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14. ABSTRACT A novel method to delay transition in hypervelocity flows in air over slender bodies by injecting CO ₂ into the boundary layer is presented. The dominant transition mechanism in hypersonic flow is the inviscid second (Mack) mode, which is associated with acoustic disturbances which are trapped and amplified inside the boundary layer [8]. In dissociated CO ₂ -rich flows, nonequilibrium molecular vibration damps the acoustic instability, and for the high-temperature, high-pressure conditions associated with hypervelocity flows, the effect is most pronounced in the frequency bands amplified by the second mode [3]. Experimental data were obtained in Caltech's T5 reflected shock tunnel. The experimental model was a 5 degree half-angle sharp cone instrumented with 80 thermocouples, providing heat transfer measurements from which transition locations were from turbulent intermittency based upon laminar and turbulent heat flux correlations. An appropriate injector was designed and fabricated, and the efficacy of injecting CO ₂ in delaying transition was gauged at various mass flow rates, and compared with both no injection and chemically inert Argon injection cases. Argon was chosen for its similar density to CO ₂ . At an enthalpy of approximately 10 MJ/kg (Eckert's reference temperature $T_r = 2550$ K), transition delays in terms of Reynolds number were documented. For Argon injection cases at similar mass flow rates, transition is promoted.					
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Effect of gas injection on transition in hypervelocity boundary layers

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AFOSR Grant F49620-IHOUSE07E0000

October 20, 2011



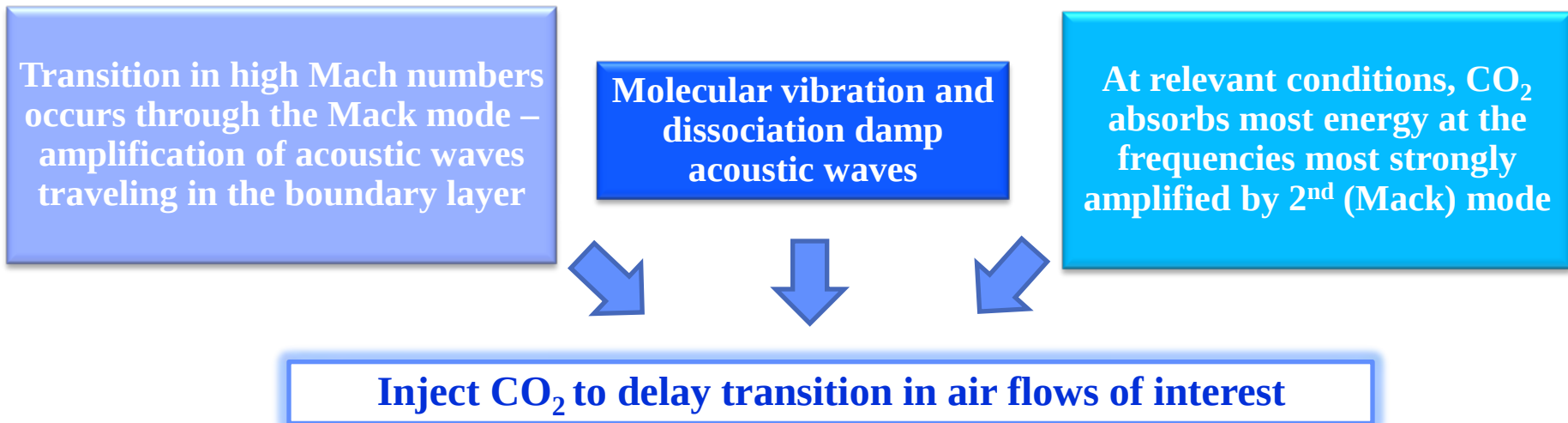
Delay transition using non-equilibrium CO₂

PROBLEM: In hypersonic flight, heating loads are typically a dominant design factor

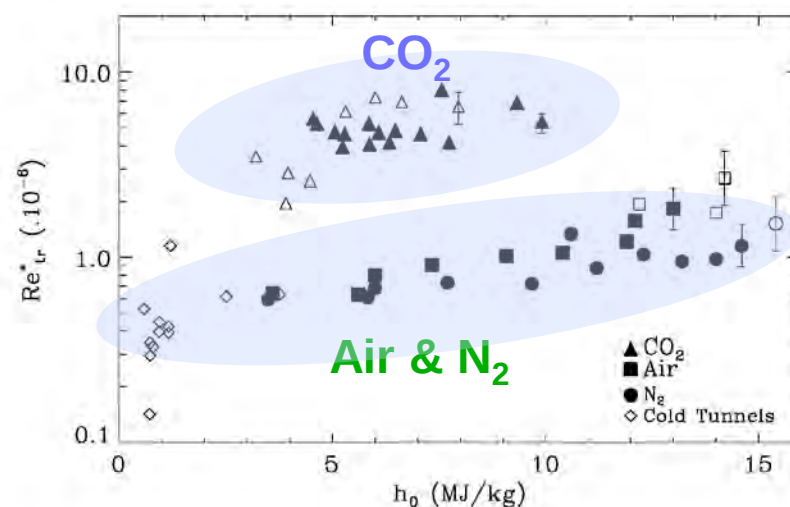
Turbulent heat transfer rates can be about an order of magnitude higher than laminar rates at hypersonic Mach numbers

A reduction in heating loads by keeping the boundary layer laminar longer means less thermal protection needed and hence less weight to carry, or conversely more payload deliverable for a given thrust.

OBJECTIVE: Delay transition from laminar to turbulent flow in the boundary layer of a slender hypersonic body by using nonequilibrium CO₂



- Experimental data show that transition is delayed for CO₂ flows compared with N₂ and air flows for a given stagnation enthalpy, h_0
- These observations point to a second mode transition (or Mack mode) for the conditions studied as well as to the importance of non-equilibrium effects of CO₂ on stabilizing the flow



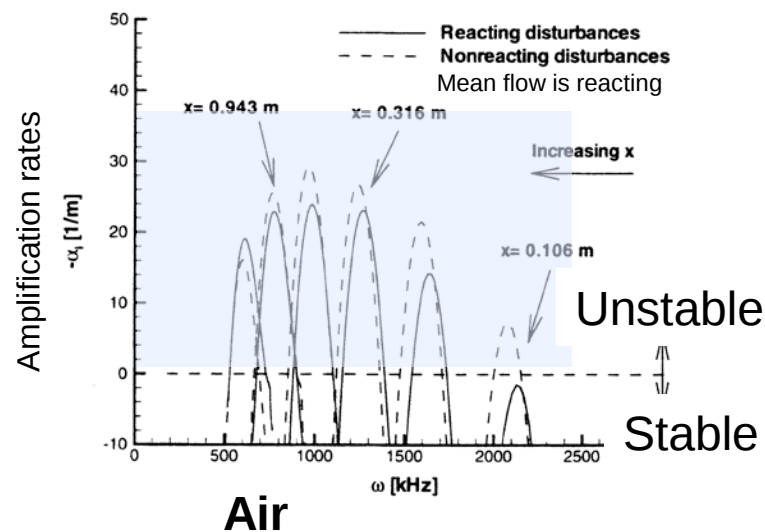
CO₂ Transition Re^* is
about 5X that of Air and N₂

From Hornung, H.G., Adam, P.H., Germain, P., Fujii, K., Rasheed, A., "On transition and transition control in hypervelocity flows," *Proceedings of the Ninth Asian Congress of Fluid Mechanics*, 2002

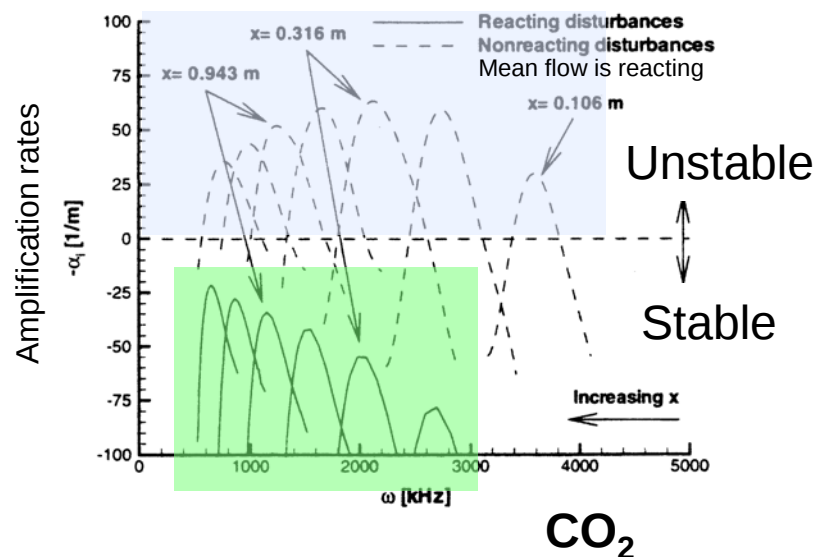
Computations show that when pure CO_2 is in vibrational and chemical non-equilibrium, these relaxation processes absorb energy from acoustic disturbances in the boundary layer whose growth is responsible for transition in hypervelocity flows

Confirms trends seen in experiments where CO_2 exhibits delayed transition with respect to Air or N_2 for $h_0 \sim 5\text{--}10\text{ MJ/kg}$

For air – no effect from vibrational relaxation and chemical reactions on stabilizing the boundary layer

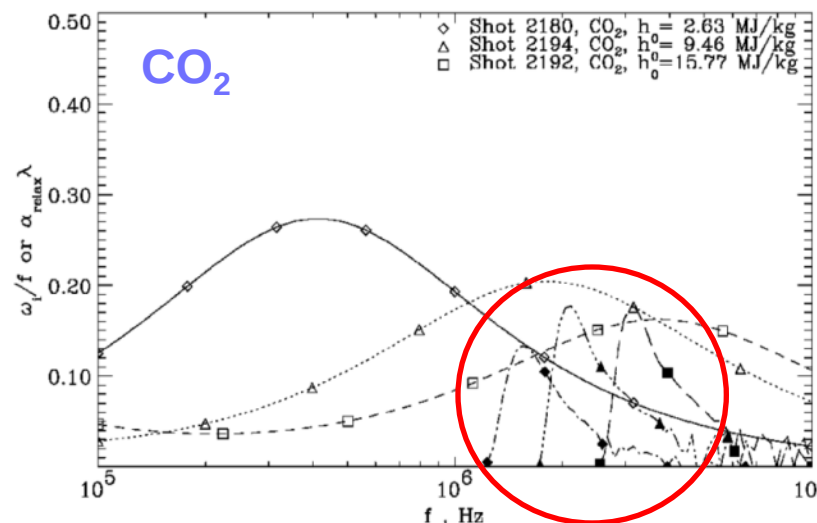
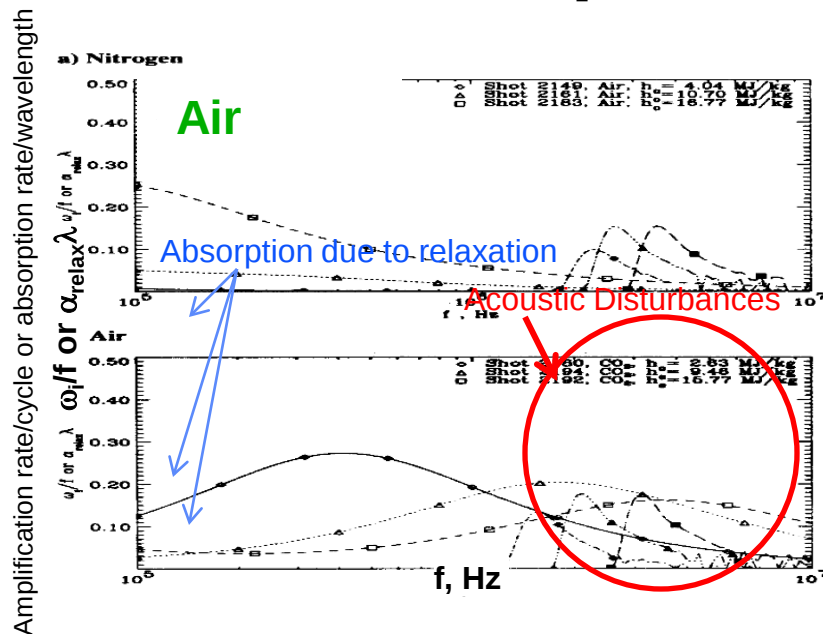


For CO_2 – vibrational relaxation and chemical reactions stabilizes the boundary layer

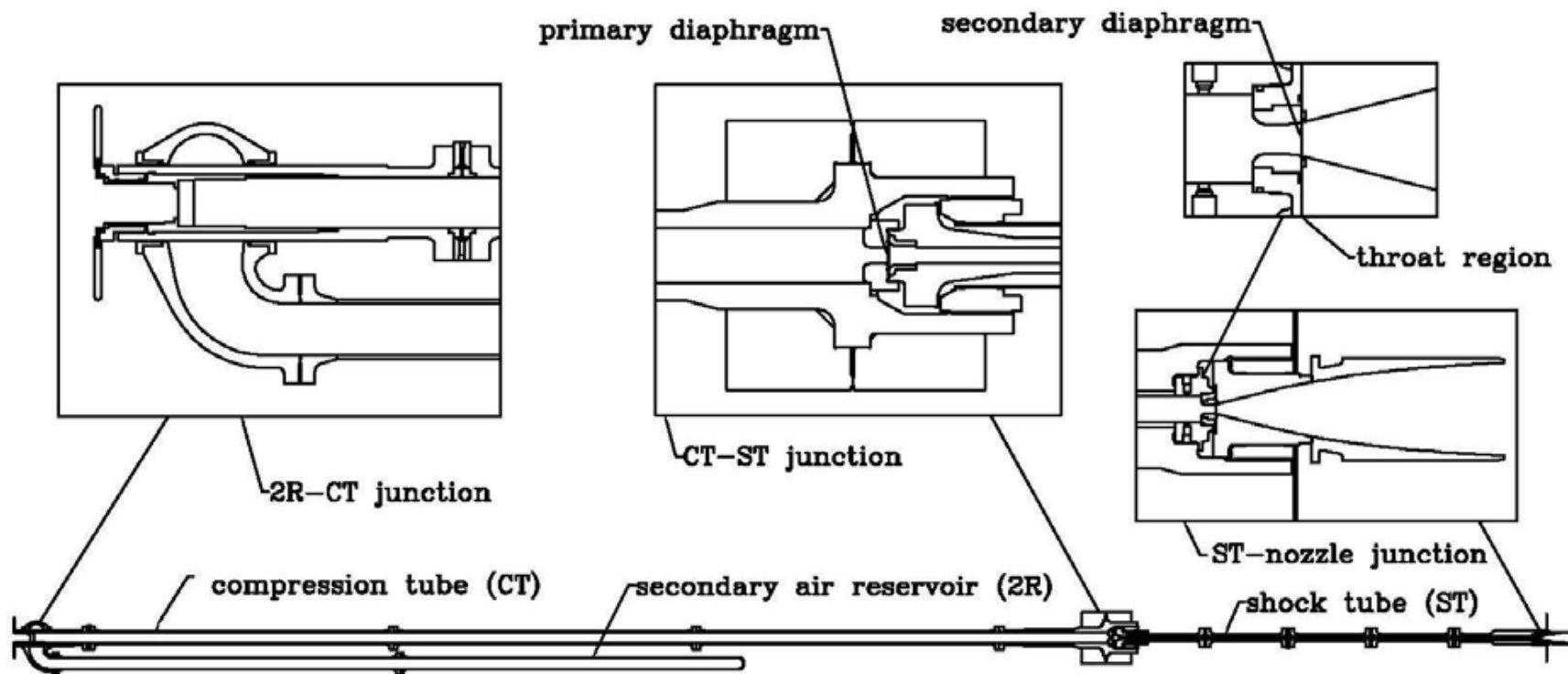


From Johnson, H.B., Seipp, T.G., Candler, G.V., "Numerical study of hypersonic reacting boundary layer transition on cones," *Physics of Fluids*, 10 (10): 2676-2685 Oct. 1998.

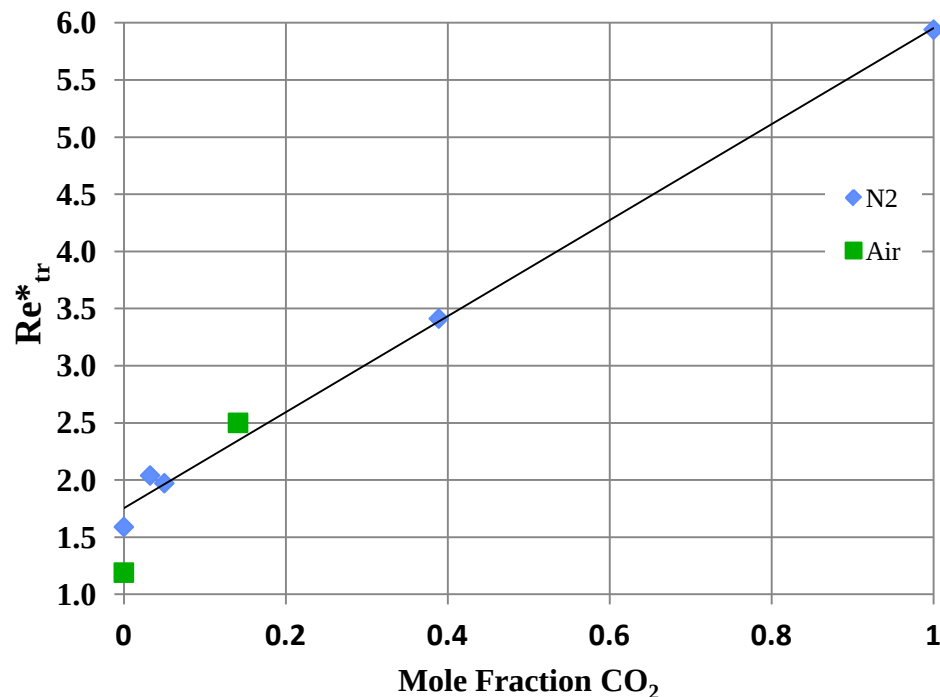
- Computed acoustic absorption rates (open symbols) – Fujii et. al
- Computed acoustic amplification rates (solid symbols) – after Reshotko/Beckwith and Mack
- For CO₂ the broad sound absorption curve peak coincides with the amplification peaks
- This coincidence is most pronounced at enthalpies of ~10 MJ/kg



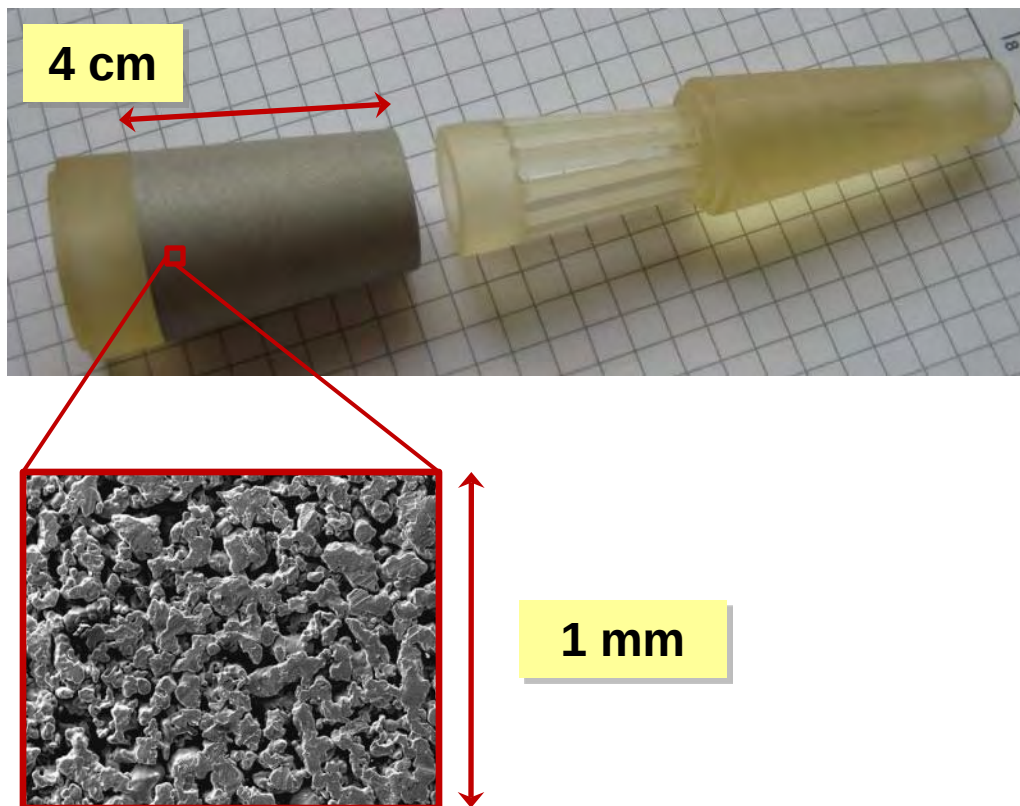
From: Fujii, K., Hornung, H.G, "Experimental Investigation of High-Enthalpy Effects on Attachment-Line Boundary Layer Transition," AIAA Journal, Vol. 41, No. 7, July 2003



Impulse Facility, test time in the order of ms, but high stagnation enthalpies and pressures



From Leyva, IA, Laurence, S, Beierholm, AK-W, Hornung, HG, Wagnild, R, and Candler, G, "Transition delay in hypervelocity boundary layers by means of CO₂/acoustic instability interactions," 47th AIAA Aerospace Sciences Meeting, AIAA 2009-1287.

