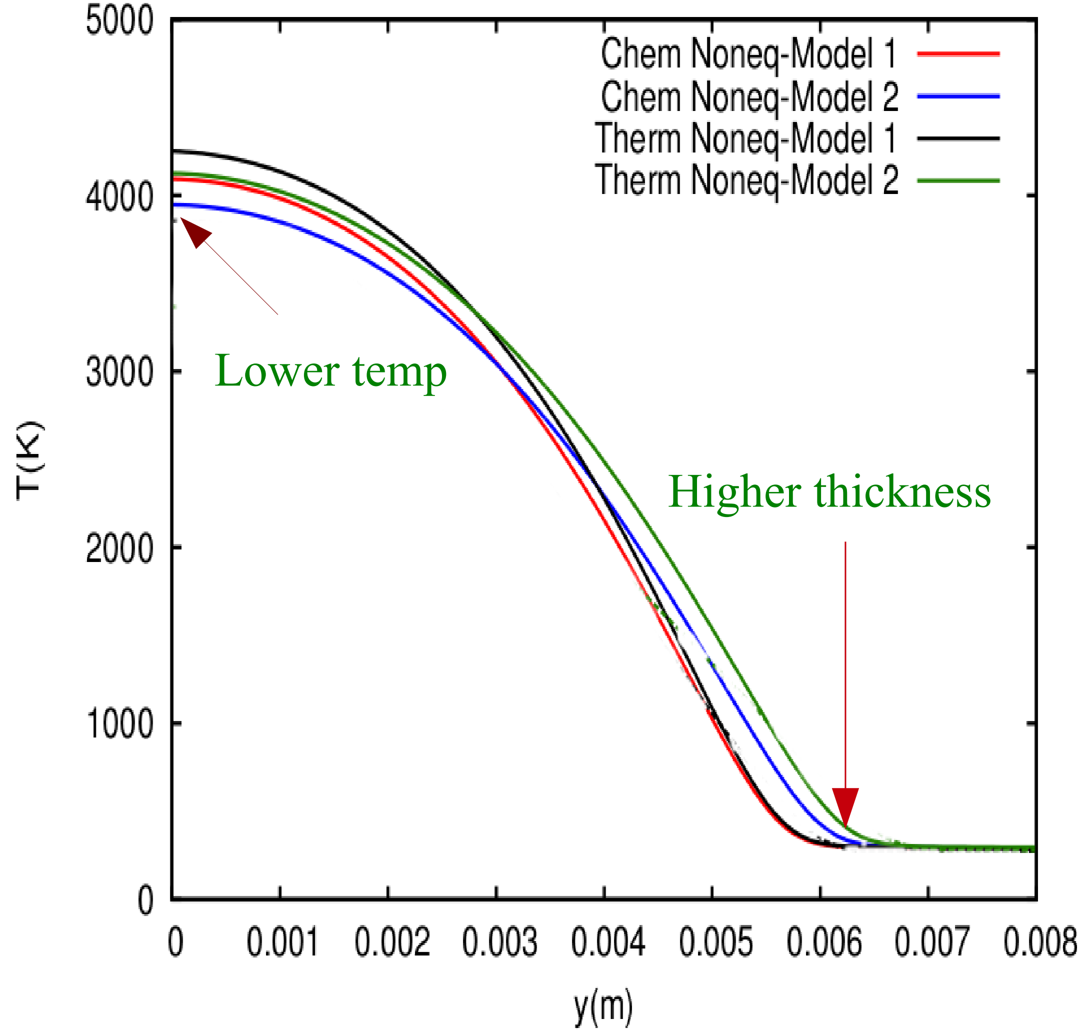
Freestream temperature: 278K

BC at wall: Adiabatic

Axial Location used x= 0.4 m

Thermal Boundary layer



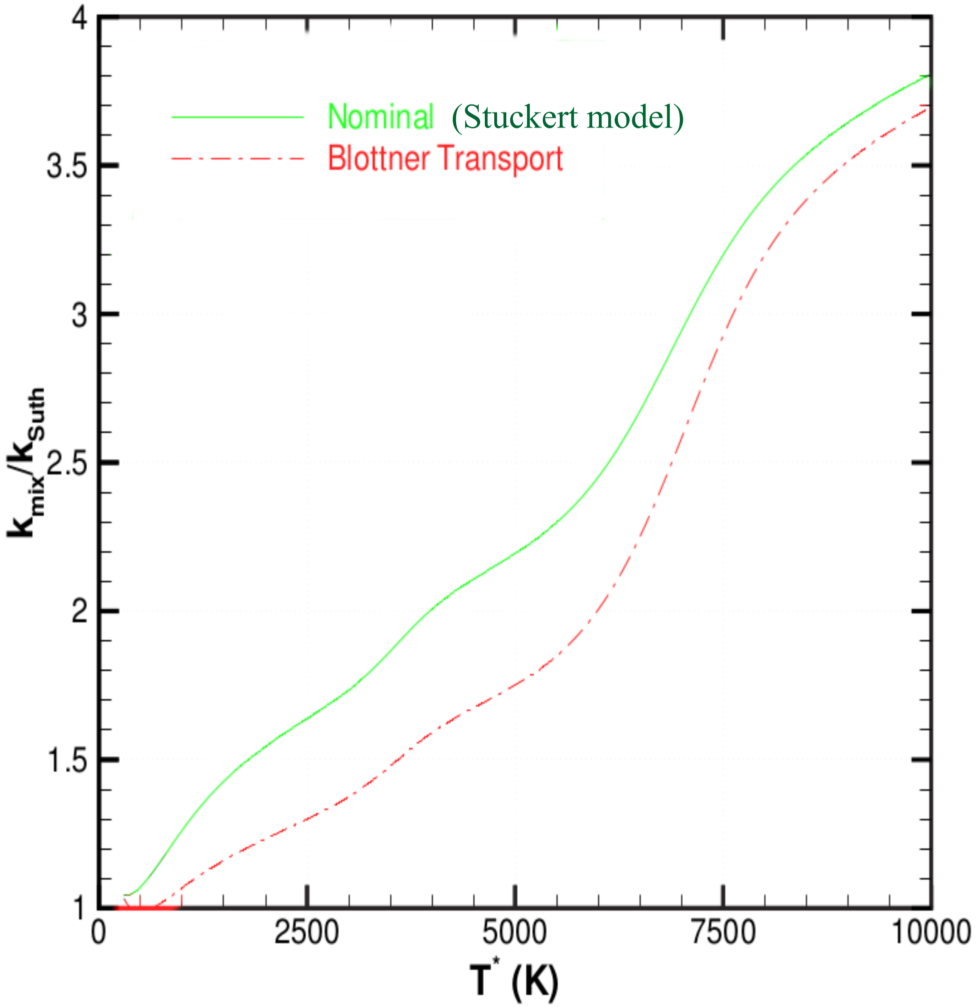


Case 1: Isothermal wall

Case 2: Adiabatic wall

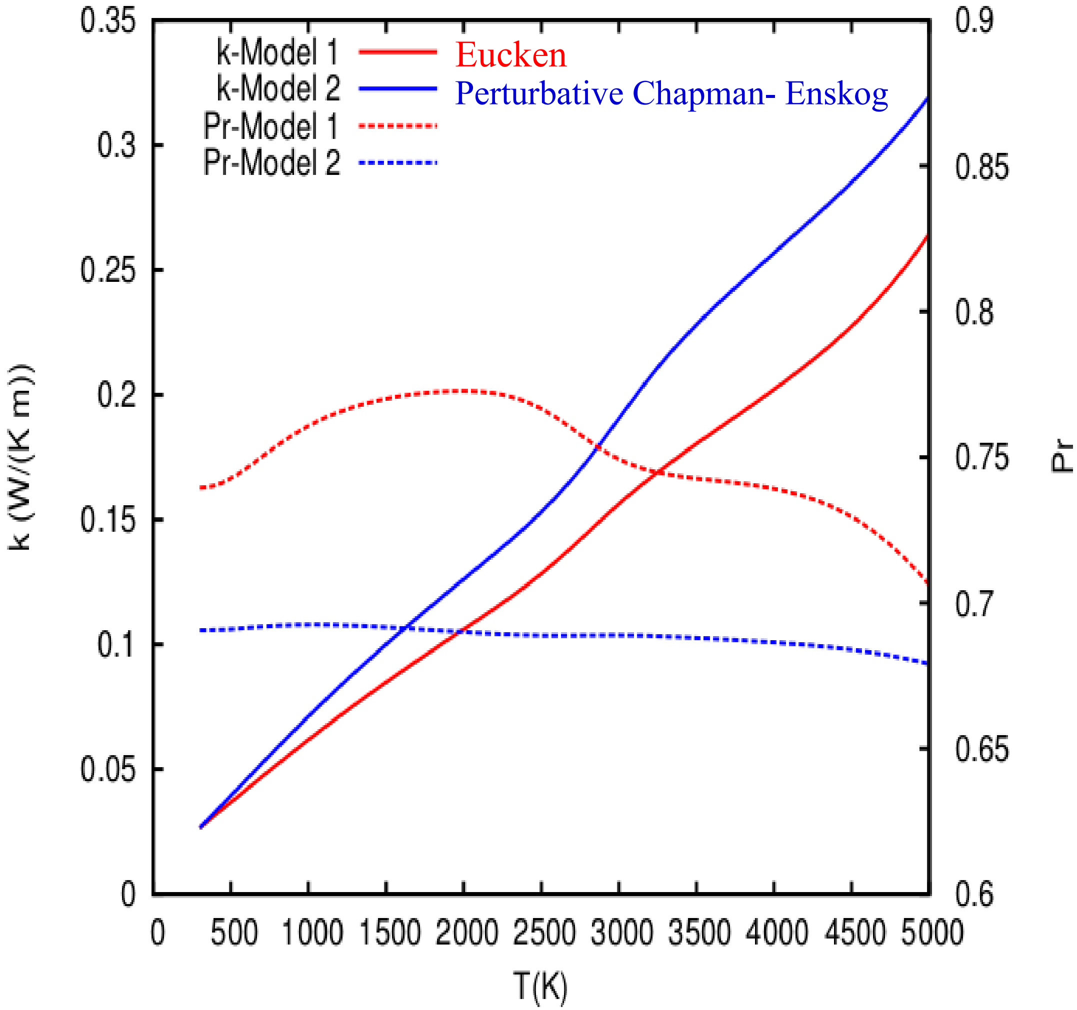
Thermal conductivity variation

Case 1



$K_{nominal} > K_{blottner}$ (25%)