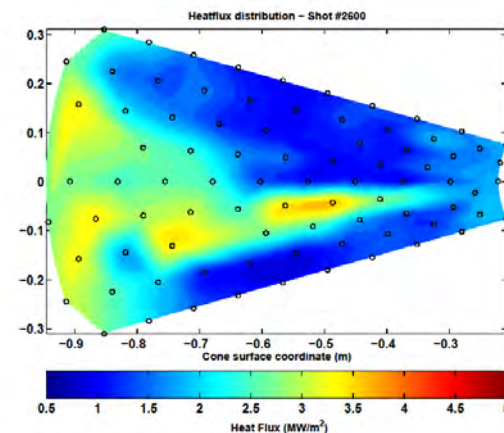
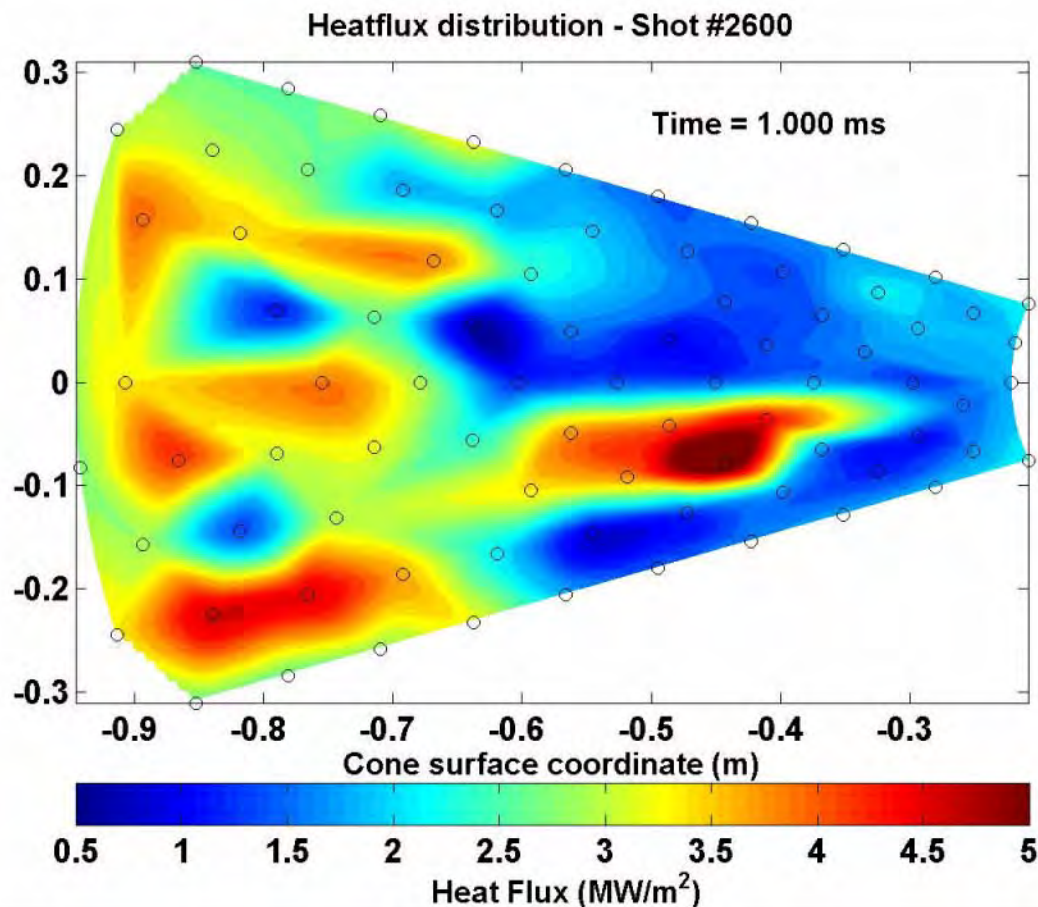


Porous Injector Rationale

- Move to a transpiration-like approach instead of discrete jets
- High velocity jets disturbed the boundary layer – penetrate to shock layer
- Need lower flow penetration into the boundary layer
- Can achieve same flow rates as with jets ~ 0-50 g/s

Porous injector section
Sintered 316LL Stainless Steel
10 μ m media grade

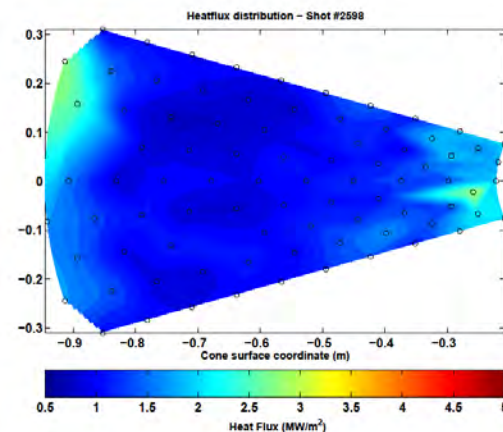
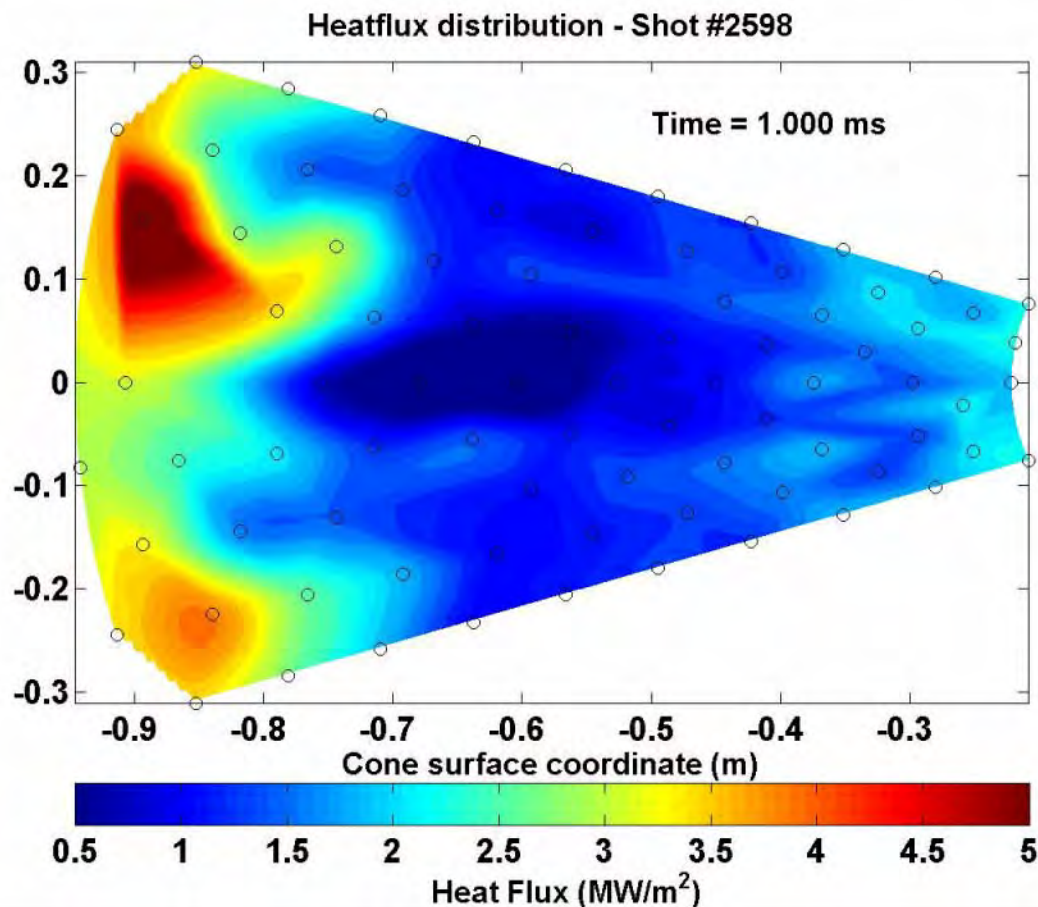
10-micron Porous Injector (Ar injection at 3.7 grams/sec)



Average over test time

(1.500 – 2.100 ms)

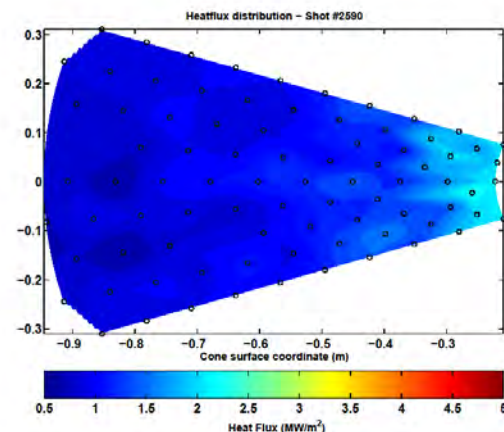
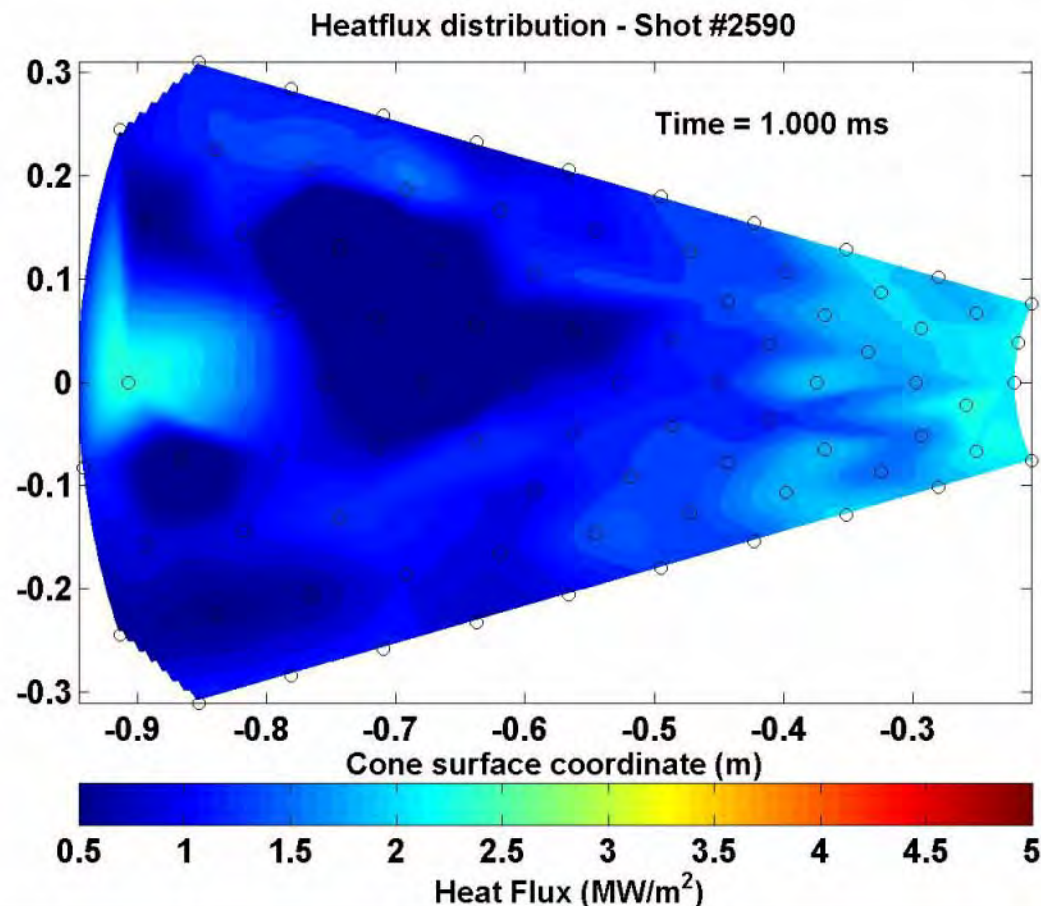
10-micron Porous Injector (no injection)



Average over test time

(1.500 – 2.100 ms)

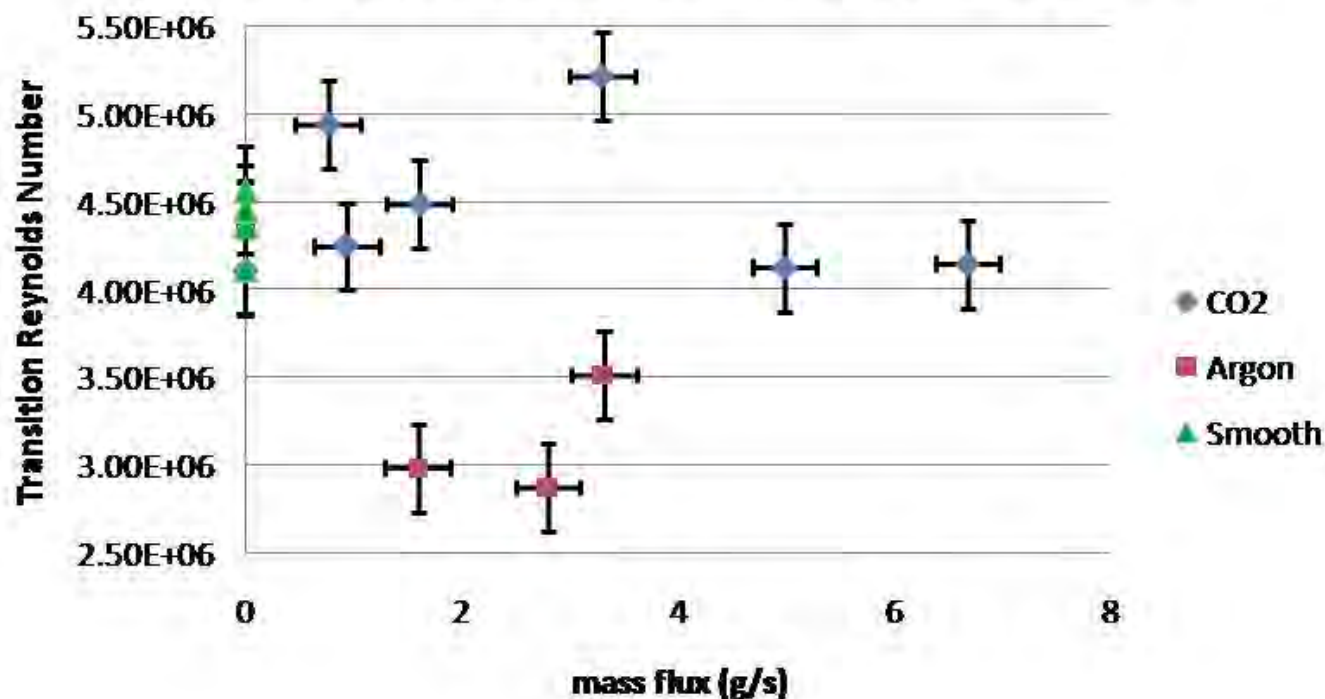
10-micron Porous Injector (CO_2 injection at 3.7 grams/sec)



Average over test time

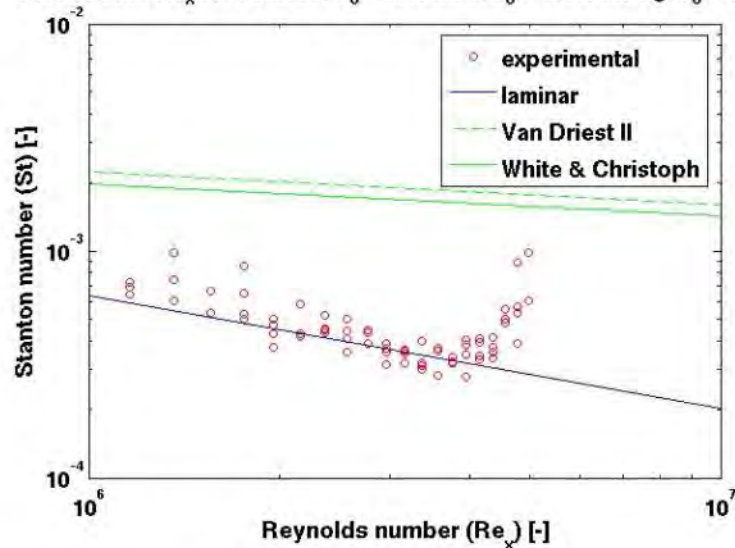
(1.500 – 2.100 ms)

Re vs. injection @ ~10 MJ/kg, ~55 MPa

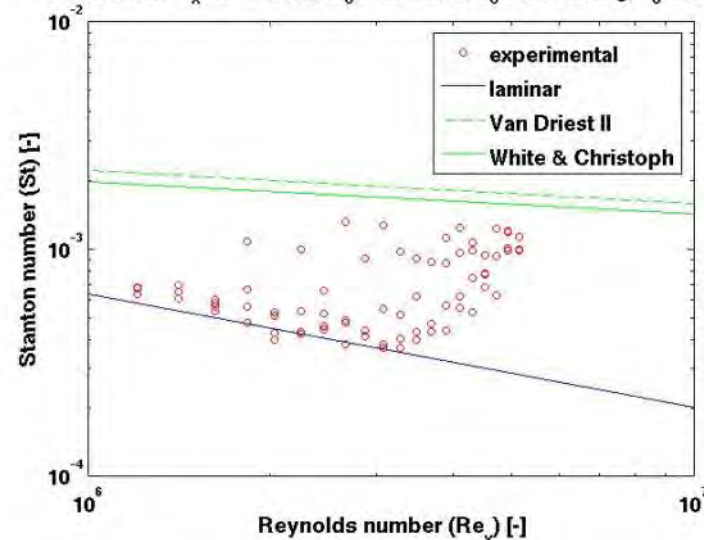


Data reduction: Average Heat Transfer Method

Plot of St vs Re_x for T5-2598; $P_0 = 55.3$ MPa, $h_0 = 10.26$ MJ/kg, $T_0 = 6204$ K

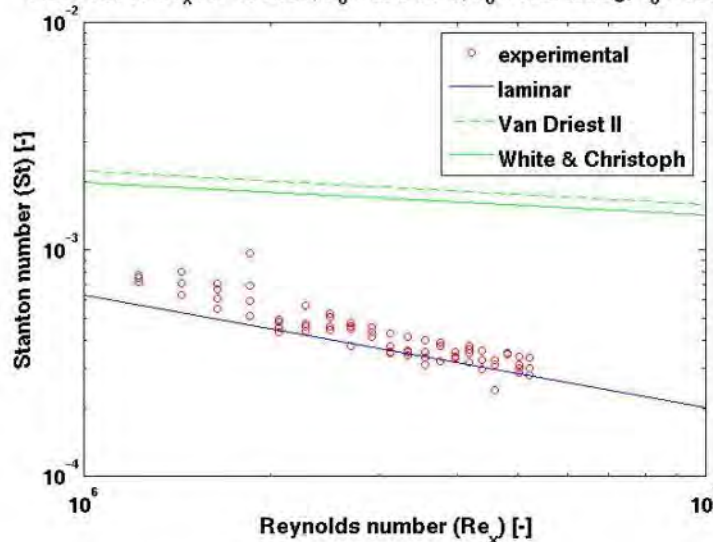


Plot of St vs Re_x for T5-2600; $P_0 = 54.7$ MPa, $h_0 = 9.88$ MJ/kg, $T_0 = 6044$ K



No injection: porous section

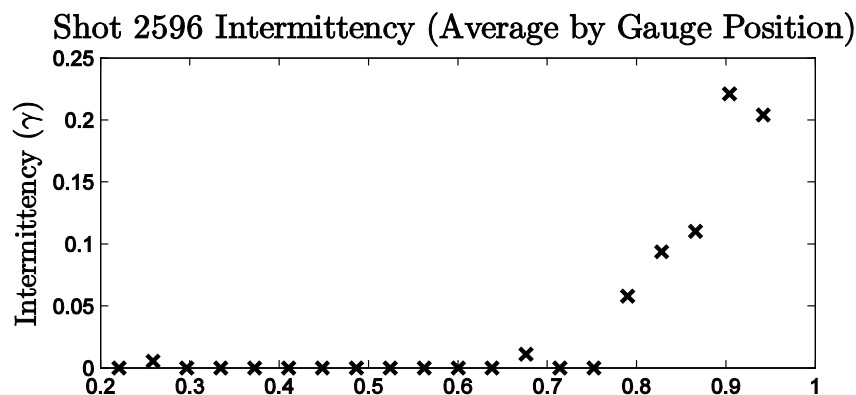
Plot of St vs Re_x for T5-2590; $P_0 = 55.9$ MPa, $h_0 = 9.92$ MJ/kg, $T_0 = 6064.3$ K



Argon Injection: 3.7 g/s

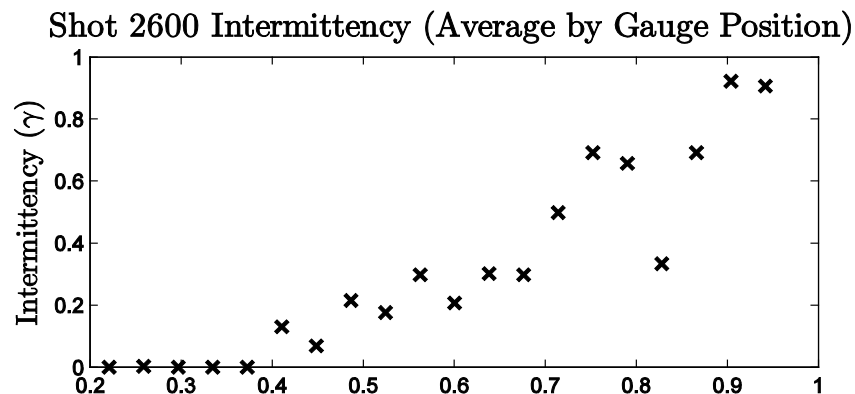
CO2 injection: 3.7 g/s





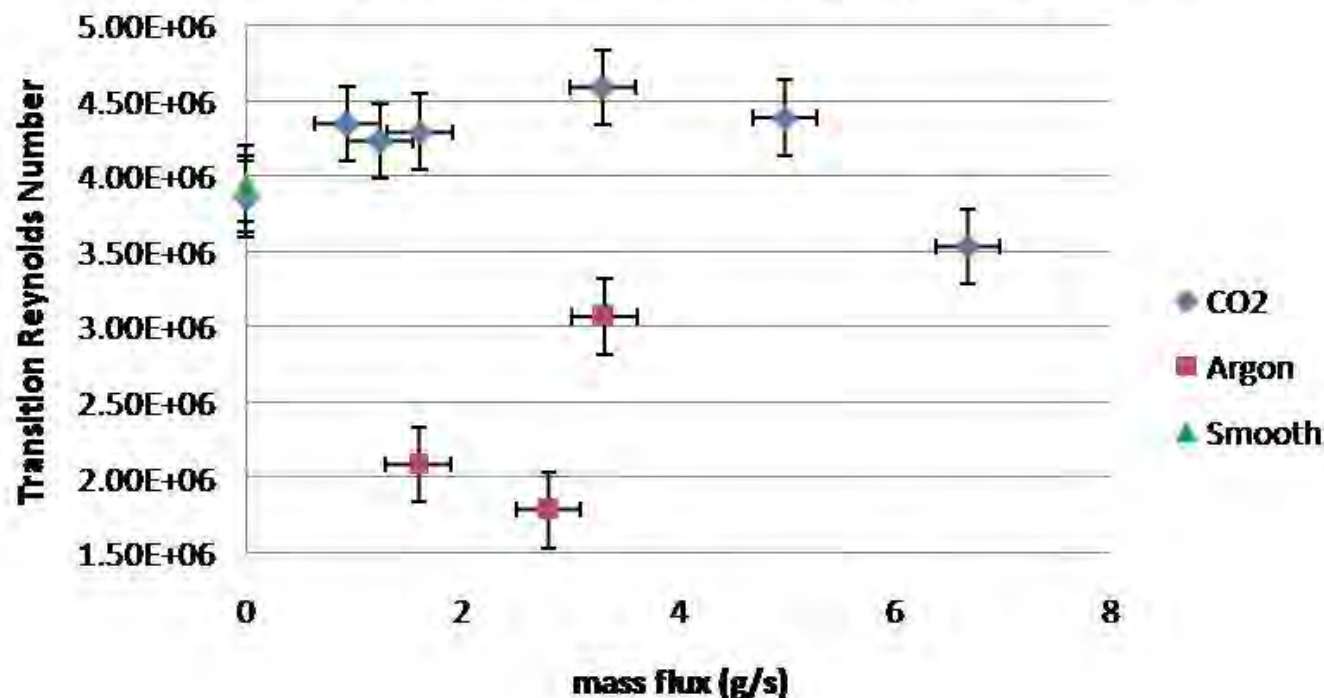
Turbulent intermittency

- Mee D.J. and Goyne C.P. (1996) Turbulent spots in boundary layers in a free-piston shock tunnel flow. Shock Waves, Vol. 6, No. 6:337–343.
- Narasimha R. (1985) The Laminar-Turbulent Transition Zone in the Boundary Layer. Progress in Aerospace Sciences, Vol. 22, 29–80.



Alternate method to determine transition location

Re vs. injection @ ~10 MJ/kg, ~55 MPa



**Summary of results
(intermittency method)**

- Free-stream gas is Nitrogen
- Different injection geometry
 - 5 degree cone, transpiration from 10 to 90 cm on the cone

Stagnation Conditions		Free-stream Conditions	
Pressure (MPa)	55.0	Density (kg/m ³)	0.051855
Temperature (K)	6958	Temperature (K)	925.5
Enthalpy (MJ/kg)	9.39	Velocity (m/s)	4039.7

- Injection based on profile suggested by Malik*
 - $\dot{m}$ based on edge conditions and parameter, f_w

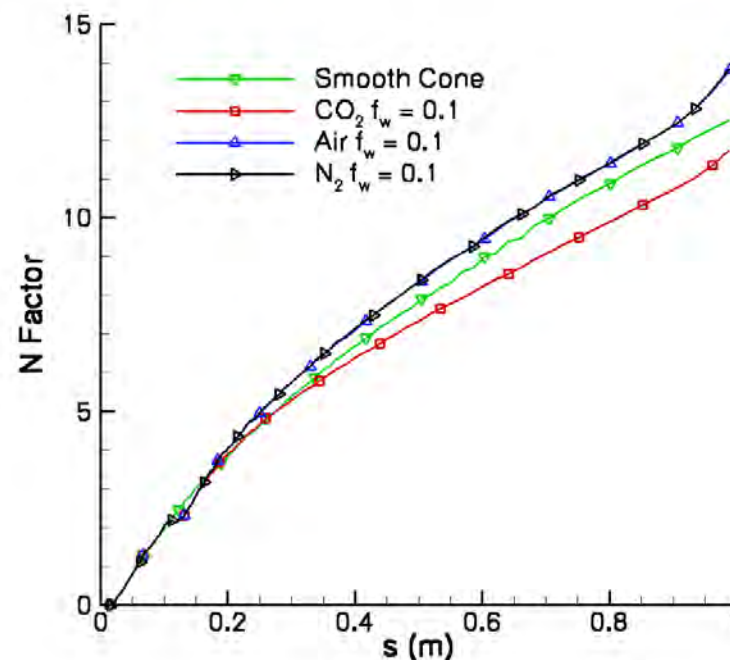
- For these cases, f_w held constant
 - Mass flux decreases down the length of the cone

$$f_w = \frac{\sqrt{2 \text{Re}_x} \rho_w v_w}{\rho_e v_e}$$

f_w	Mass Flux (g/s)
0.05	1.24
0.1	2.47
0.2	4.96
0.3	7.43
0.4	9.92
0.6	14.88

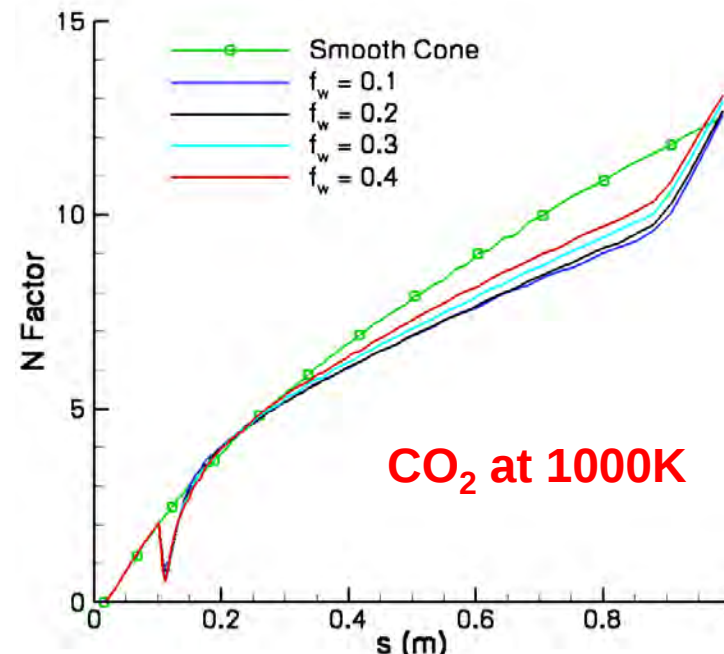
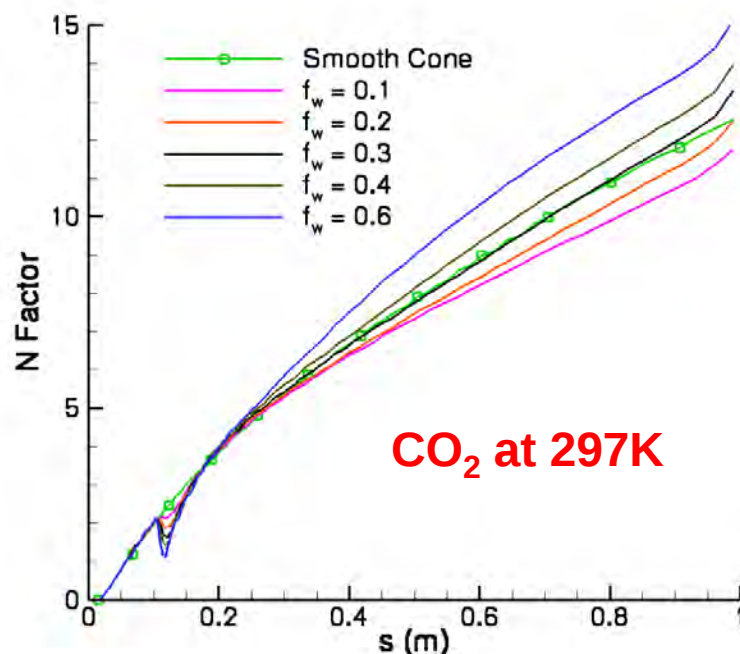
*Malik, M. R., "Prediction and Control of Transition in Supersonic and Hypersonic Boundary Layers," AIAA Journal, vol. 27, no. 11, November 1989, pp. 1487-1493.

- Transition occurs at $N = \sim 9.2$
- Significant transition delay vs. smooth cone for CO₂
- Air and N₂ injection both *promote* transition
- Mass flux = 2.5 grams/sec (but over entire surface; “Malik cone”)
- Smooth cone, $x_{tr} = 63$ cm



N factor versus distance
along cone surface

From Wagnild et al 2010

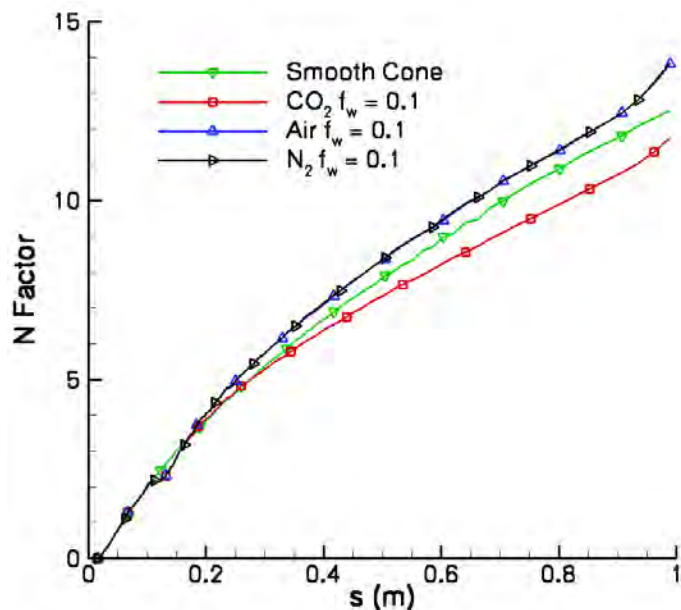


- **Transition delay predicted**
 - Increase in CO₂ initially results in further delay but further increase causes more amplification
- **For $N_{cr} = 9.2$**
 - Smooth cone, $x_{tr} = 63$ cm, $f_w = 0.1$, $x_{tr} = 72$ cm

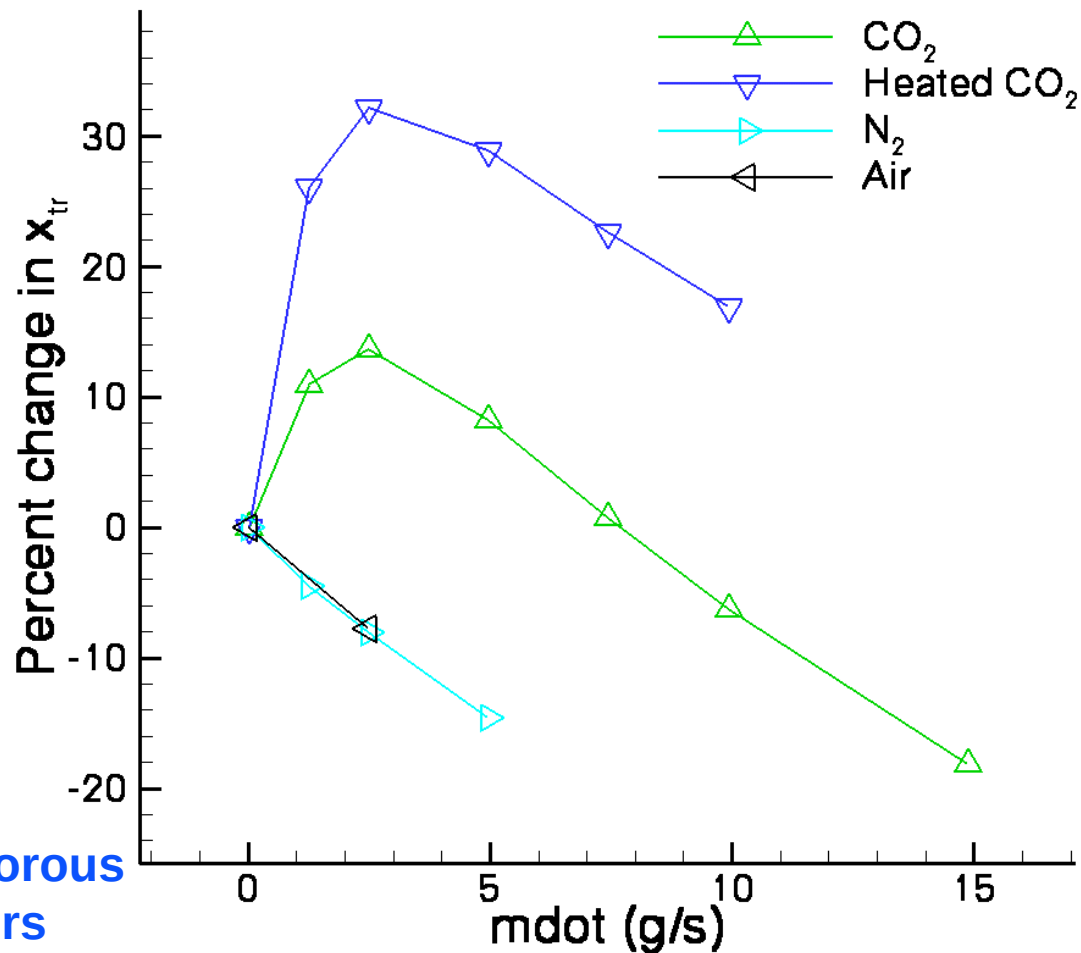
- **Pre-heating further delays transition**
 - CO₂ able to absorb acoustic energy earlier
 - Higher temperature gas could also contribute
- **For $N_{cr} = 9.2$**
 - Smooth cone, $x_{tr} = 63$ cm
 - $f_w = 0.1$, $x_{tr} = 83$ cm

From Wagnild et al 2010

Effect of gas and Temperature on Transition Delay: CFD predictions



Alternate gases only
increase disturbance



CFD predicts that for the current porous design and longer porous injectors transition could be delayed for optimum flow rates and temperature of CO_2

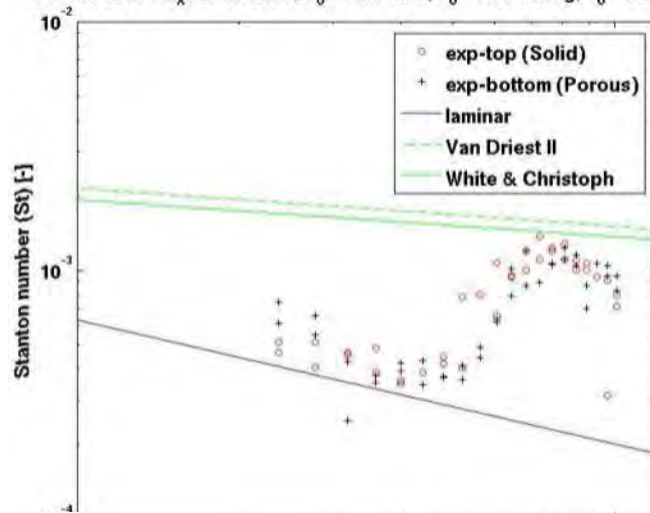
- **Aerospace America 2009 – Year in Review: Fluid Mechanics**
“AFRL, Caltech, and the University of Minnesota have collaborated in a numerical and experimental study on control of high-speed boundary layers. The team has demonstrated significant delays in transition”
- **Annual Reviews of Fluid Mechanics 2011, 43:79-95. – Federov, A.**
“Transition and Stability of High-Speed Boundary Layers”:

“..Another way to stabilize the second mode and thereby delay transition is to add CO₂ into high enthalpy boundary-layer flow (Leyva et al. 2009). The motivation for this new technique lies in the following findings: Molecular vibration and dissociation suppress the acoustic instability, and at relevant conditions for hypersonic flight, CO₂ absorbs energy most strongly in the frequency band associated with the second mode.

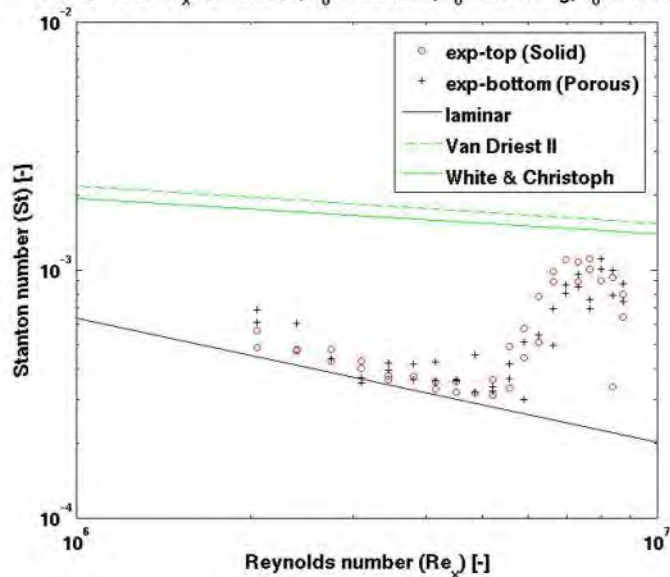
The experiments of Leyva et al. (2009) on a sharp slender cone in the GALCIT T5 tunnel showed that the CO₂/N₂ free-stream blends (without injection) lead to significant delay of transition. The transition Reynolds number more than doubled for mixtures with 40% CO₂ mole fraction compared with the case of 100% N₂. A similar effect was noted in experiments using mixtures of air and CO₂ as the test gas. Experimental and numerical studies of the CO₂ injection system suitable for this LFC concept are in progress. The effect of the injection and the transition location is gauged by solving the PSEs and using the semiempirical *eN method* (Wagnild et al. 2010)..”

Half-Porous/Half-Smooth Injector

Plot of St vs Re_x for T5-2656; $P_0 = 78.4$ MPa, $h_0 = 7.59$ MJ/kg, $T_0 = 5128.1$ K

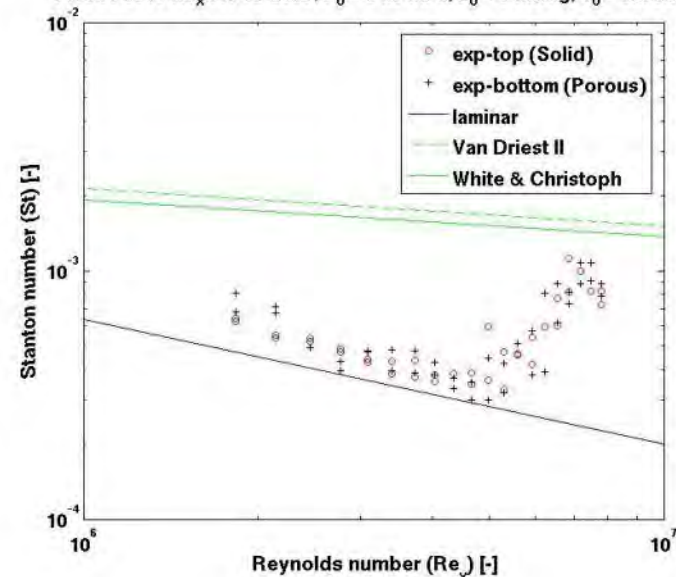


Plot of St vs Re_x for T5-2657; $P_0 = 78.3$ MPa, $h_0 = 8.6$ MJ/kg, $T_0 = 5577.5$ K

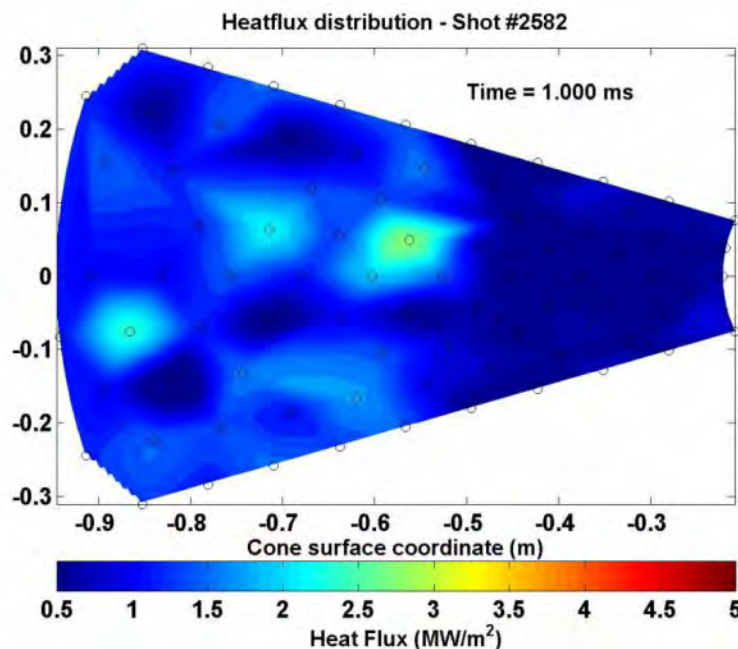


Reynolds number (Re_x) [-]

Plot of St vs Re_x for T5-2658; $P_0 = 64.8$ MPa, $h_0 = 8$ MJ/kg, $T_0 = 5278.9$ K



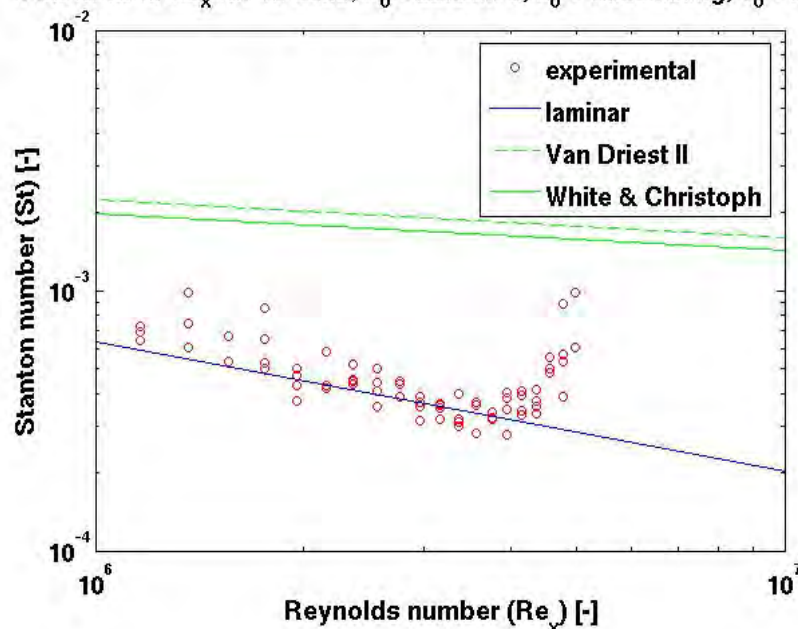
Reynolds number (Re_x) [-]



H_0 (MJ/kg)	P_0 (MPa)	T^* (Eckert)	T_{edge}
5.69 – 5.92	~ 30	1465 K	779 K
8.29	53.8	2149 K	1272 K
8.60	78.3	2246 K	1355 K
8.85	53.2	2295 K	1395 K
9.46 – 10.32	~55	2725 K	1728 K

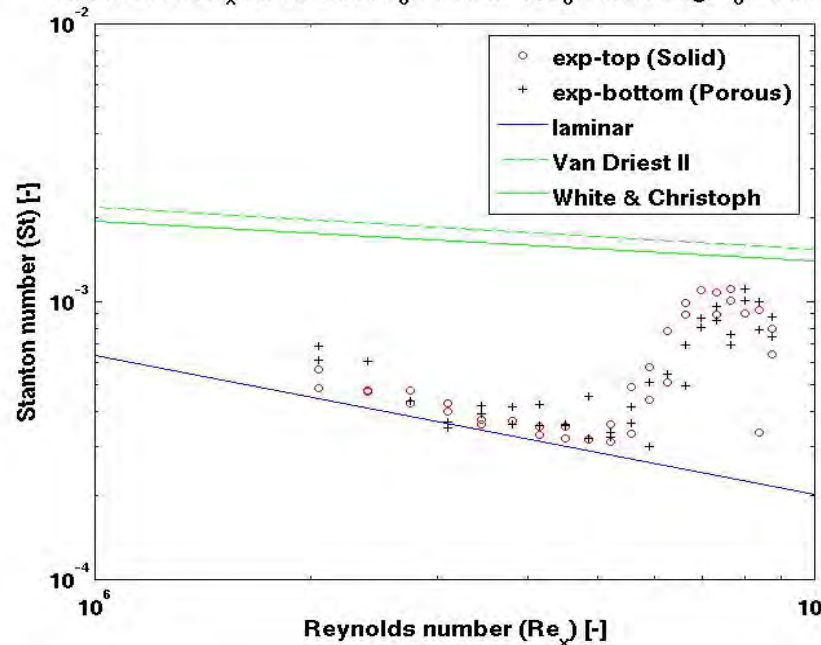
Latest →

Plot of St vs Re_x for T5-2598; $P_0 = 55.3$ MPa, $h_0 = 10.26$ MJ/kg, $T_0 = 6204$ K



10.3 MJ/kg, 55 MPa
Natural transition @ 72 cm
Delay observed

Plot of St vs Re_x for T5-2657; $P_0 = 78.3$ MPa, $h_0 = 8.6$ MJ/kg, $T_0 = 5577.5$ K



8.6 MJ/kg, 78 MPa
Natural transition @ 54 cm
Delay NOT observed

- In both cases, T^* and T_e are above the critical 960K for CO_2
- Why is delay not observed for injection in the case on the right?