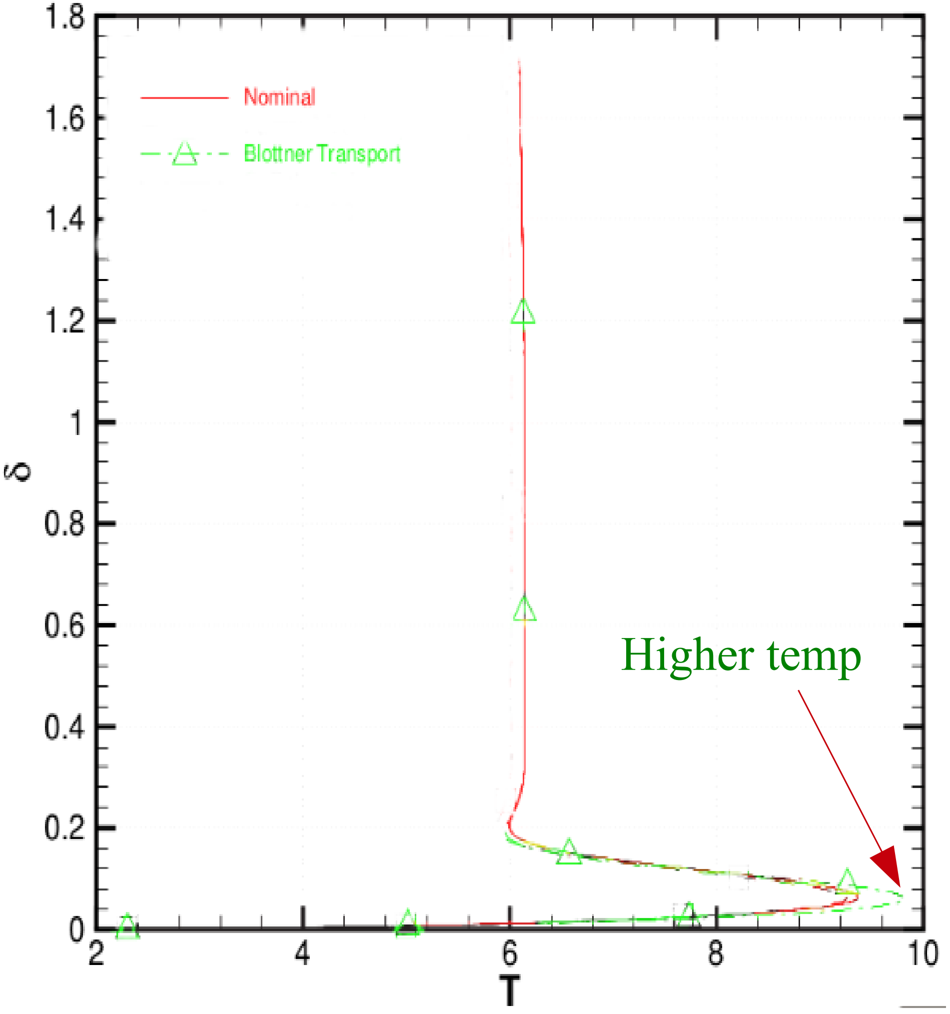
Case 2

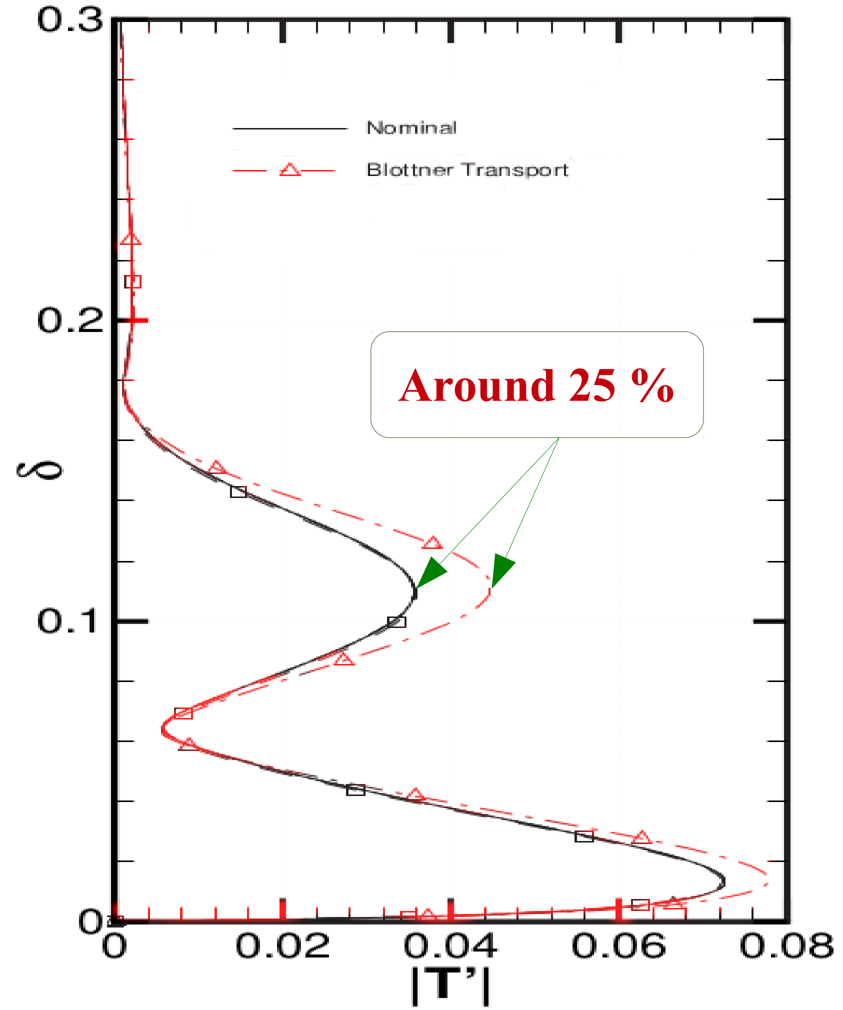


$K_{model2} > K_{model1}$ & $Pr_{model1} > Pr_{model2}$

→ **Lower wall temp**

Amplitude of temperature perturbation for case 1

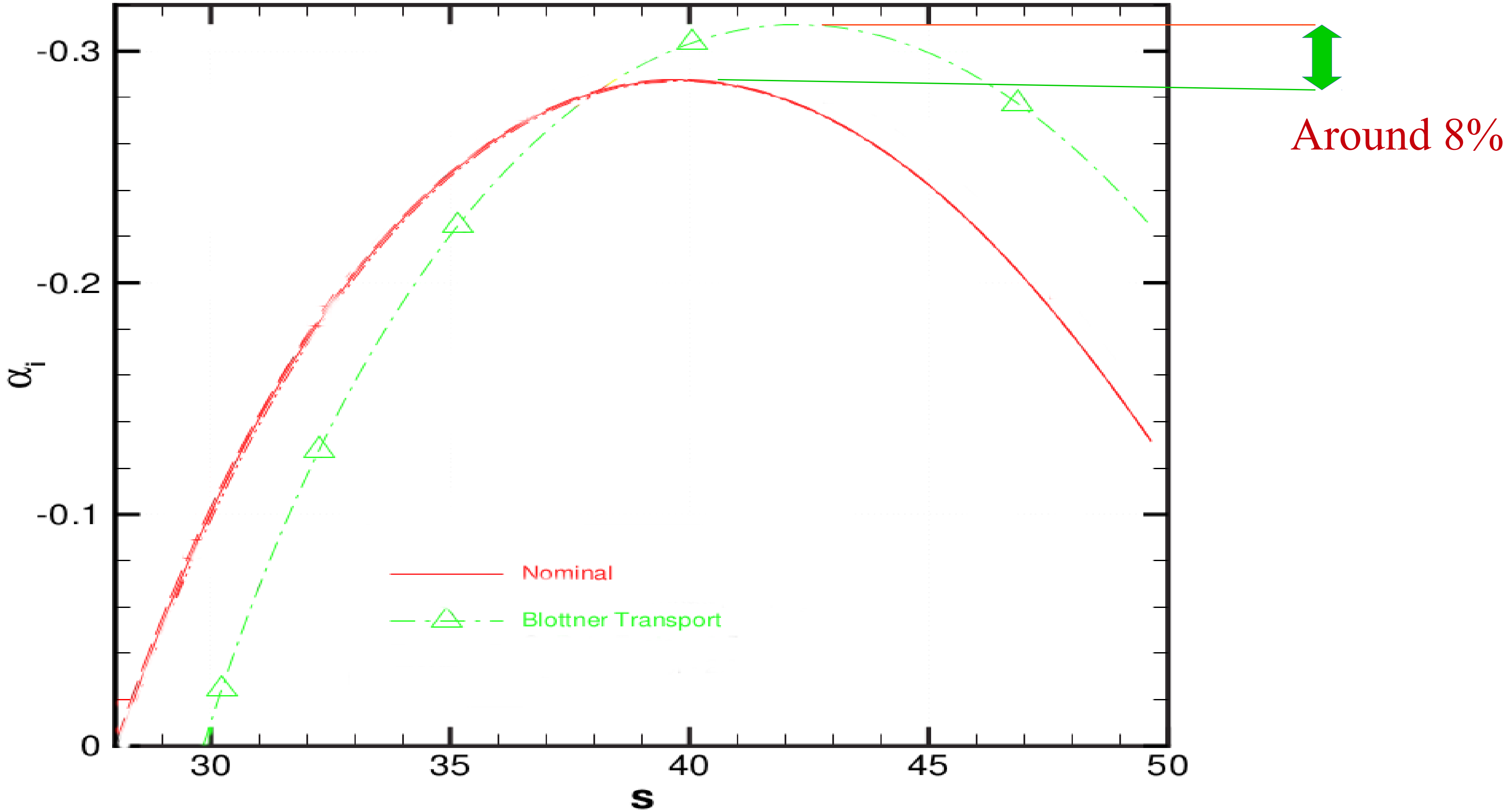




Case 1: Isothermal wall

ω=10.51, β=0

Growth rate



Case	$\max(\alpha_i)$	$\max(\alpha_i) / \max(\alpha_i)_{nominal}$