Possible Explanation

- N-factor at transition is **similar** (5.0-5.6 for a noisy tunnel) in both cases
- N-factor at the injector section location (13.3 cm from the tip) is therefore **significantly higher** for the case with earlier natural transition (right hand plot on previous slide)
- To suppress the 2nd mode, mixing must be achieved at a **relatively low** (but not precisely known) N-factor

Variables to optimize for attaining delay by injecting CO₂

- N-factor at injection location
- $(T^* \text{ or } T_e \text{ of boundary layer base flow}) / (T_{vib} \text{ of CO}_2)$
- $(\text{mixing distance for CO}_2 \text{ with boundary layer base flow}) / (\text{cone length})$
- $(\text{CO}_2 \text{ mass flow rate}) / (\text{boundary layer base mass flow})$

Collaboration with Alexander Fedorov – Moscow Inst of Physics and Tech

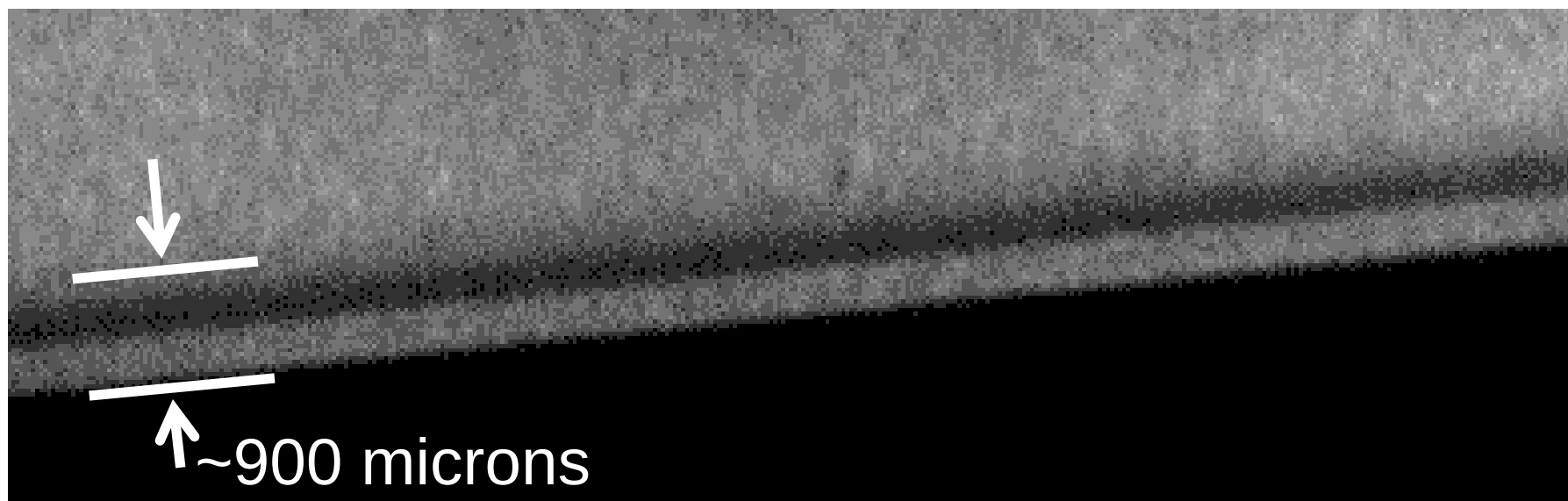
- Determine how low the N-factor at injection must be, and where this physically occurs on the cone
- Redesign of injector section to move it closer to the tip, achieving injection before the 2nd mode acoustic waves appear

- **At 10 MJ/kg enthalpy, demonstrated delay versus Argon injection and also versus a smooth injector**
 - **CO₂ does make a difference!**
- **Selected a new condition at about 8-9 MJ/kg for further study**
 - **Meant to show a greater effect because natural transition occurs near the middle of the cone**
 - **However, CO₂ injection did NOT seem to delay transition at this condition**
- **Designed and installed a half-porous, half-smooth porous injector**
 - **Provides a non-injection “control” with every injection experiment**
- **Collaboration with Alexander Federov to for theoretical/computational input into injector design and placement**

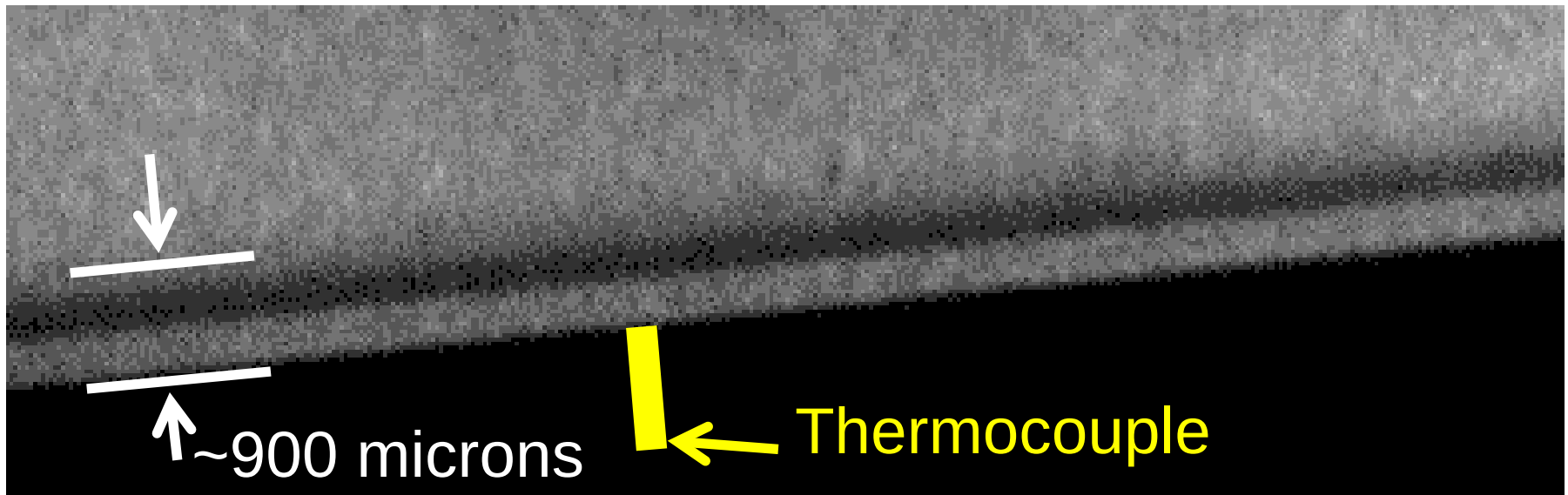
Questions ?

Back up

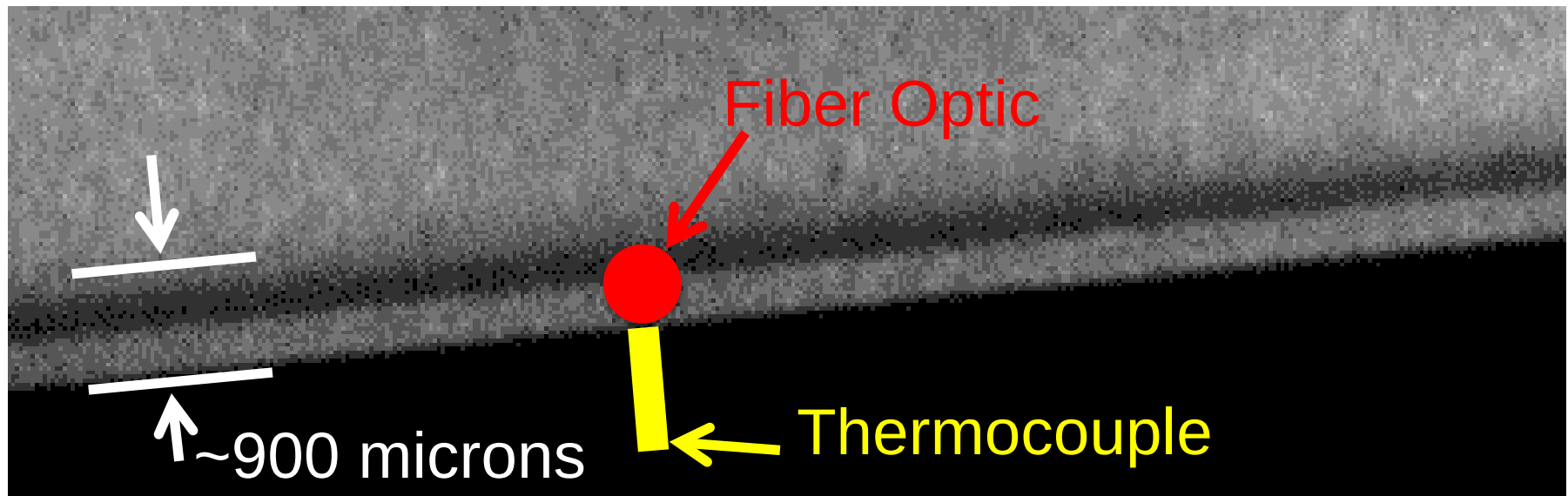
Preliminary results from resonantly enhanced field focused schlieren system (REFFSS)



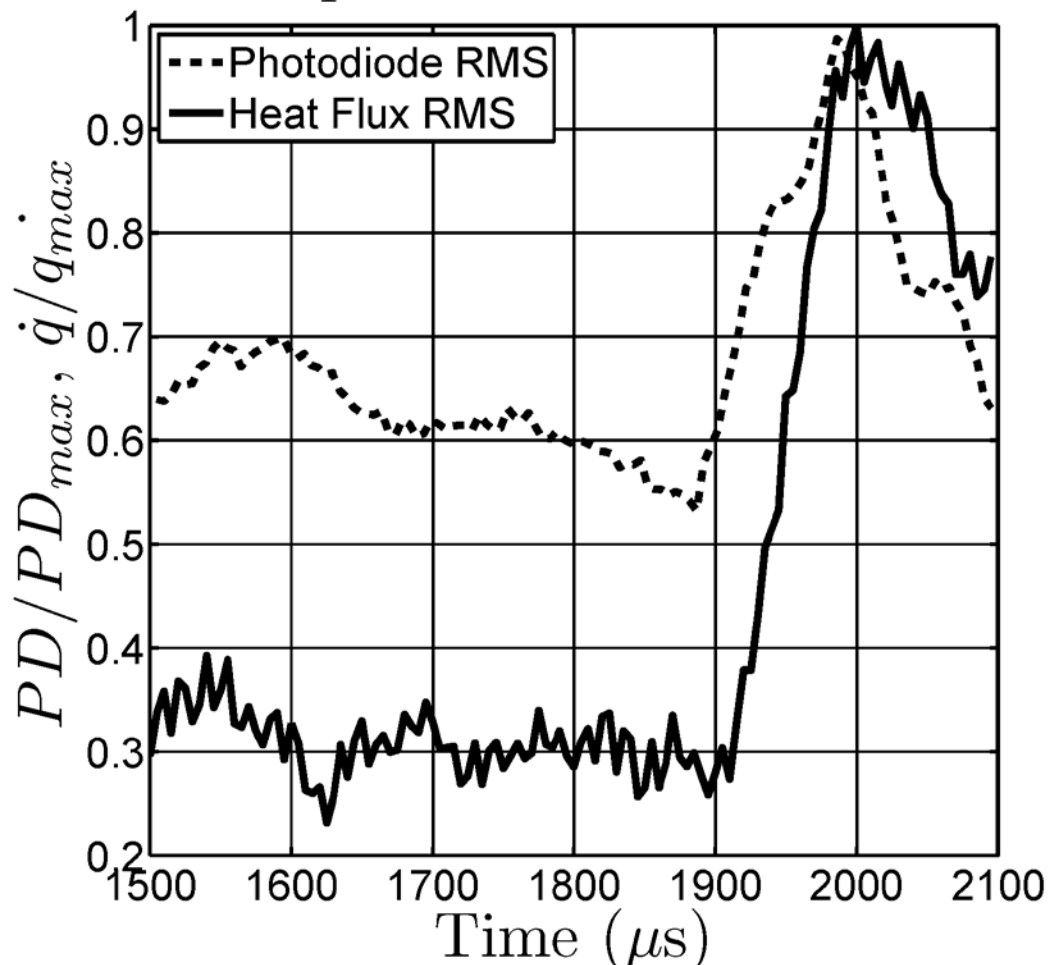
Preliminary results from resonantly enhanced field focused schlieren system (REFFSS)



Preliminary results from resonantly enhanced field focused schlieren system (REFFSS)

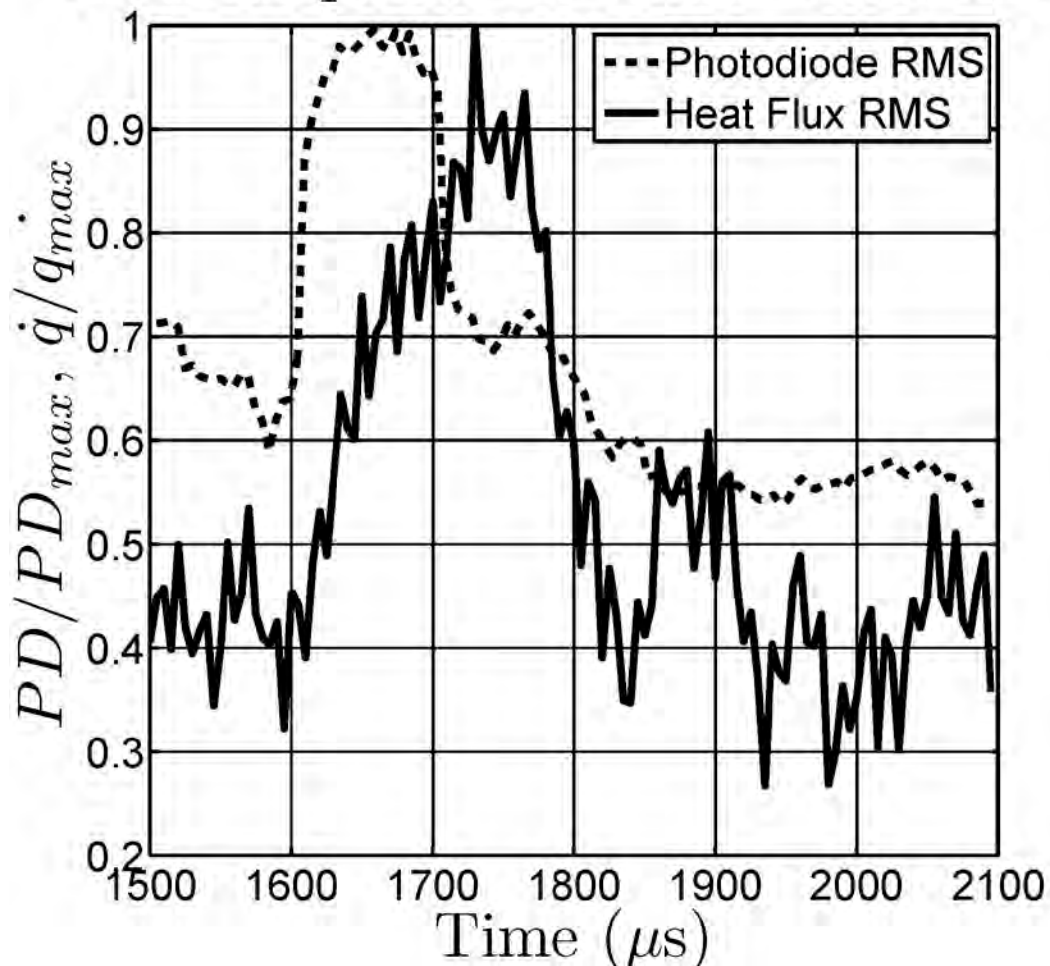


RMS Response vs. Time - Shot 2644



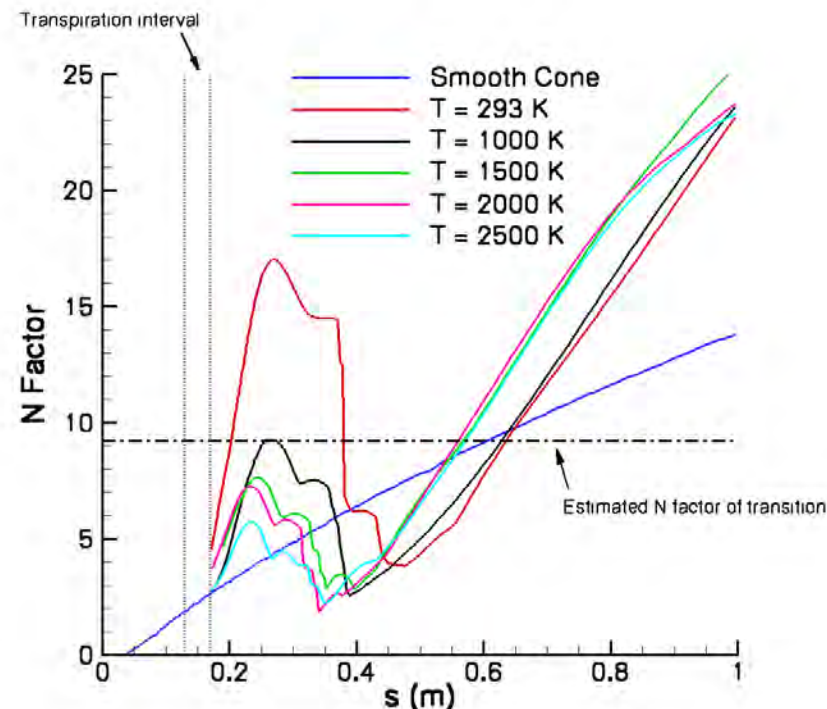
$h_R = 6 \text{ MJ/kg}$; $p_R = 50 \text{ MPa}$

RMS Response vs. Time - Shot 2647



$h_R = 6 \text{ MJ/kg}$; $p_R = 30 \text{ MPa}$

- **Baseline condition similar to shot 2541**
 - Test gas is air
 - Free-stream Mach is 5.3
 - Isothermal wall at 293 K
- **Pre-heated CO₂**
 - Momentum of injection matched with 13.5 g/s of cold carbon dioxide
- **Increase in heating results in decreased amplification**
 - Reduction in amplification more efficient near 1000 K

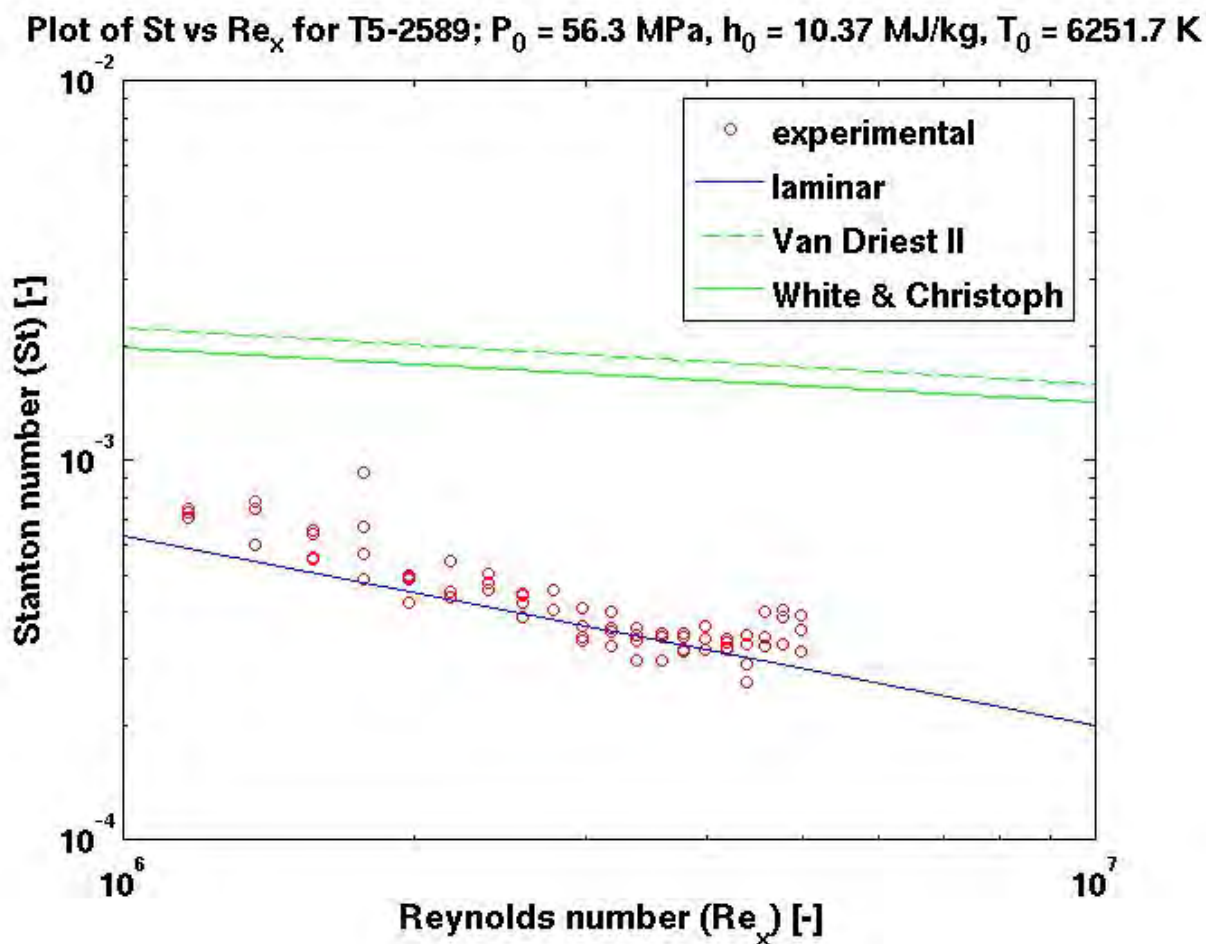


**N factor versus distance
along cone surface**

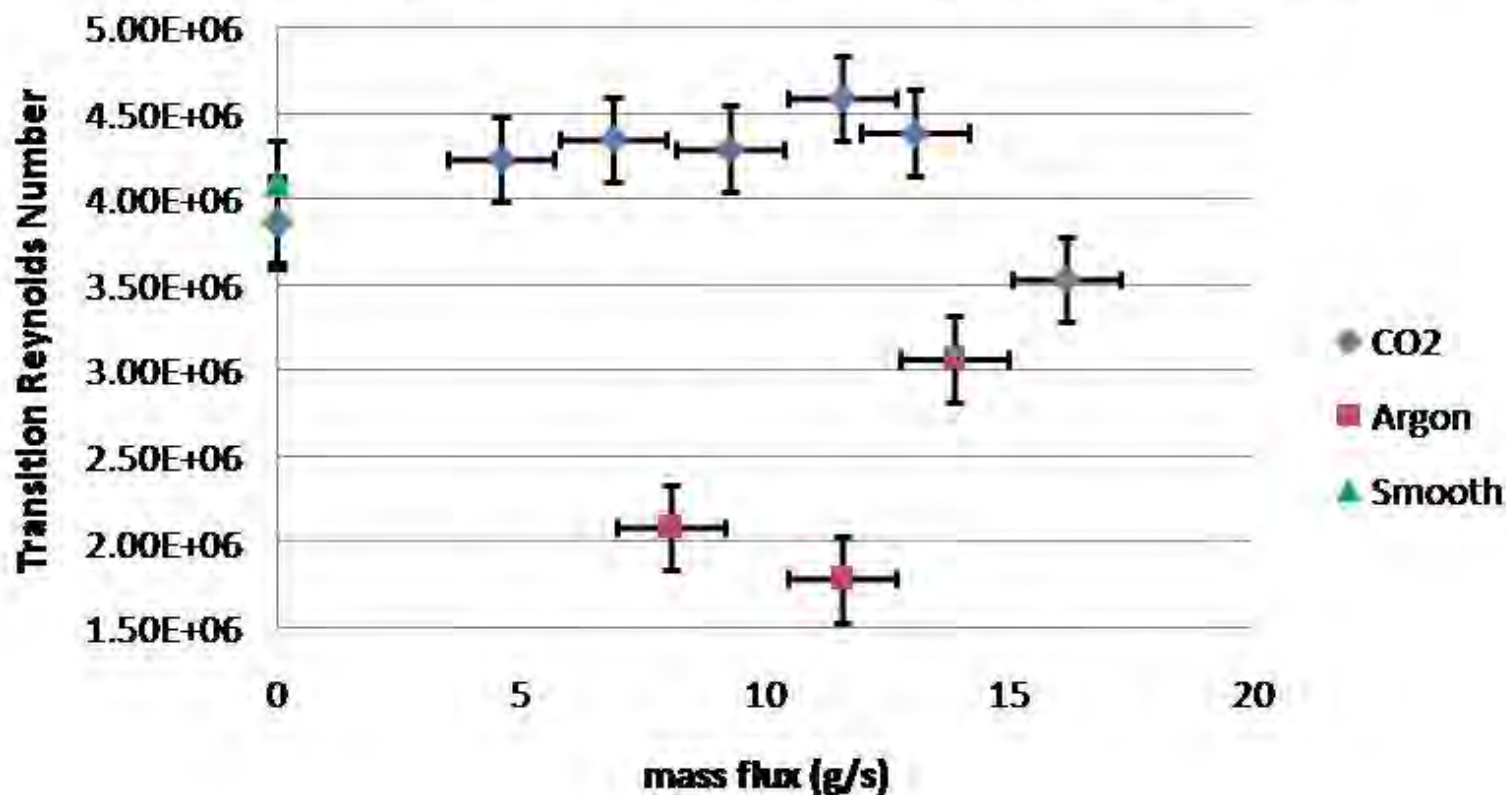
Stagnation Conditions		Free-stream Conditions	
Pressure (MPa)	50.92	Density (kg/m ³)	0.05572
Temperature (K)	5968.5	Temperature (K)	1369.4
Enthalpy (MJ/kg)	9.51	Velocity (m/s)	3957.9