Nominal	−0.287416	1
Blottner	−0.311482	1.084

Why Growth rate is showing opposite trend??

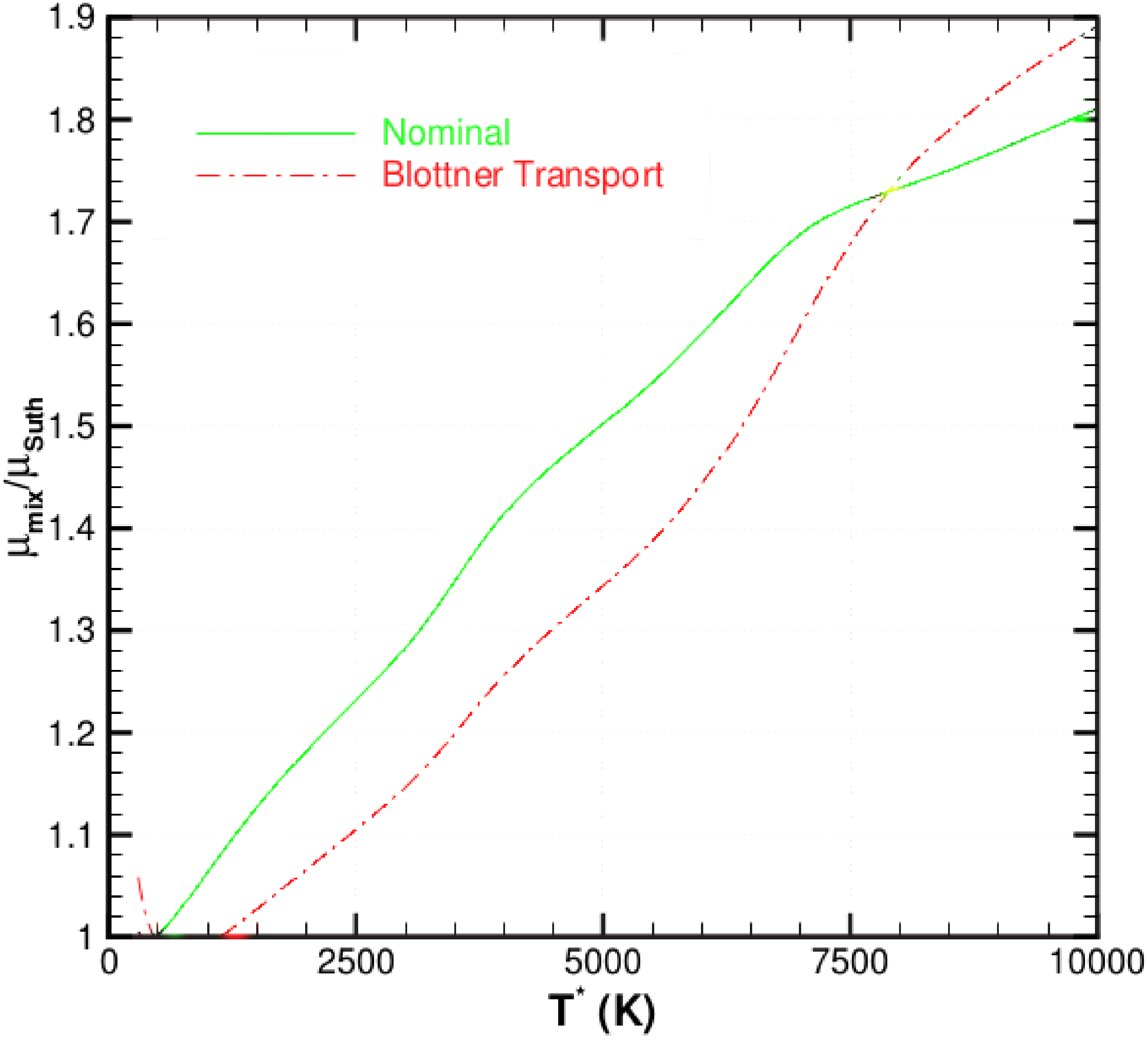
Blottner transport-case has a hotter thermal profile, so it should have lower amplification rate compared to nominal case.

↓

Because cooling destabilizes the flow

But growth rate fig shows opposite trend...Why???

Is this because of viscosity??



Blottner viscosity < Nominal

↓

Thinner boundary layer

↓

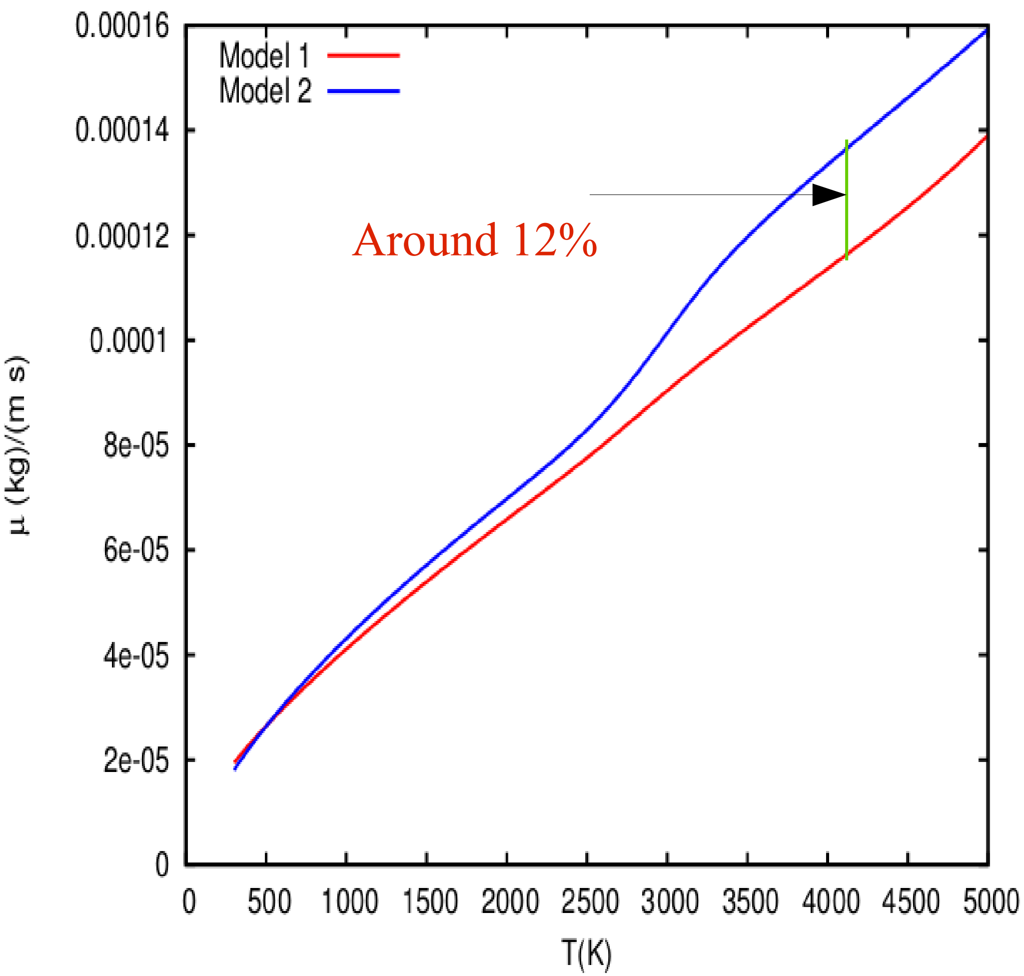
Same affect as cooling

↓

So, High amplification in growth rate

Effect of Viscosity variation on thermal boundary layer

Case 2:



$$\frac{T_{w_{ad}}}{T_\infty} = 1 + r\left(\frac{\gamma - 1}{2}\right)M^2$$

$$r = Pr^{1/2}$$

Low Pr means lower T_w

Model 2 >Model 1 → Leads to higher bl thickness

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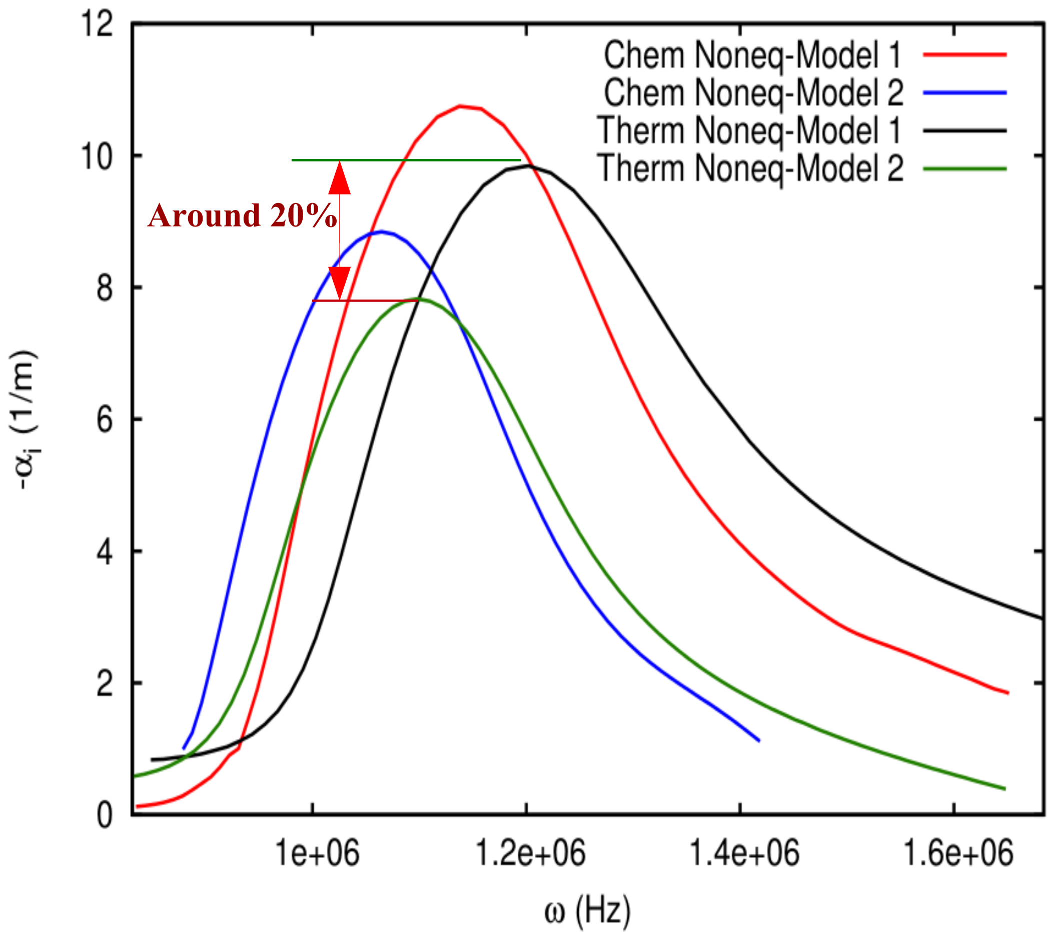
Growth rate comparison



- High amplification for model 1: Lower viscosity
- Shift in location of max growth rate to lower freq. for model 2: high bl thickness

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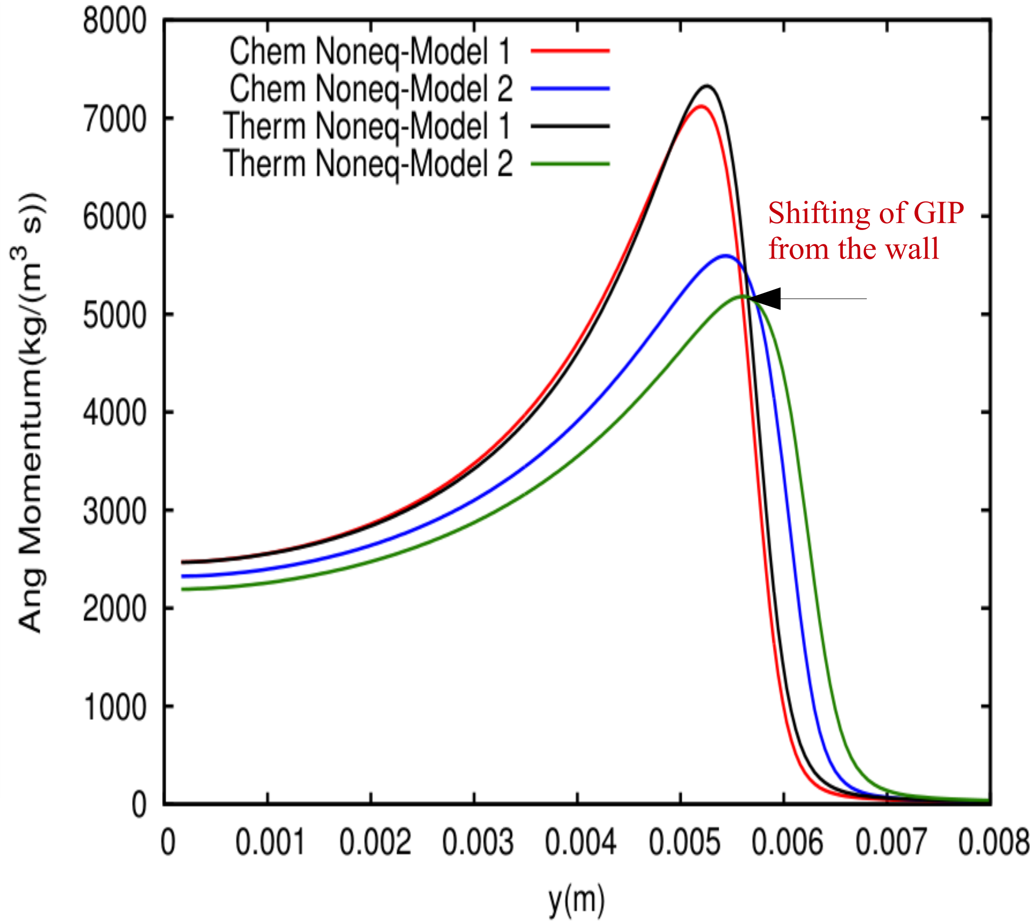
Angular momentum comparison