- **Computations done using STABL software suite**
 - **Mean flow**
 - **2nd order accurate fluxes**
 - **Modified Steger-Warming**
 - **1st order Implicit DPLR method for time integration**
 - **Finite rate chemistry and T-V energy exchange**
 - **Disturbances**
 - **STABL PSE-chem solves the parabolized stability equations**
 - **PSE predict amplification of disturbances**
 - **Finite rate chemistry and T-V energy exchange**
 - **Semi-empirical e^N method used for determining transition location**

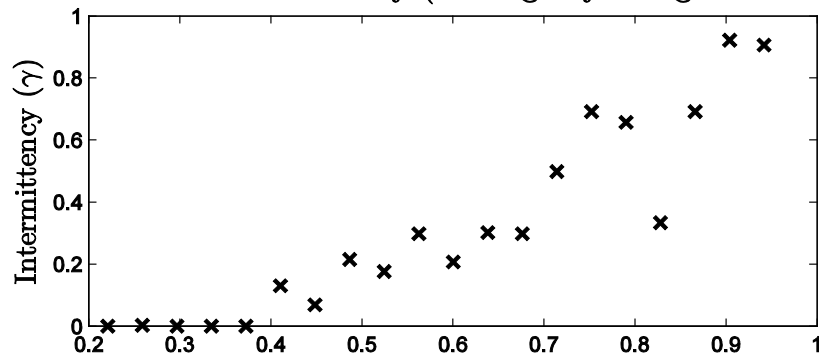
Transition Determination Uncertainty



Re vs. injection @ ~10 MJ/kg, ~55 MPa

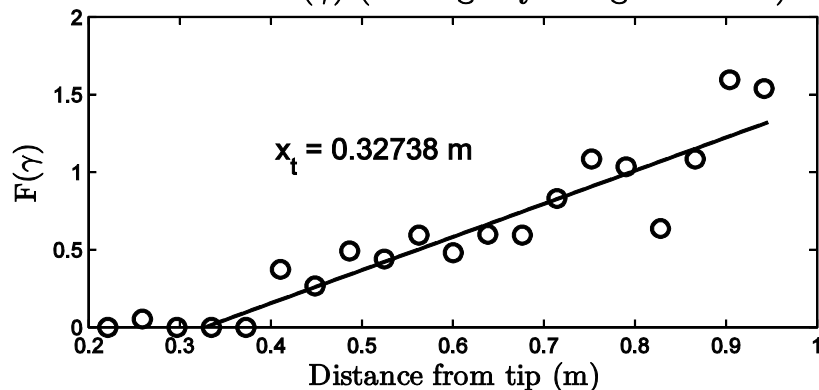


Shot 2600 Intermittency (Average by Gauge Position)

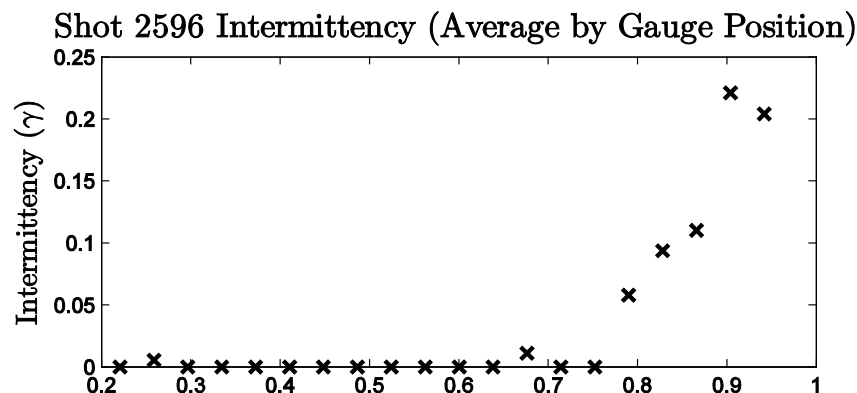


Turbulent intermittency

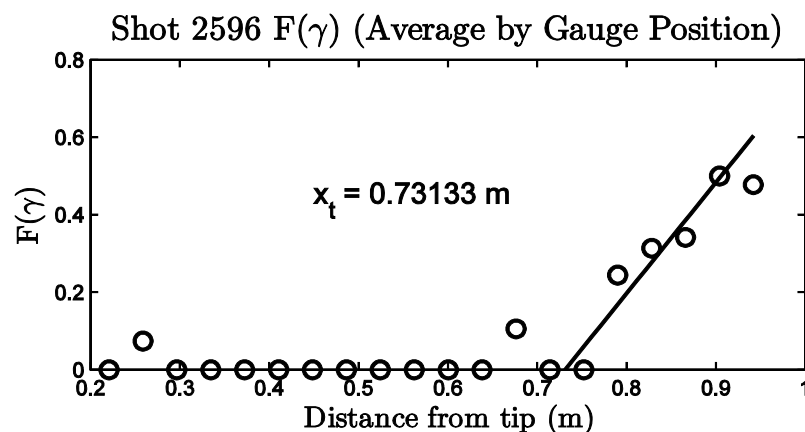
Shot 2600 $F(\gamma)$ (Average by Gauge Position)



**Transition location
determined from intersection**



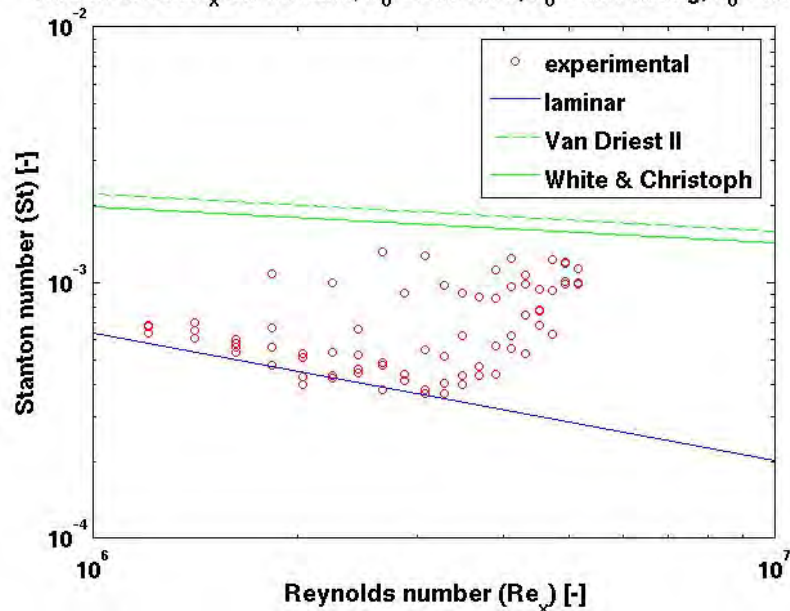
Turbulent intermittency



**Transition location
determined from intersection**

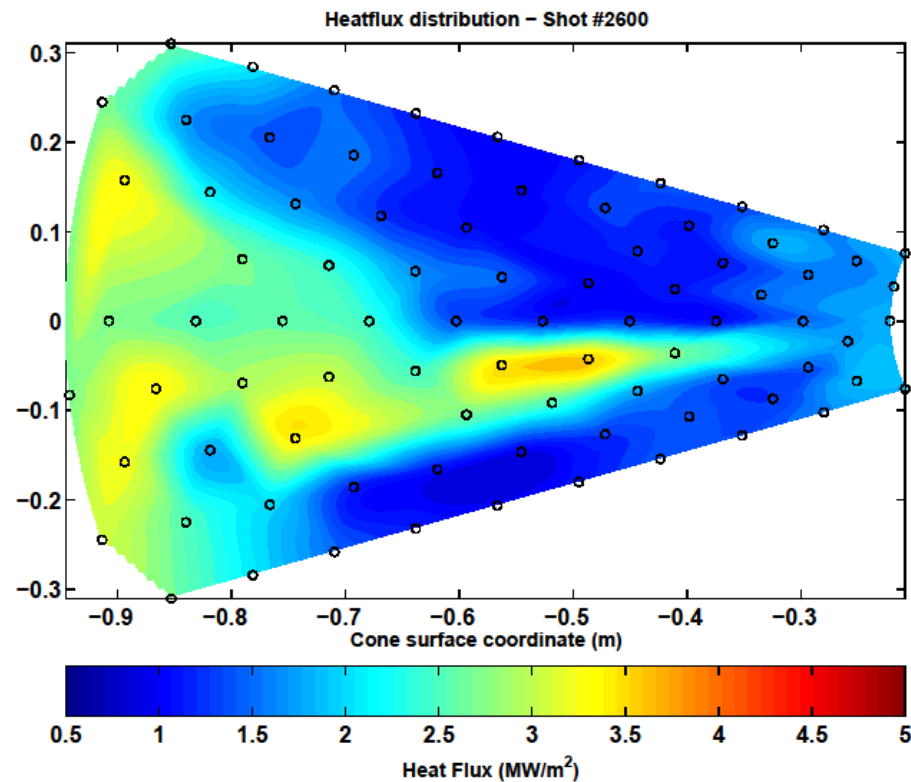
10-micron Porous Injector (Ar injection at 11.6 grams/sec)

Plot of St vs Re_x for T5-2600; $P_0 = 54.7$ MPa, $h_0 = 9.88$ MJ/kg, $T_0 = 6044$ K



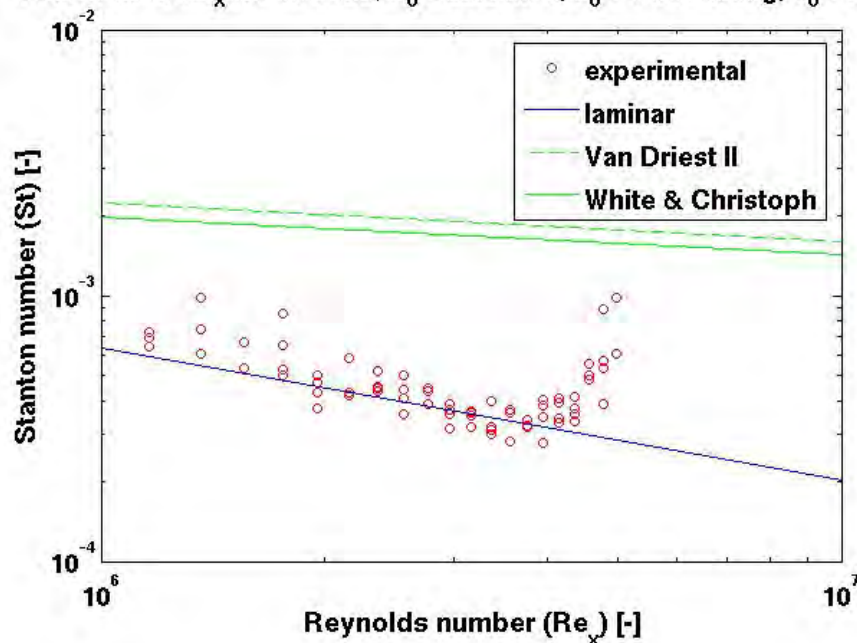
Transitional flow

$$Re_{tr} = 2.88 \times 10^6$$



10-micron Porous Injector (no injection)

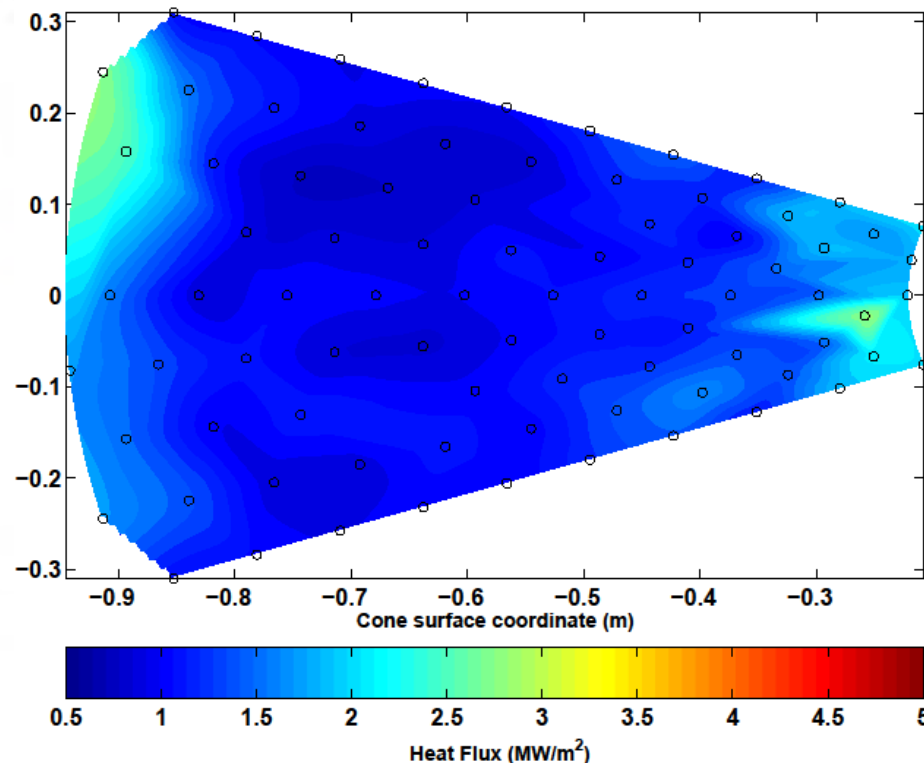
Plot of St vs Re_x for T5-2598; $P_0 = 55.3$ MPa, $h_0 = 10.26$ MJ/kg, $T_0 = 6204$ K



Initially laminar flow

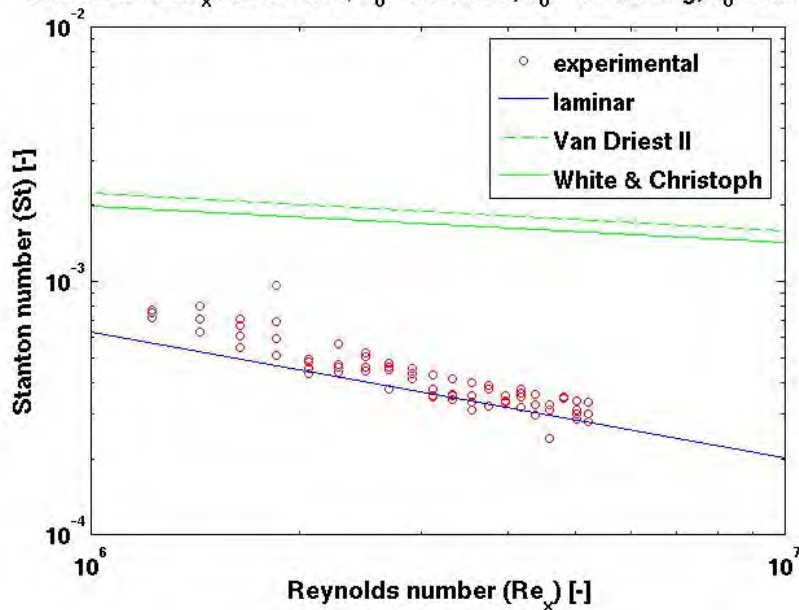
$$Re_{tr} = 4.12 \times 10^6$$

Heatflux distribution – Shot #2598



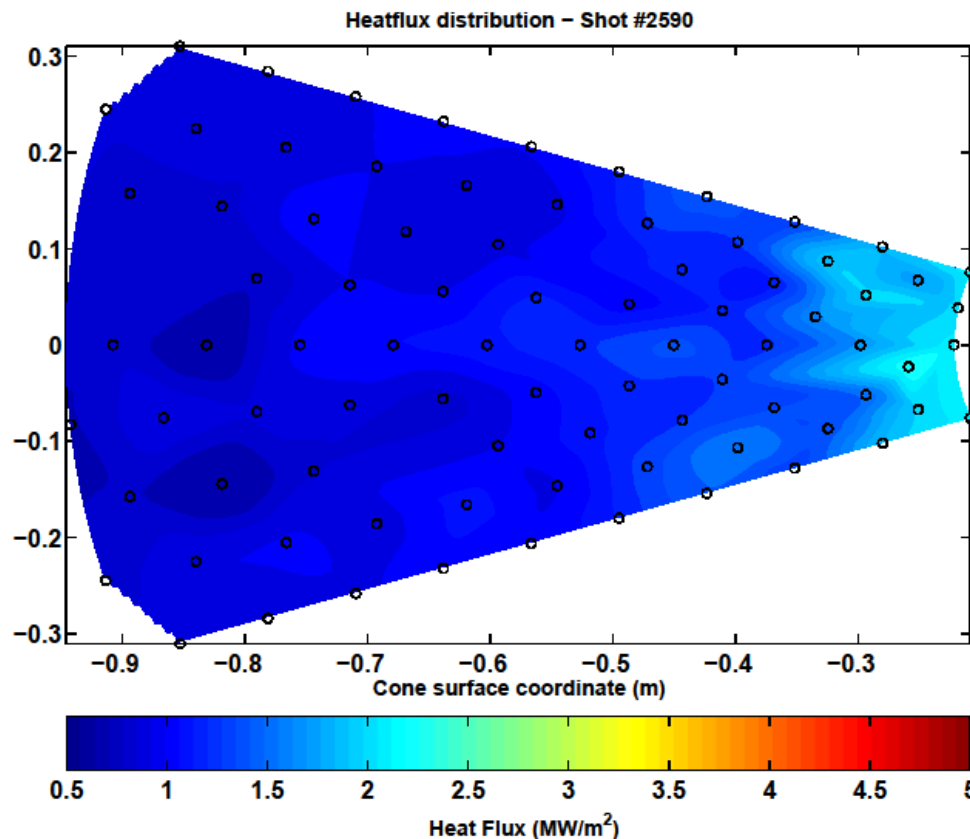
10-micron Porous Injector (CO_2 injection at 11.6 grams/sec)

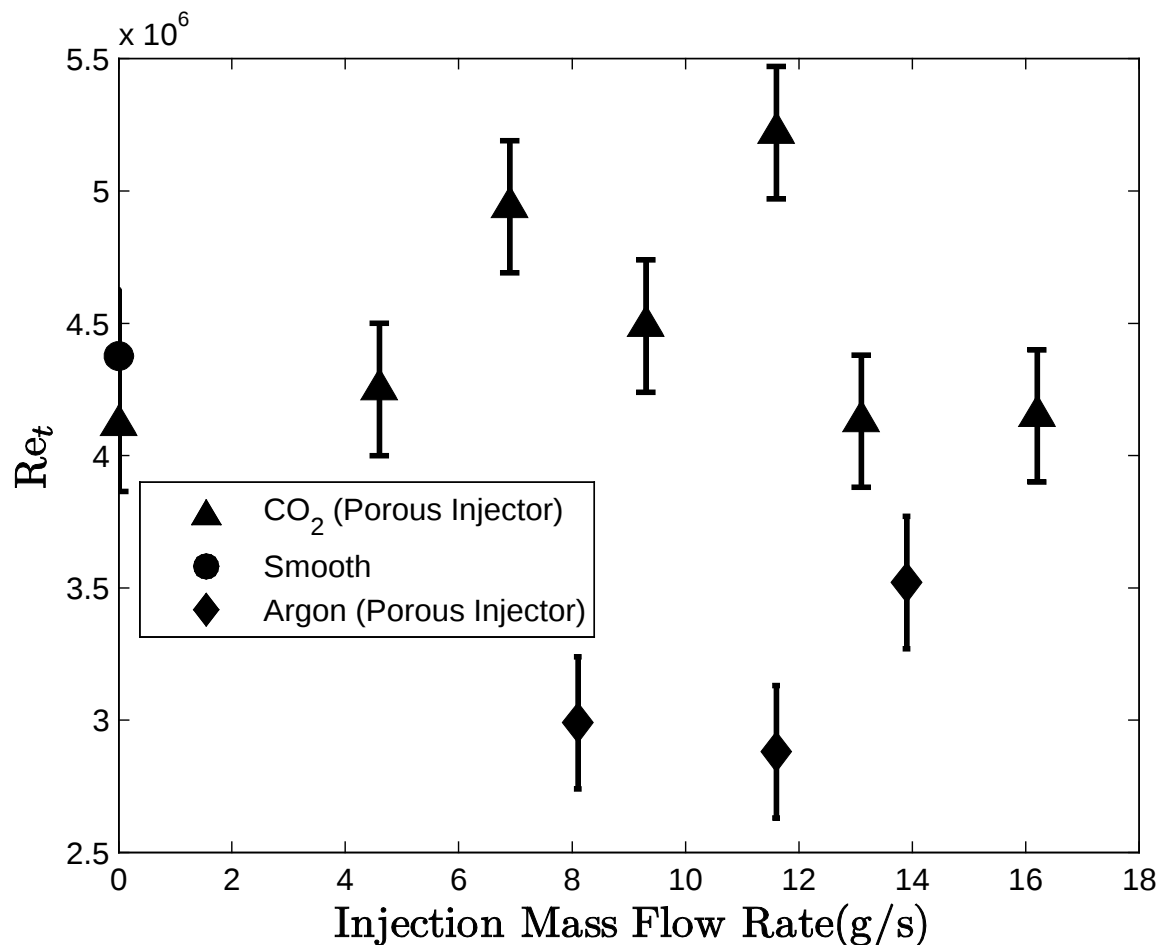
Plot of St vs Re_x for T5-2590; $P_0 = 55.9$ MPa, $h_0 = 9.92$ MJ/kg, $T_0 = 6064.3$ K