Higher bl thickness for model 2: Shifting of GIP away from the wall

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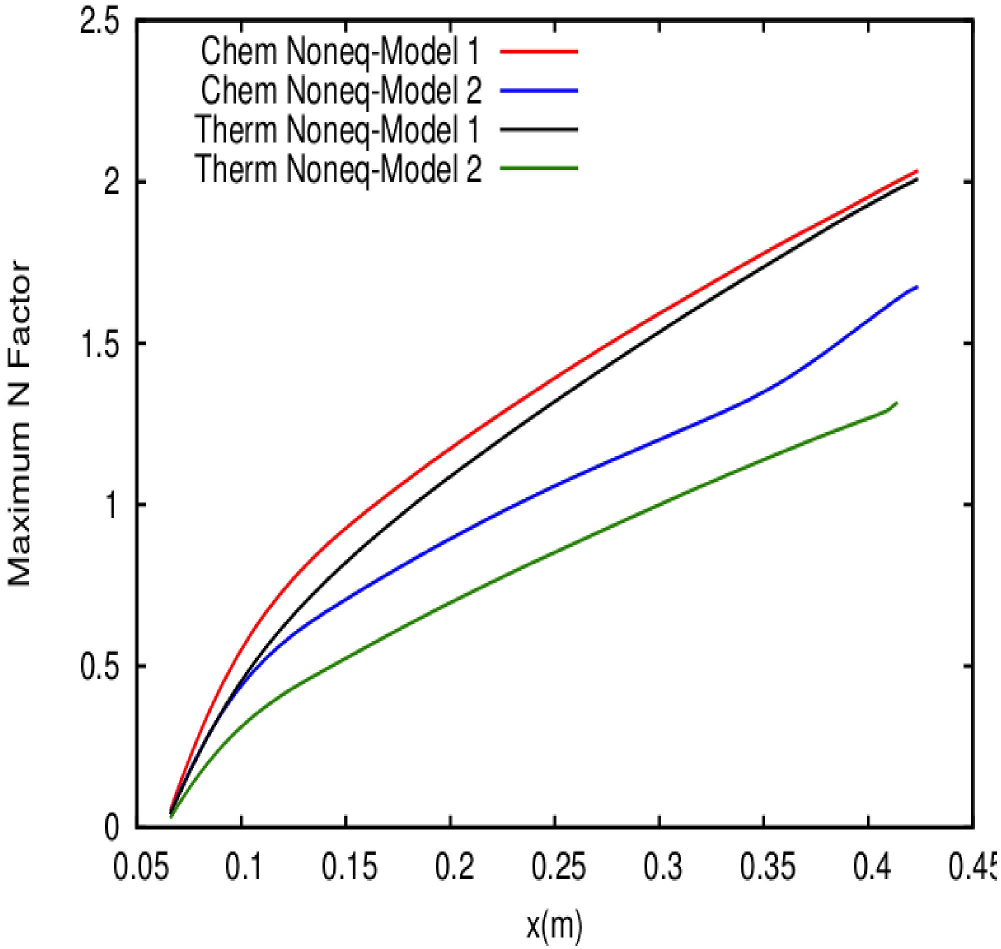
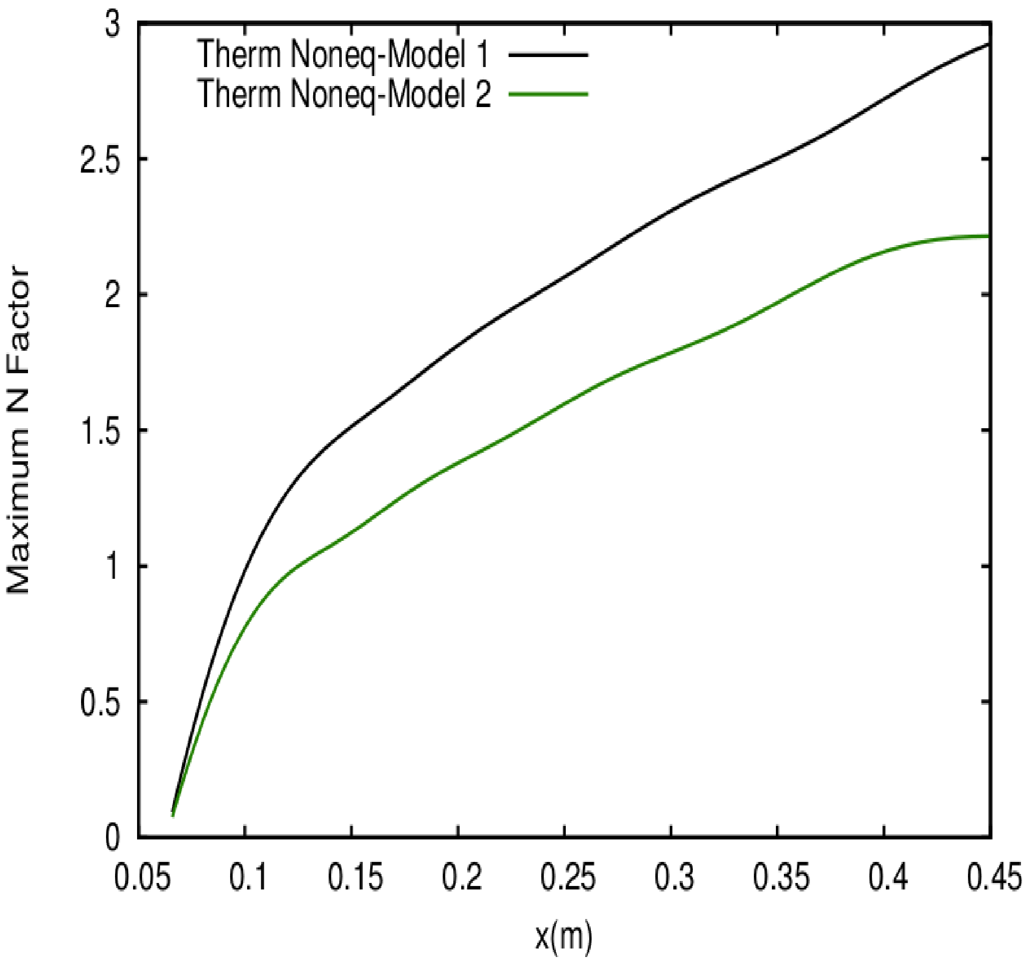
N factor comparison

Adiabatic wall



Low max N for Model 2 --> Stable bl

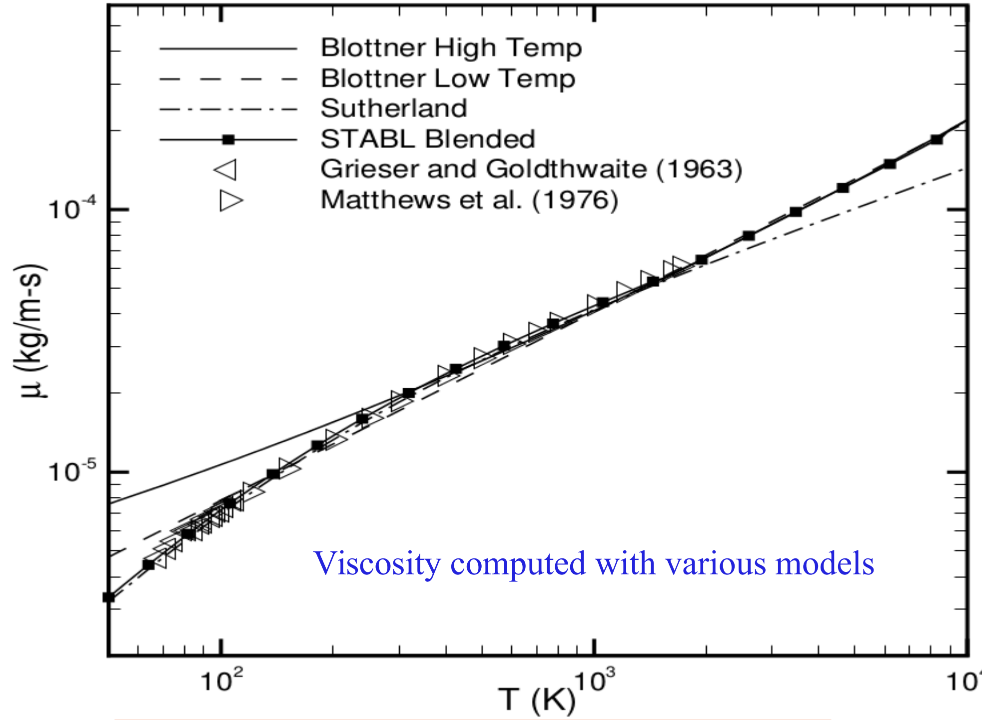
Cooled wall(1200K)