Completely laminar flow

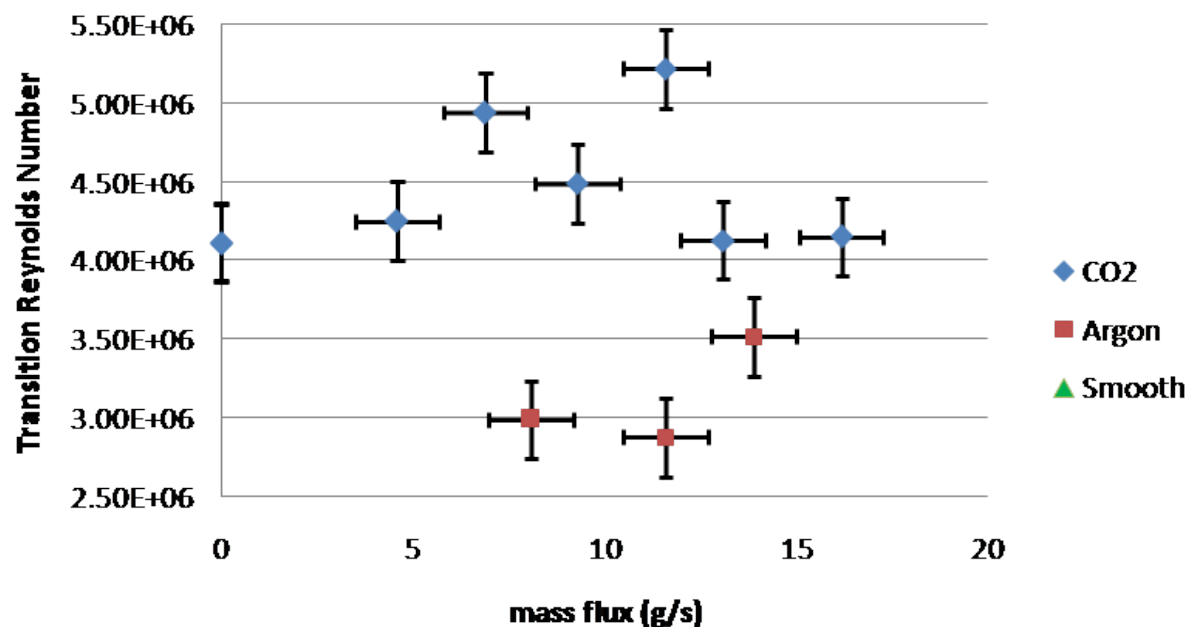
$$Re_{tr} \geq 5.22 \times 10^6$$





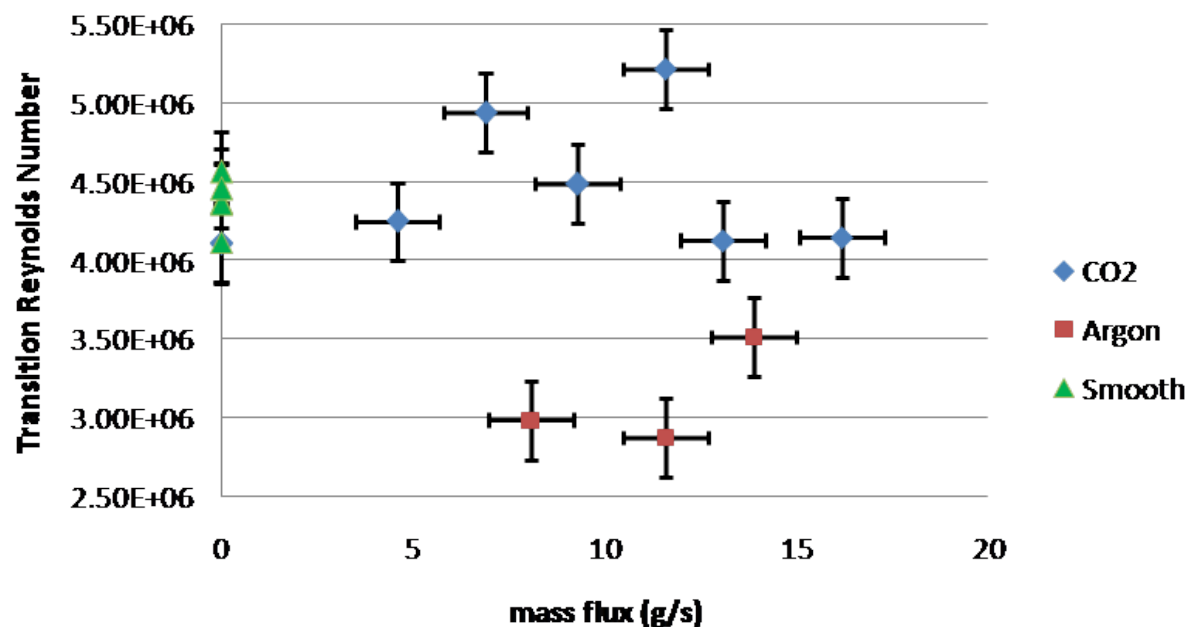
**Summary of results (average
heat transfer method)**

Re vs. injection @ ~10 MJ/kg, ~55 MPa



Two porous control shots

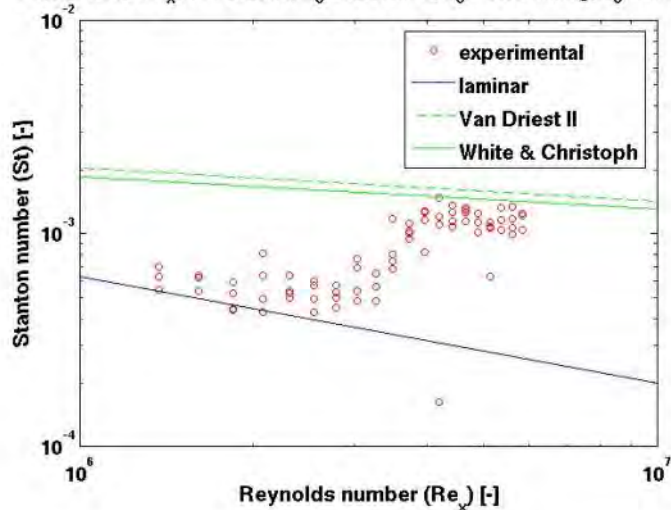
Re vs. injection @ ~10 MJ/kg, ~55 MPa



Five smooth control shots

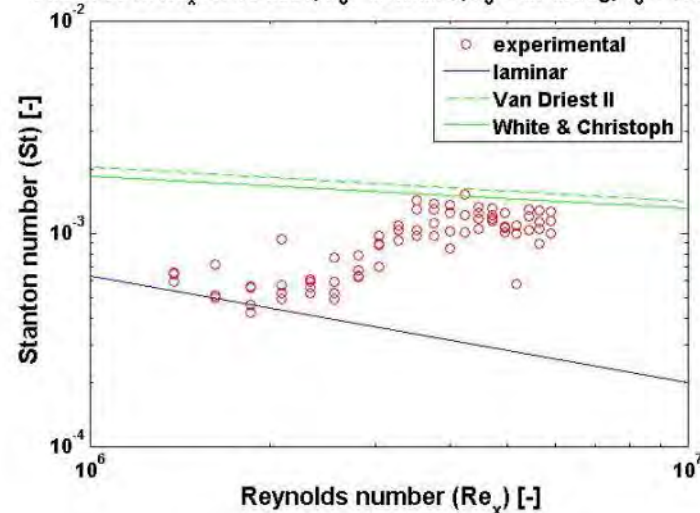
Porous Injector Results (6 MJ/kg)

Plot of St vs Re_x for T5-2582; $P_0 = 29.6$ MPa, $h_0 = 5.69$ MJ/kg, $T_0 = 4129.1$ K



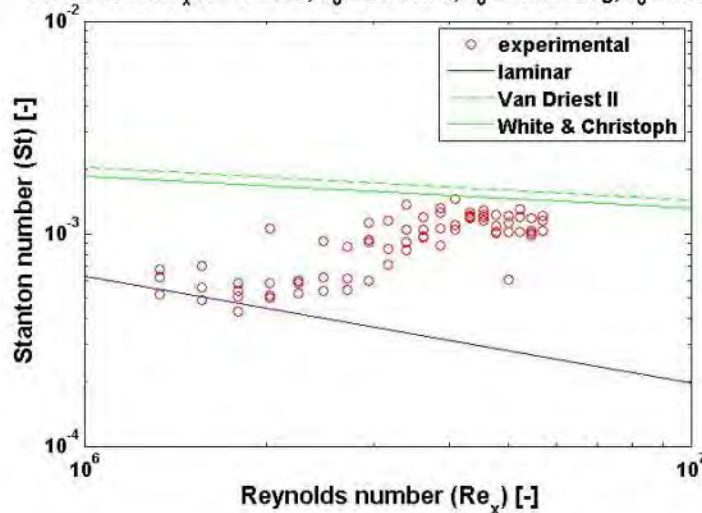
Porous tip – no
injection
vacuum plenum

Plot of St vs Re_x for T5-2584; $P_0 = 29.9$ MPa, $h_0 = 5.7$ MJ/kg, $T_0 = 4134.8$ K



CO₂ injection 4 g/s

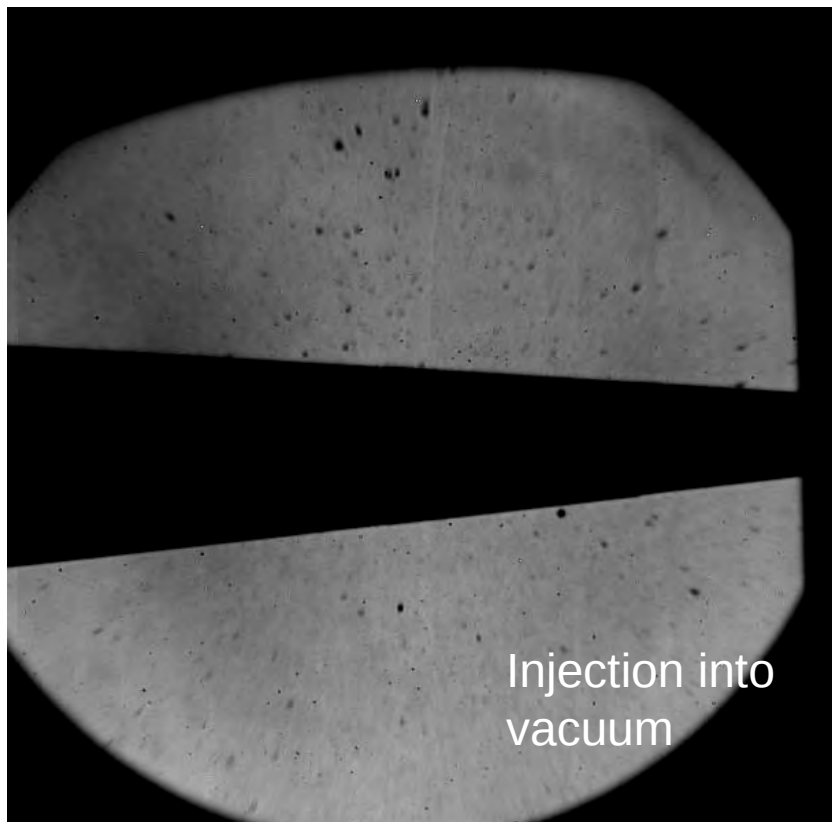
Plot of St vs Re_x for T5-2585; $P_0 = 30.4$ MPa, $h_0 = 5.92$ MJ/kg, $T_0 = 4242.6$ K



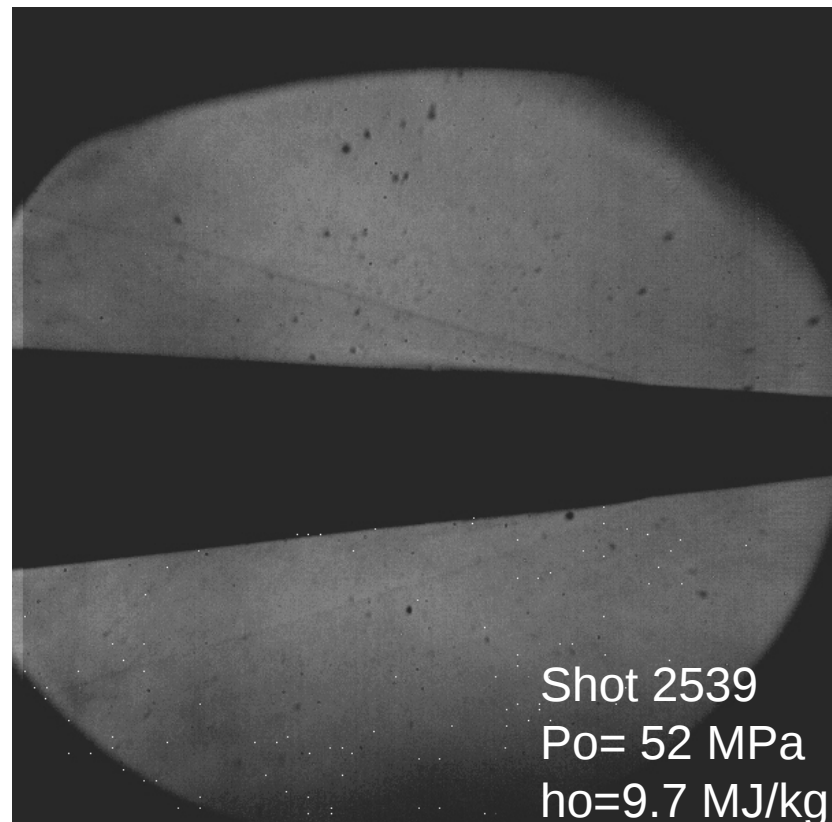
Injection of CO₂ and argon
destabilize boundary layer
and transition occurs earlier
at lower enthalpy/temp.

Ar injection 4 g/s

Before shot

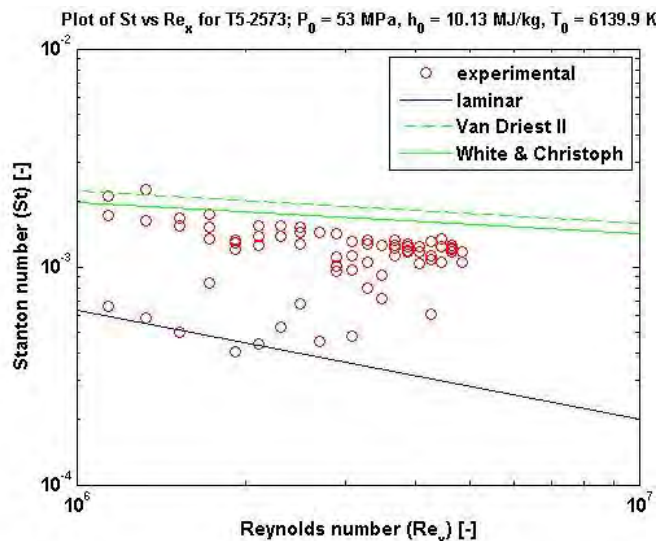


Porous Injector with cone downstream and 80 psi injection



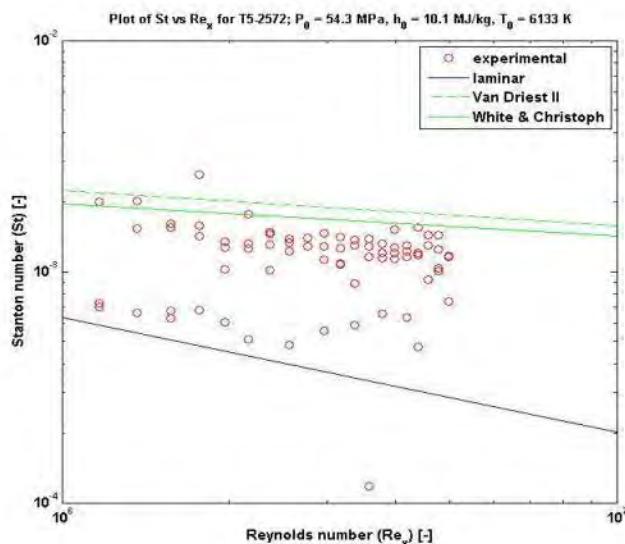
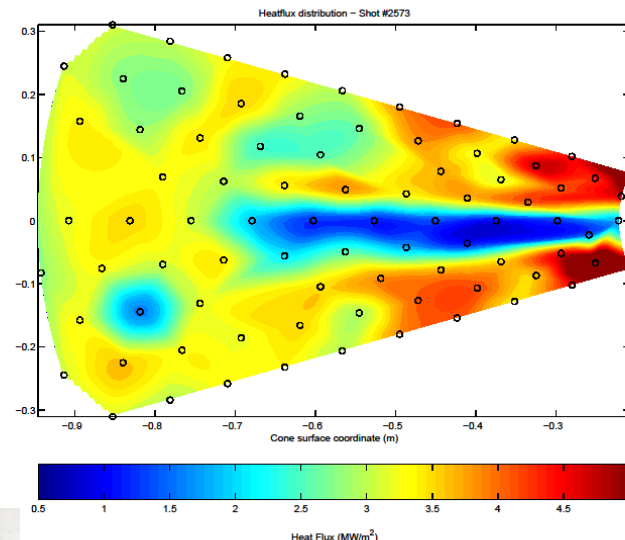
Schlieren seems to capture the CO2 injection clearly

Porous Injector Results

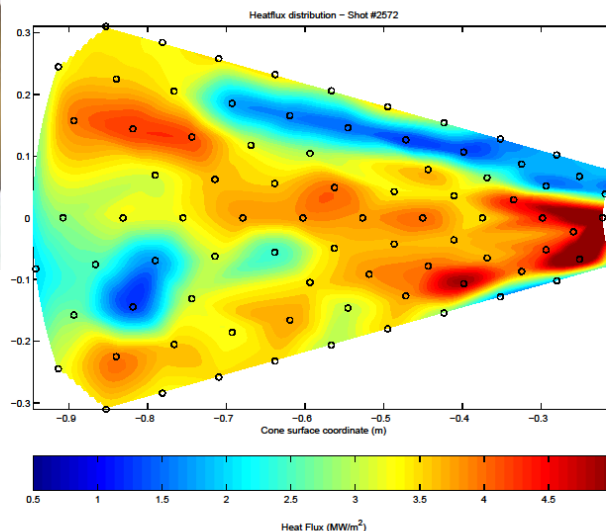


CO_2 injection
at 18.5 g/s

Immediately
turbulent flow
(streak due to
injector flaw)



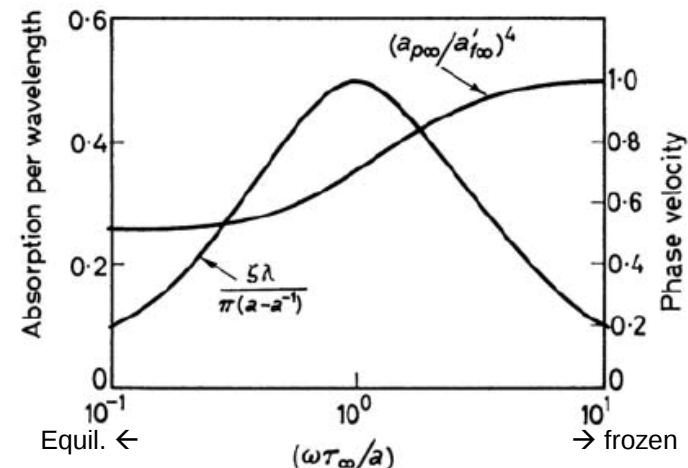
CO_2 injection
at 26.6 g/s



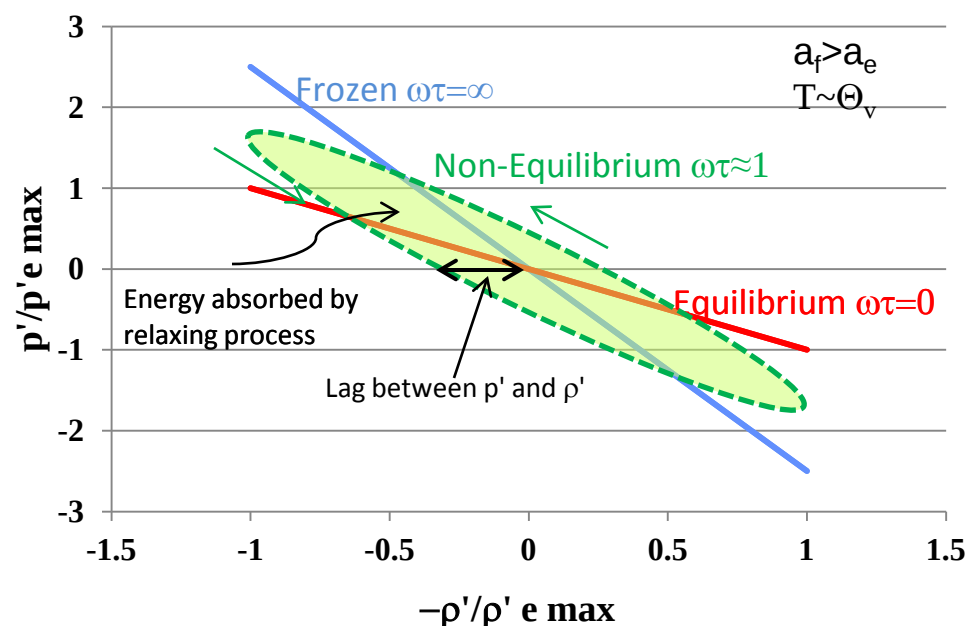
Gas Composition (by mass fraction)	
N2	0.7345
O2	0.1844
NO	0.0654
N	0.0
O	0.0157

Why vibration relaxation and dissociation damp acoustic waves

- Theory known for decades (Lighthill, 1956, Herzfeld and Litovitz, 1959, Clarke and McChesney, 1964, Vincentti and Kruger 1967)
- Following Clarke and McChesney, the linearization of perturbations of the N-S equations leads to damping curve as shown – Maximum damping occurs when $\omega\tau = a_f/a_e$
- Relaxation processes such as molecular vibration and dissociation cause damping of acoustic waves through *phase lag between pressure and density*



From Clarke and McChesney



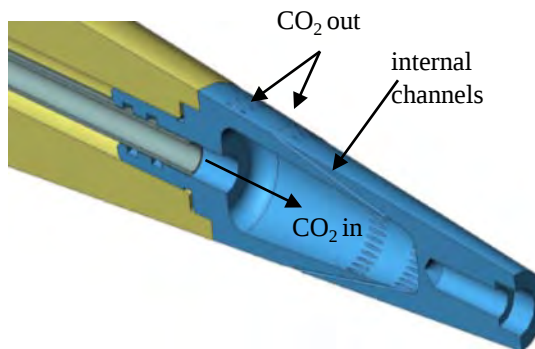
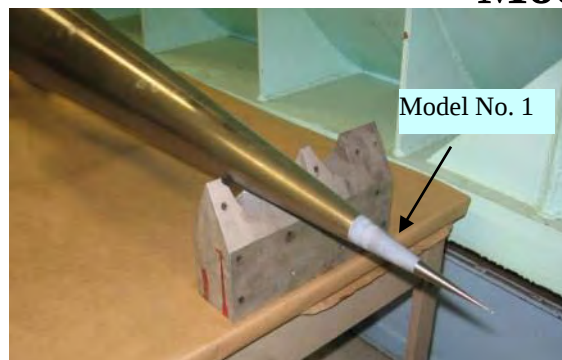
Model No.	Hole diameter, d (mm)	No. Rows	Injection angle, α (deg)
1	0.51	2	12
2	0.76	1	11
3	0.76	1	12
4	1.02	1	11

Injector Variants

Model No. 2



Model No. 1



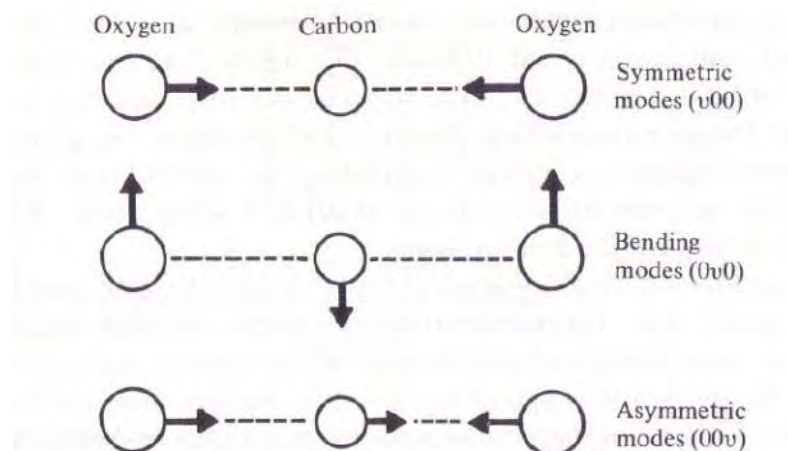
Four injectors designed and built

REFERENCES

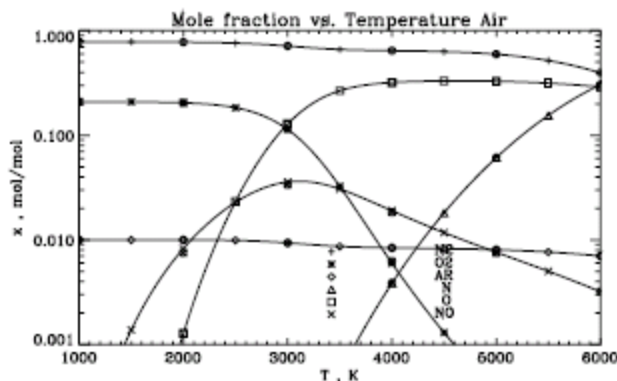
1. Hornung, H.G., Adam, P.H., Germain, P., Fujii, K., Rasheed, A., “On transition and transition control in hypervelocity flows,” *Proceedings of the Ninth Asian Congress of Fluid Mechanics*
2. Fujii, K., Hornung, H.G., “Experimental investigation of high-enthalpy effects on attachment-line boundary layer transition,” *AIAA Journal*, Vol. 41, No. 7, July 2003.
3. Johnson, H.B., Seipp, T.G., Candler, G.V., “Numerical study of hypersonic reacting boundary layer transition on cones,” *Physics of Fluids*, 10 (10): 2676-2685 Oct. 1998.

Vibrational temperatures

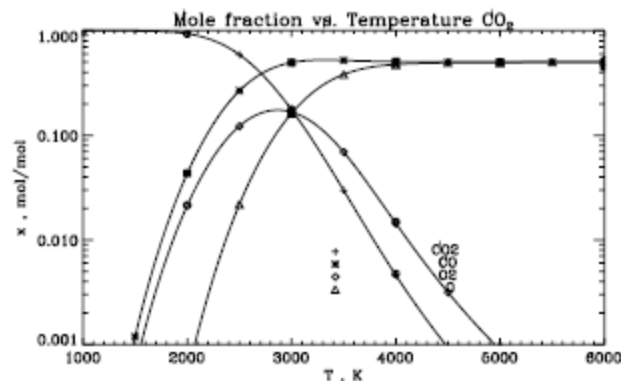
species	M_w g/mol	$\sigma\Theta_{rot}$ K	h_f° J/mol	g_v	Θ_v K	g_{e_o}	g_{e_i}	ϵ_e J/mol
N ₂	28.016	5.79	0.0	1	3353.2	1	3	6.015×10^5
							6	7.136×10^5
							1	7.342×10^5
O ₂	32.000	4.16	0.0	1	2239.0	3	2	9.225×10^4
							1	1.579×10^5
							3	4.320×10^5
							3	5.960×10^5
Ar	39.944	—	0.0	—	—	1	5	1.115×10^6
							3	1.122×10^6
N	14.008	—	4.713×10^5	—	—	4	6	2.301×10^5
							4	2.308×10^5
							6	3.452×10^5
							12	9.971×10^5
O	16.000	—	2.468×10^5	—	—	5	3	1.903×10^3
							1	2.717×10^3
							5	1.899×10^5
							1	4.044×10^5
							5	8.829×10^5
NO	30.008	2.45	8.990×10^4	1	2699.2	4	2	5.262×10^5
							4	5.496×10^5
C	12.011	—	7.116×10^5	—	—	1	3	1.962×10^2
							5	5.204×10^2
							5	1.219×10^5
							1	2.590×10^5
							5	4.036×10^5
CO ₂	44.011	1.13	-3.933×10^5	2	960.1	1		
				1	1992.5			
				1	3380.2			
CO	28.011	2.78	-1.139×10^5	1	3082.0	1	6	5.824×10^5
							3	6.687×10^5
							6	7.453×10^5
							2	7.785×10^5
H ₂	2.016	175.09	0.0	1	6100.0	1	1	1.097×10^6
							2	1.196×10^6
							3	1.352×10^6
H	1.008	—	2.110×10^5	—	—	1	3	9.839×10^5
							4	1.166×10^6
							5	1.230×10^6



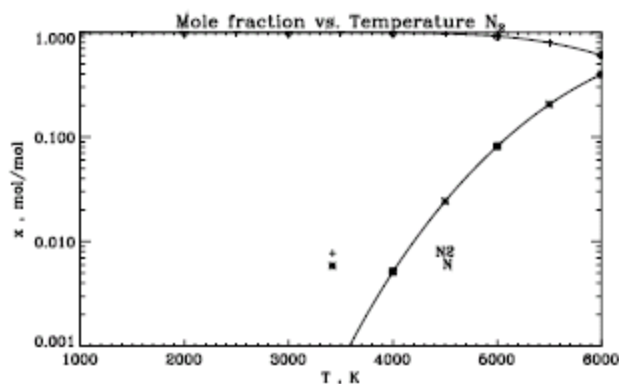
Dissociation temperatures



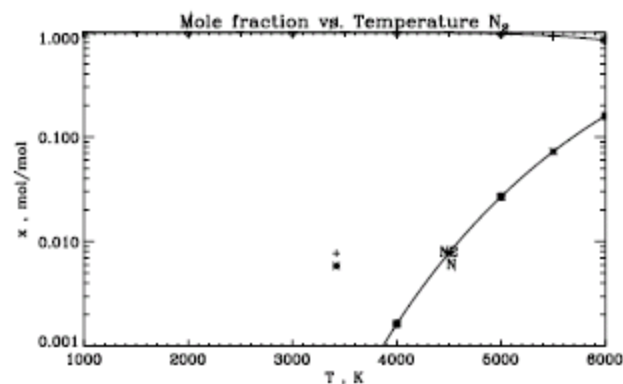
Air, $\rho = 0.01 \text{ kg/m}^3$



CO₂, $\rho = 0.01 \text{ kg/m}^3$



N₂, $\rho = 0.01 \text{ kg/m}^3$



N₂, $\rho = 0.10 \text{ kg/m}^3$

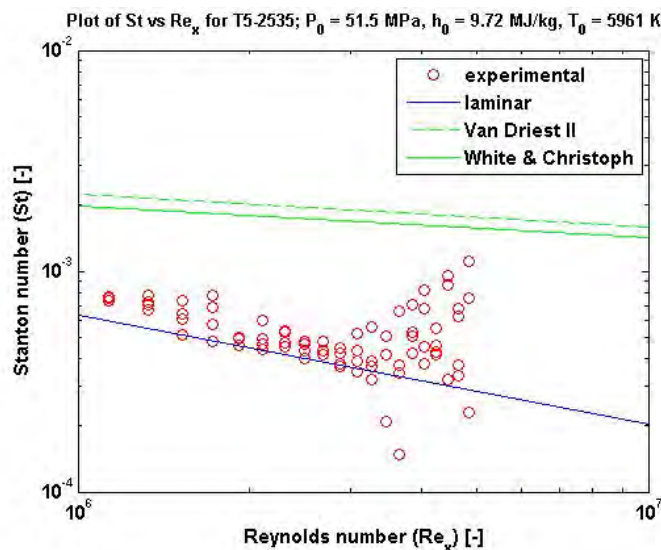
$$St = q / (\rho h_0 u_e (h_0 - 0.5 u_e^2 (1 - r) - C_p T_w))$$

Detailed condition data (old shots)

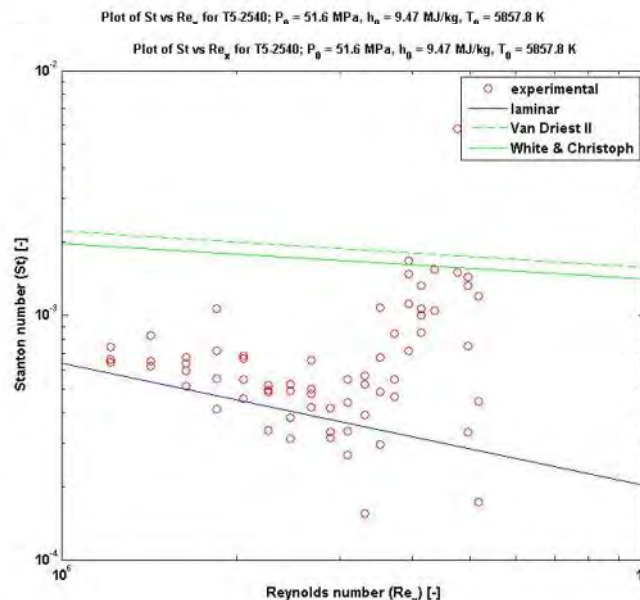
Table A.1: Summary of freestream conditions for all shots.

Shot	P_0 [MPa]	T_0 [K]	h_0 [MJ/kg]	P_∞ [kPa]	T_∞ [K]	ρ_∞ [kg/m ³]	U_∞ [m/s]	M_∞ [—]
2331	52.2	7375	10.75	21.8	1487	4.92×10^{-2}	4286	5.6
2332	51.2	7095	10.90	22.8	1569	4.96×10^{-2}	4211	5.4
2333	50.0	4434	9.43	40.9	2214	8.69×10^{-2}	3248	4.3
2334	50.1	5380	10.89	32.8	1980	6.29×10^{-2}	3799	4.7
2335	37.6	3459	5.58	27.7	1426	9.86×10^{-2}	2647	4.6
2336	37.2	3606	6.12	27.8	1532	9.12×10^{-2}	2741	4.6
2337	51.2	7379	11.37	23.2	1662	4.74×10^{-2}	4338	5.4
2433	39.1	5305	8.34	17.9	1250	5.00×10^{-2}	3712	5.4
2434	42.5	5538	8.87	20.3	1369	5.17×10^{-2}	3816	5.3
2435	48.9	5843	9.53	24.5	1522	5.60×10^{-2}	3942	5.2
2436	49.5	6069	10.07	25.7	1659	5.39×10^{-2}	4040	5.1
2437	46.8	6567	11.33	27.3	2178	4.37×10^{-2}	4363	4.8
2438	48.9	6069	10.08	25.5	1660	5.35×10^{-2}	4040	5.1
2439	55.5	5715	9.15	26.6	1423	6.51×10^{-2}	3873	5.3
2440	53.8	5216	7.99	25.1	1182	7.39×10^{-2}	3643	5.4
2441	52.6	4689	7.33	27.7	1285	8.05×10^{-2}	3407	5.1
2442	53.3	4250	7.18	33.0	1479	8.94×10^{-2}	3291	4.8
2443	53.9	3702	4.38	36.3	1448	1.13×10^{-1}	2938	4.7
2444	53.0	3616	5.99	40.3	1560	1.31×10^{-1}	2740	4.5
2445	53.3	3782	6.61	40.4	1674	1.21×10^{-1}	2834	4.5
2446	55.8	4742	6.85	22.4	931	8.36×10^{-2}	3384	5.7
2447	50.5	4357	6.06	18.9	783	8.43×10^{-2}	3193	5.8
2448	48.4	4358	6.07	18.0	783	8.01×10^{-2}	3193	5.8
2449	45.7	4286	5.94	17.1	762	7.84×10^{-2}	3164	5.8

Control Experiment – Smooth Surface

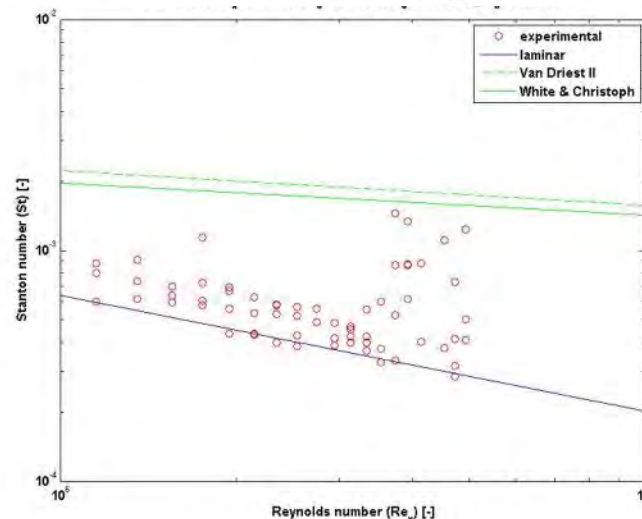


**Porous injector design
looks very promising**



porous Injector – no
flow

*boundary layer not
disturbed*

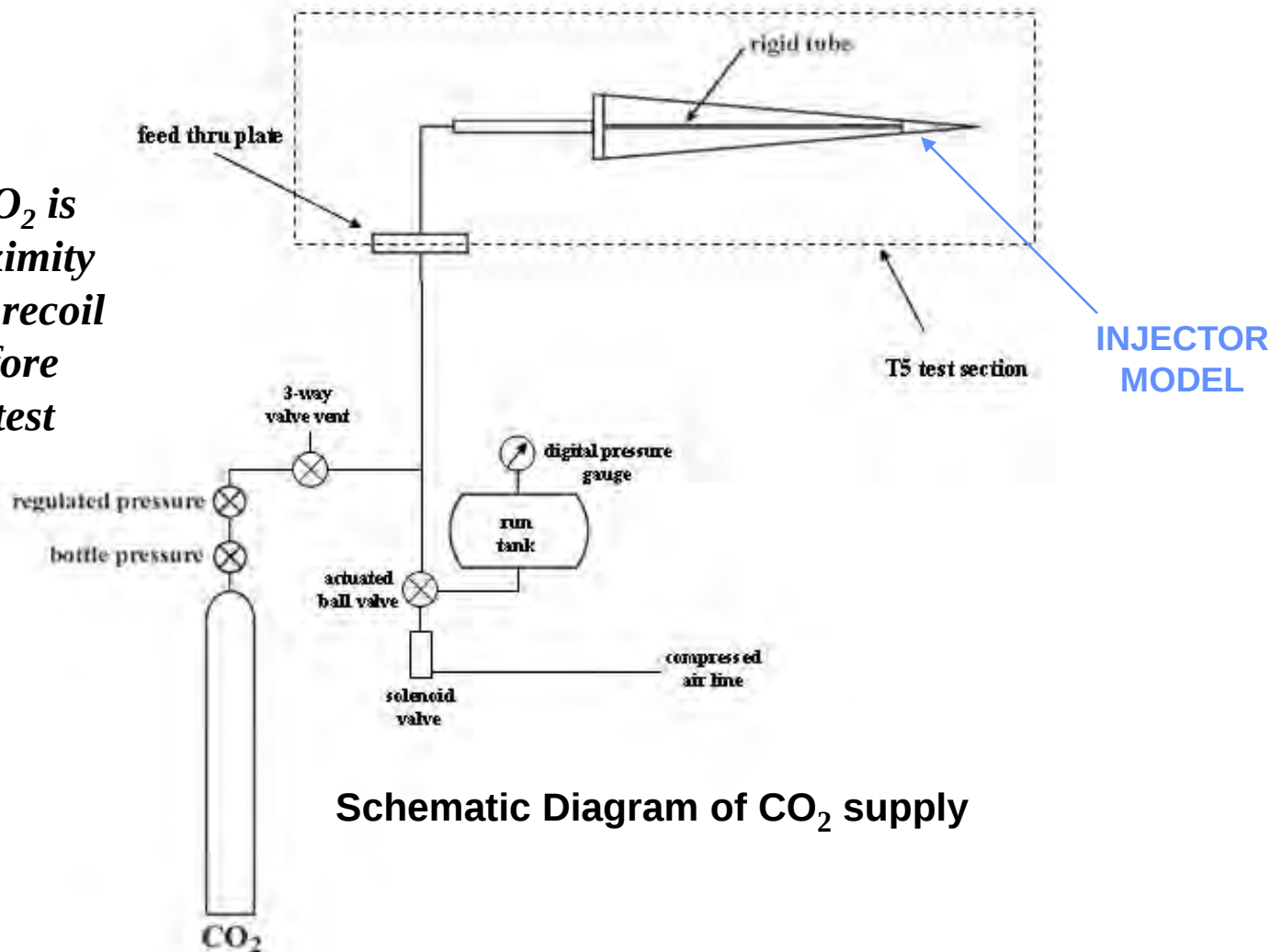


Preliminary data
with porous injector
and 20 psi CO₂ run
tank pressure

*Boundary layer not
disturbed*

CO₂ Injection System

The injection of CO₂ is triggered by a proximity switch sensing the recoil of T5, ~100 ms before flow begins in the test section



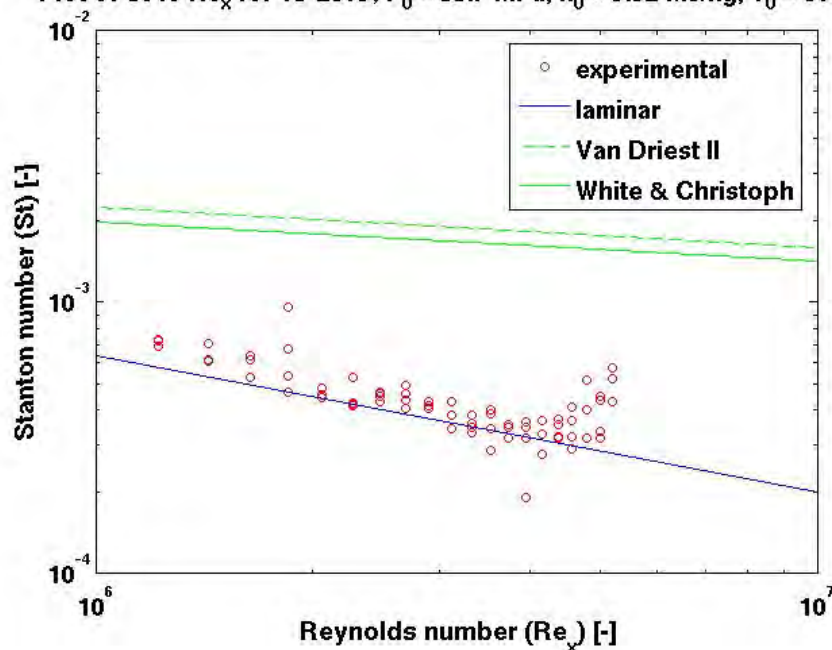
Schematic Diagram of CO₂ supply



Injector section installed in ~1m long, 5-degree half angle cone

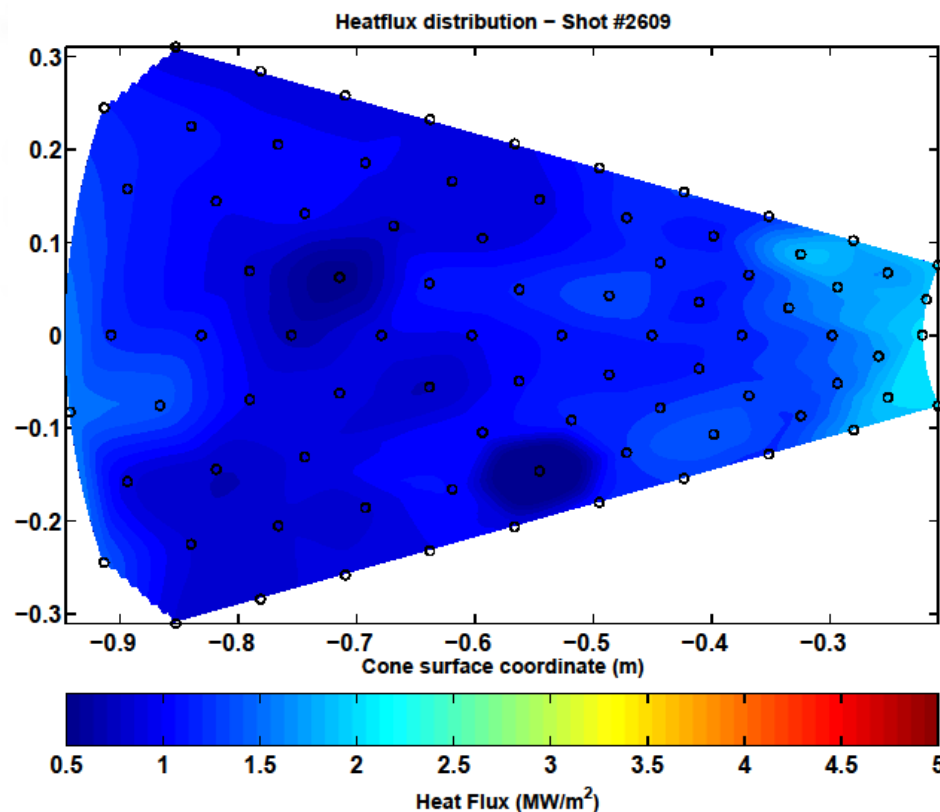
Control Experiment – Smooth Surface

Plot of St vs Re_x for T5-2609; $P_0 = 55.7$ MPa, $h_0 = 9.92$ MJ/kg, $T_0 = 6063$ K