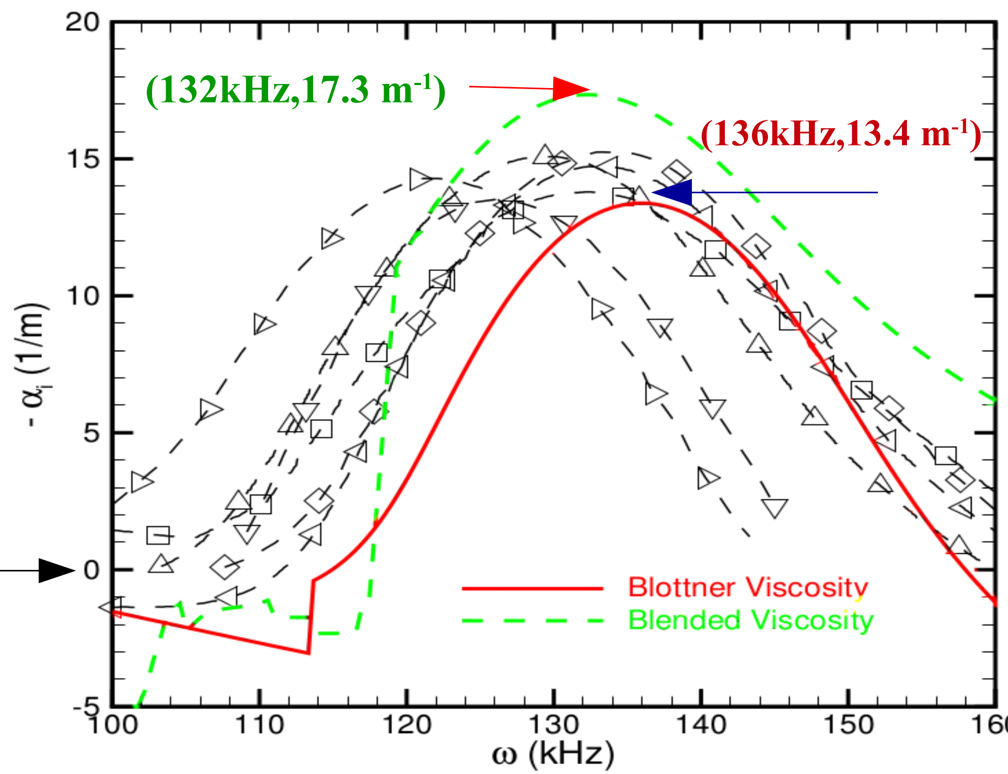


Higher max N for cool wall than insulated case

Model Specifications	
Half angle	7°
Length (m)	1.016
Base diameter (m)	0.2495
Nose radius (mm)	3.81
Wall Temperature	Adiabatic
Freestream Conditions	
Fluid	Air
M_∞	7.99
p_o (Pa)	4.0×10^6
T_o (K)	750
p_∞ (Pa)	410
T_∞ (K)	54
ρ_∞ (kg/m^3)	0.0027
Re_∞/ft	2.5×10^6

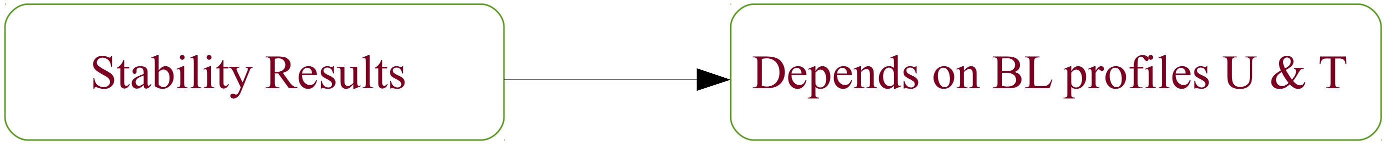
Robarge & Schneider



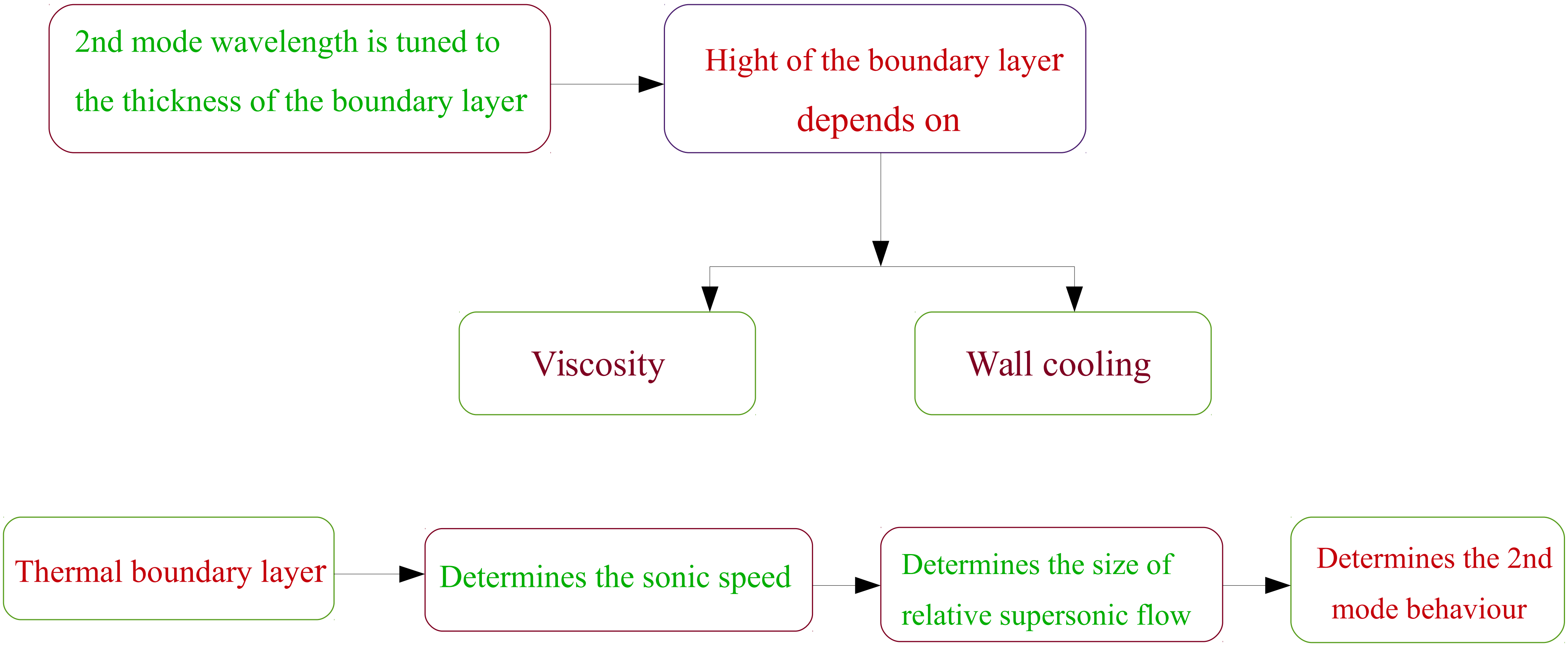


Comparison of amplification rate

Inference

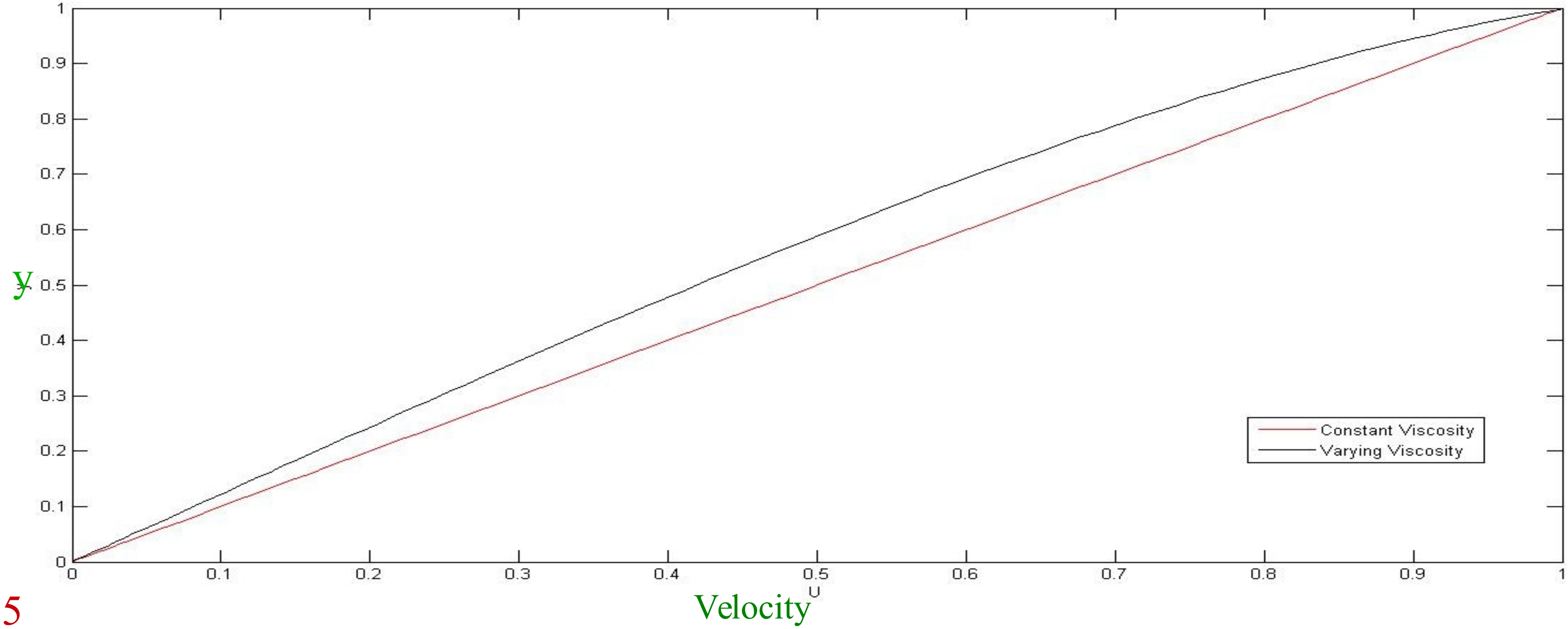


In case of 2nd mode:

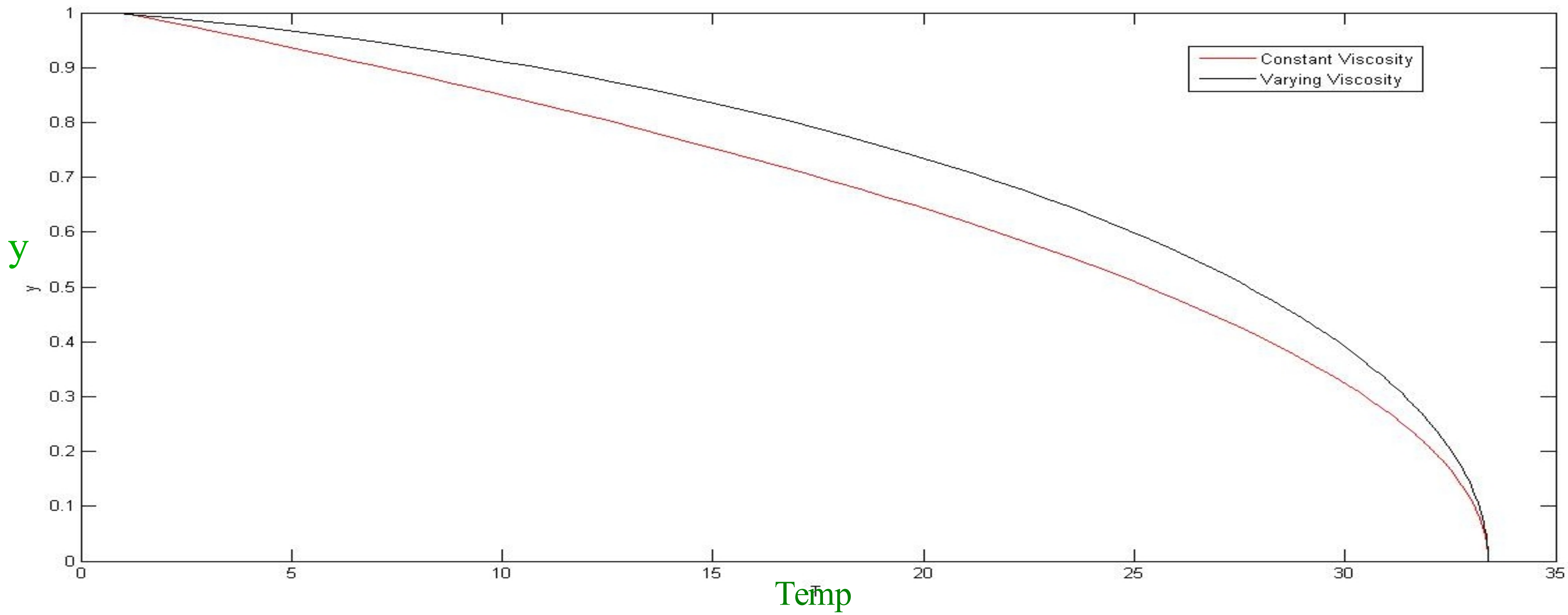


Effect of Viscosity startification
(For a Couette flow)

Comparison of boundary layer profiles for uniform vs stratified viscosity case

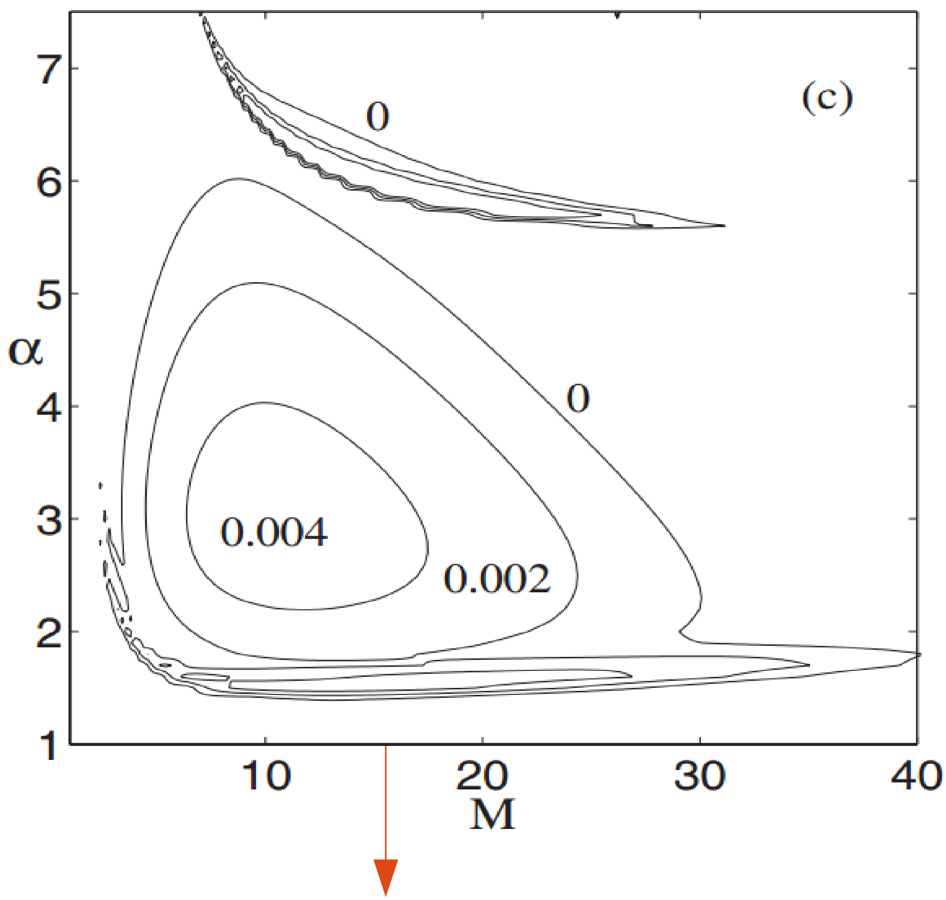


M=15

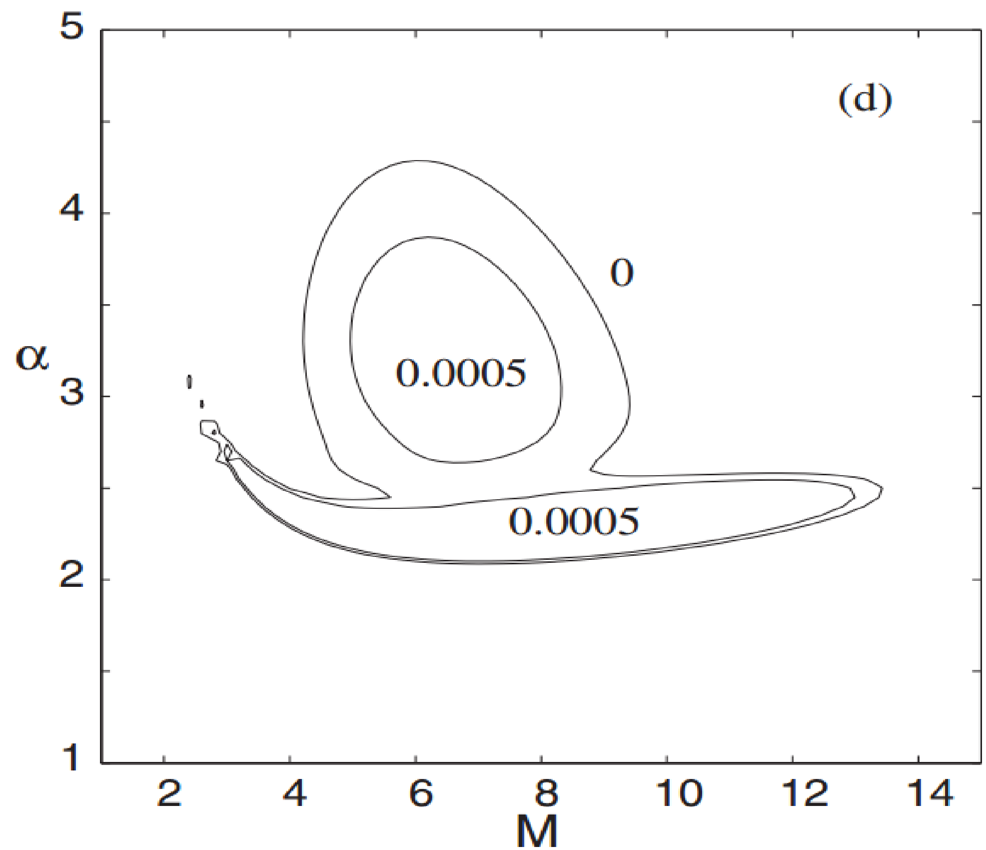


Comparison of stability profiles for Re=5*10^5 & β=0

Uniform viscosity

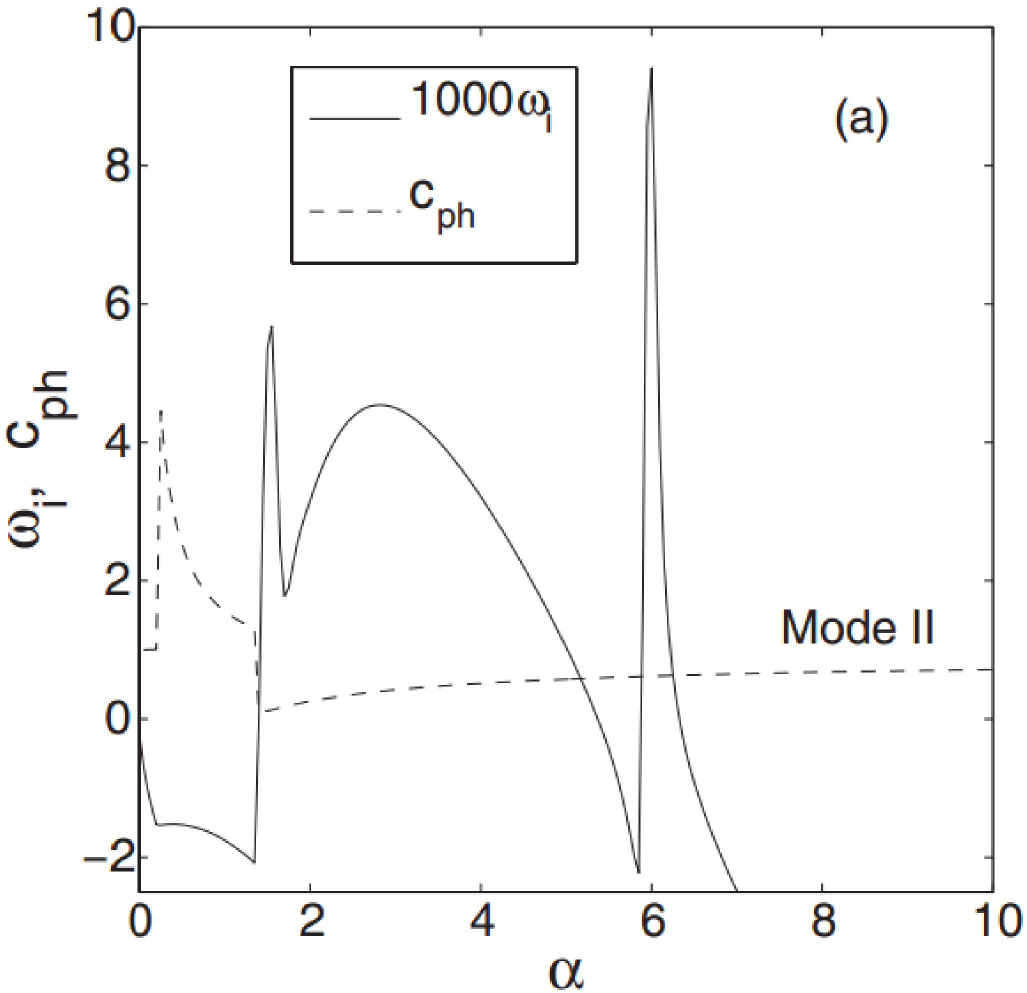


Startified viscosity

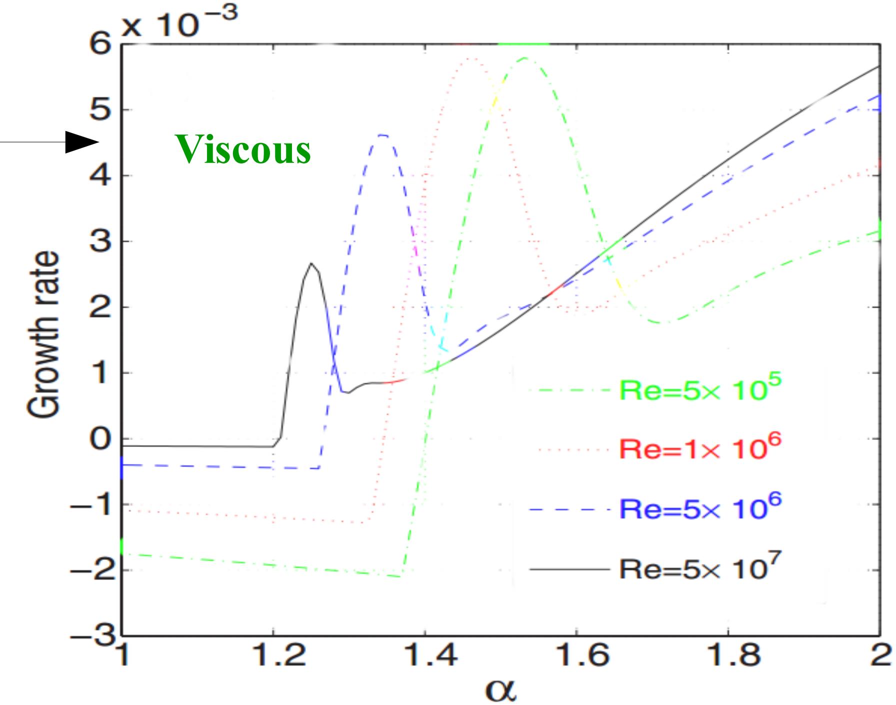


- One additional unstable loop
- One order of magnitude higher growth rate
- Range of α & M is large over which flow is unstable

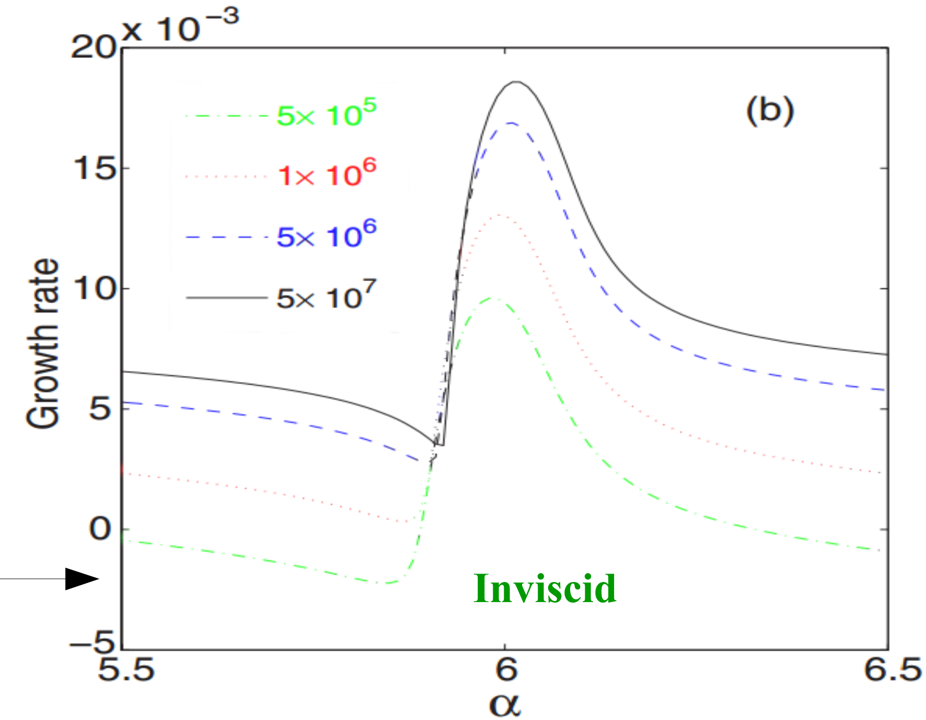
Variation of growth rate & phase speed for M=15 (UVF)



2nd peak



Highest peak



Difference between critical Re for uniform & non-uniform shear

	Uniform Shear		Non-unform shear	
Mach No.	Re_{cr}	α_{cr}	Re_{cr}	α_{cr}
3	50060	2.545	164900	2.840
5	23830	2.130	85725	2.570
10	45040	1.870	252700	2.485
15	85150	1.810	655850	2.490

Critical Re for uniform shear flow is smaller compared to its non uniform counterpart

Effects of viscosity

For Mode II

- Plays a dual role
- ➔ At small wave number it destabilizes the flow
- ➔ At moderate to high wave number its affect is stabilizing

For Mode I

- Destabilizing

Both for startified as well as uniform shear flow

References

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