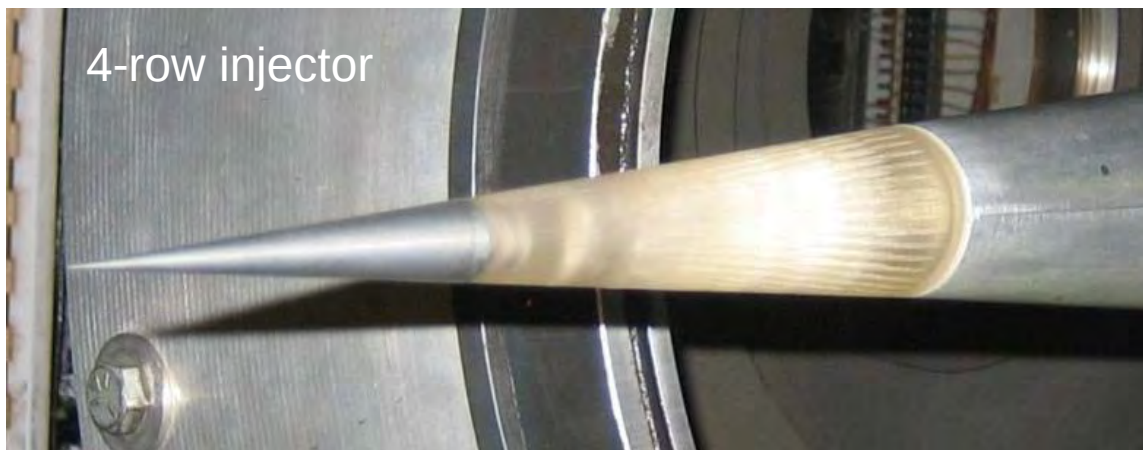


Initially laminar flow

$$Re_{tr} = 4.36 \times 10^6$$

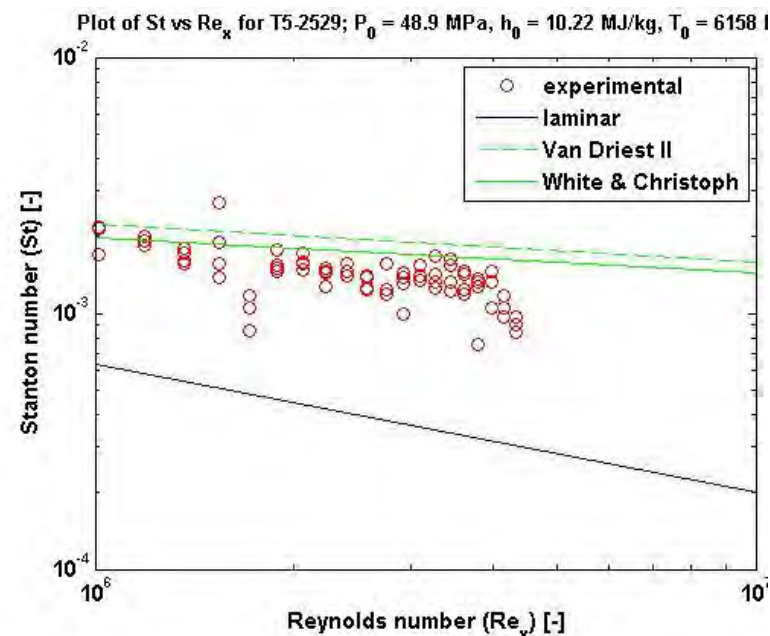


Four rows of orifices

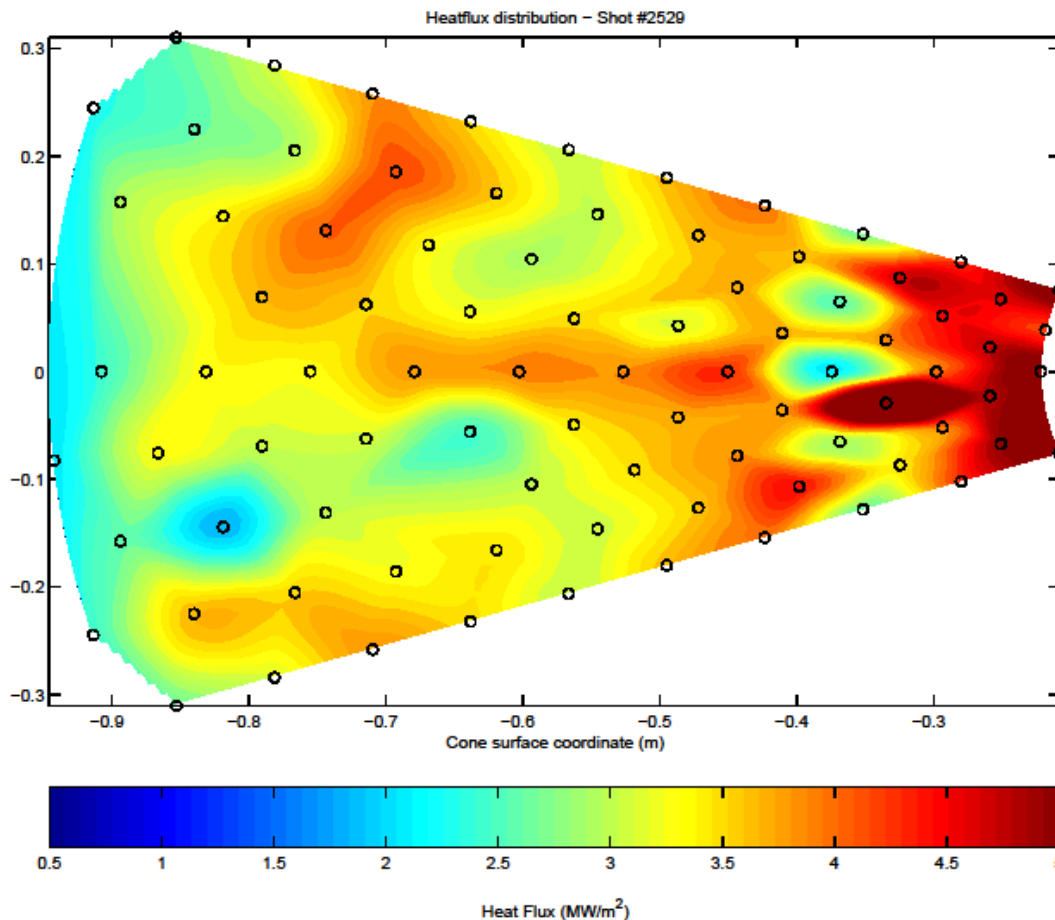


**Injector with four rows of orifices,
installed in T5 test section**

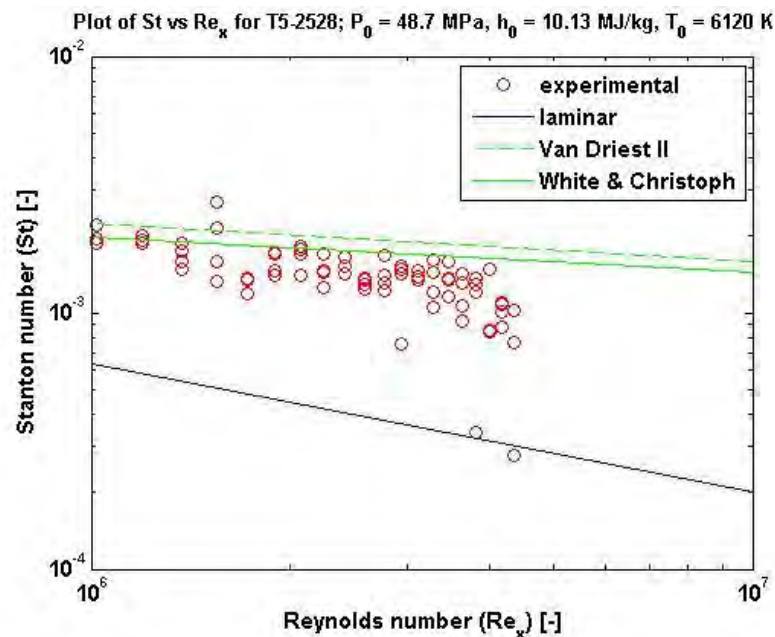
Four-Row Injector (CO₂ injection at 26.0 grams/sec)



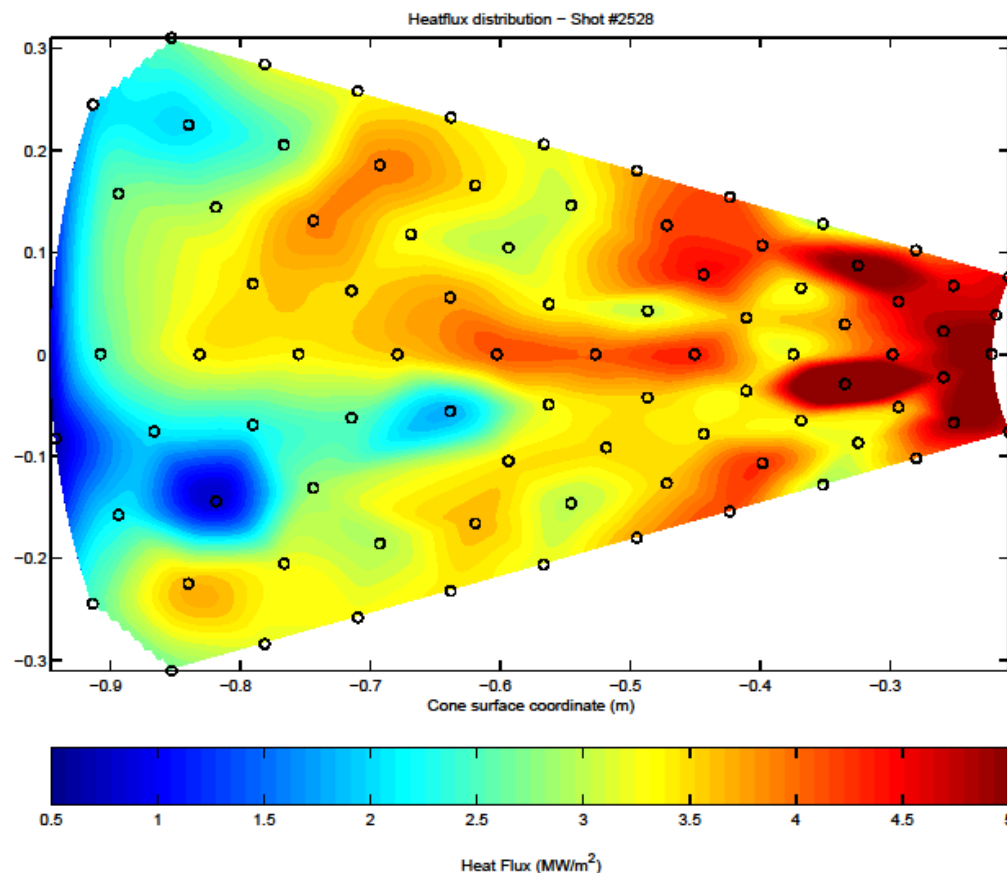
Immediate Transition



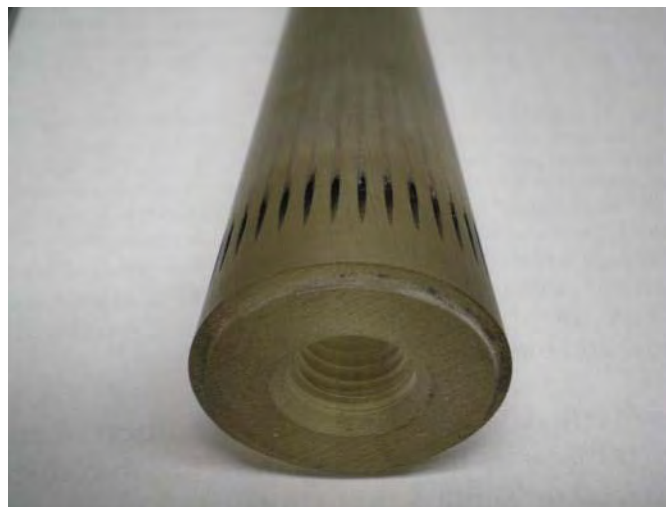
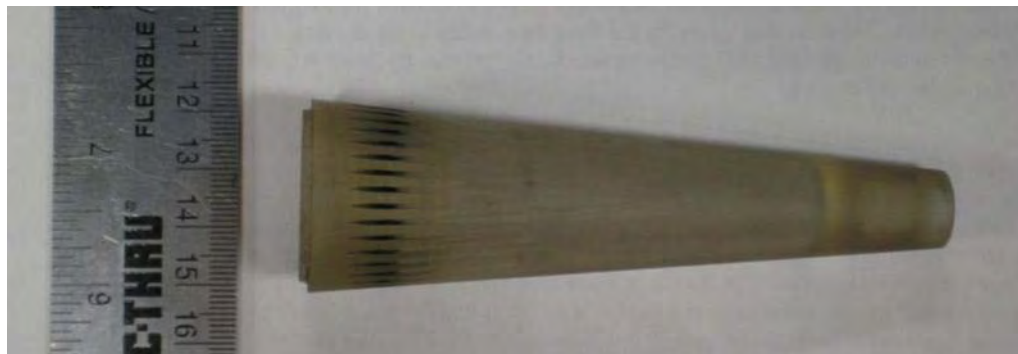
Four-Row Injector (no injection)



Immediate Transition

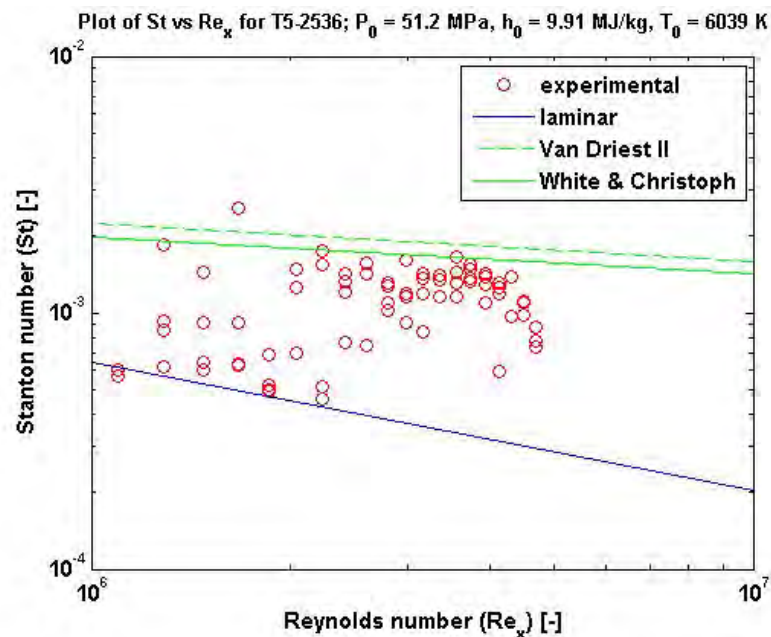


One row injector

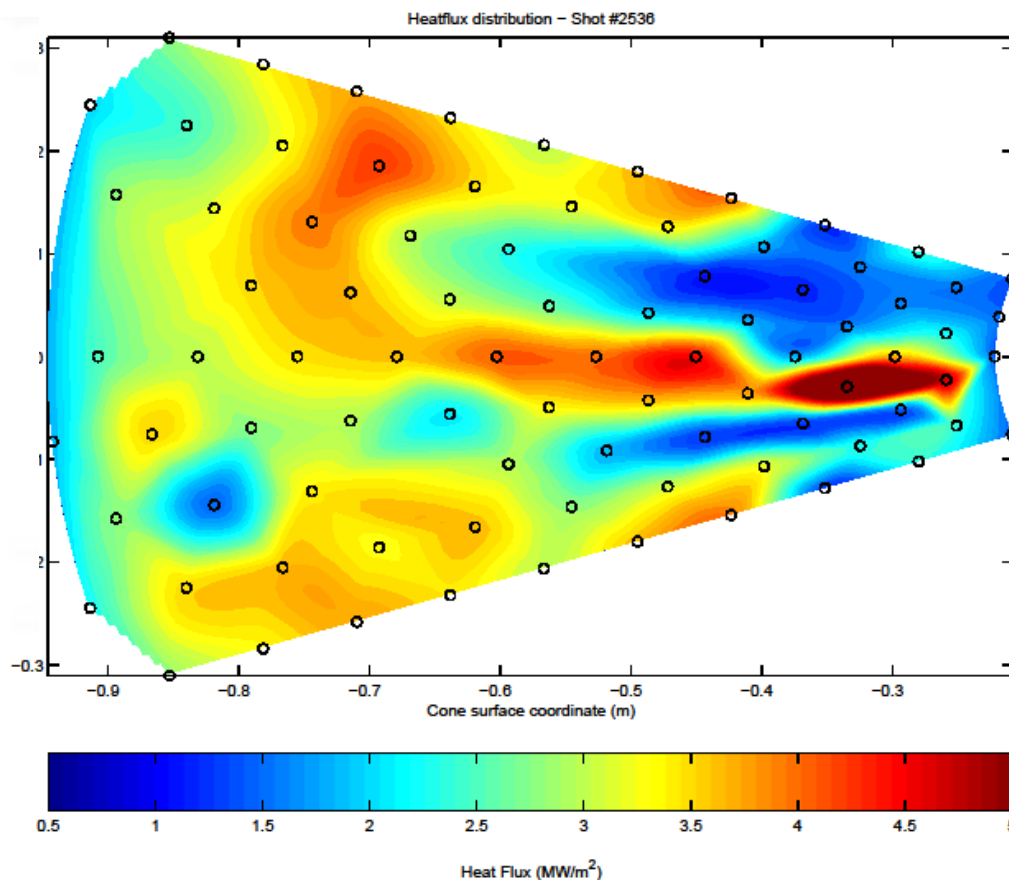


One row of orifices

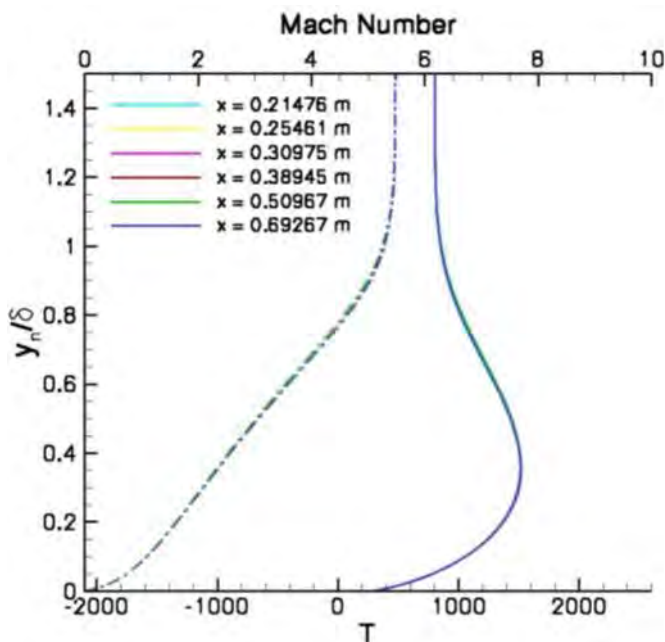
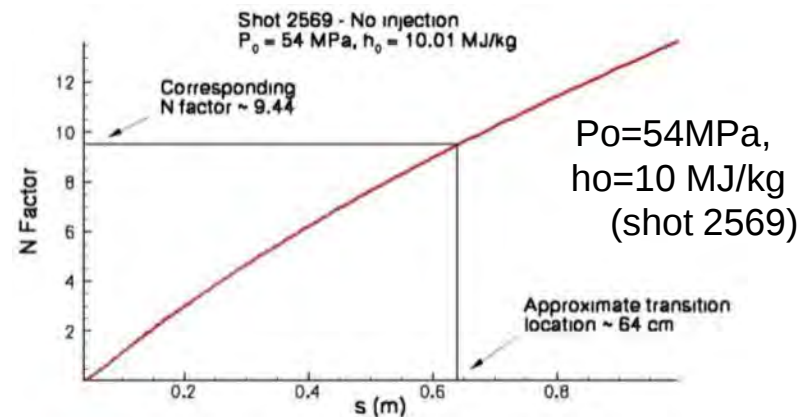
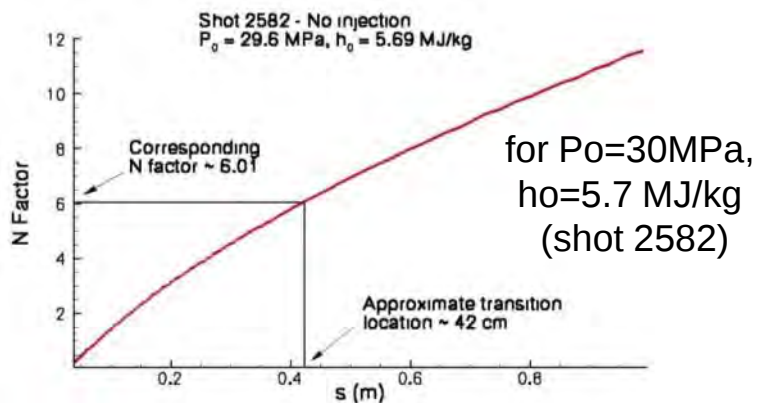
One-Row Injector (no injection)



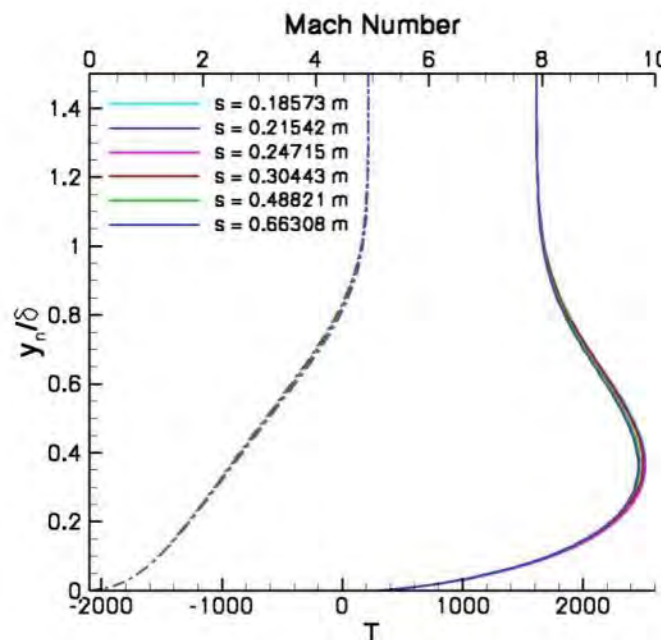
Transition (though not immediately full turbulence)



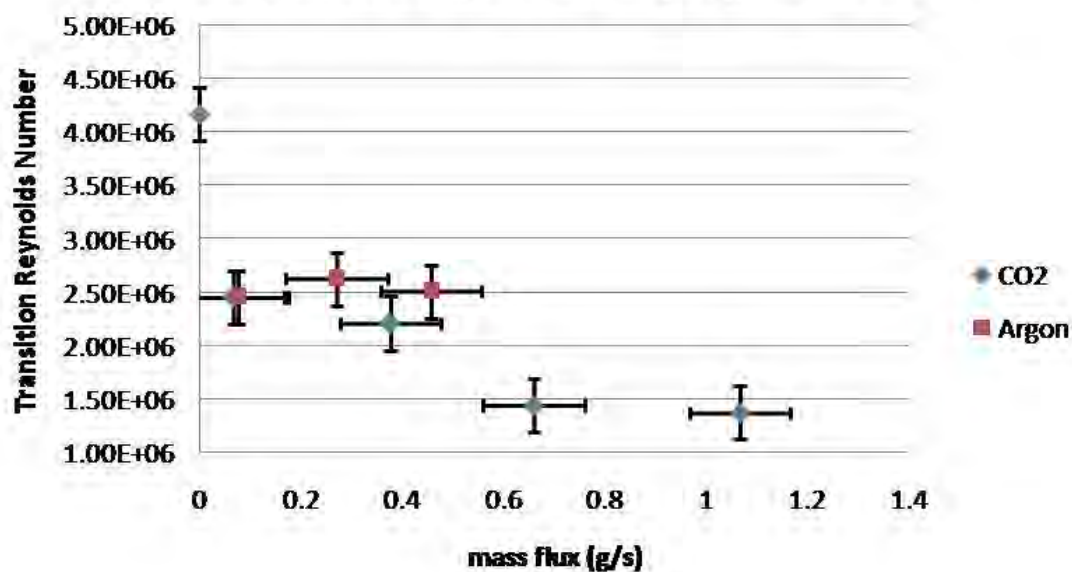
T profile and N factor for high and low enthalpy conditions

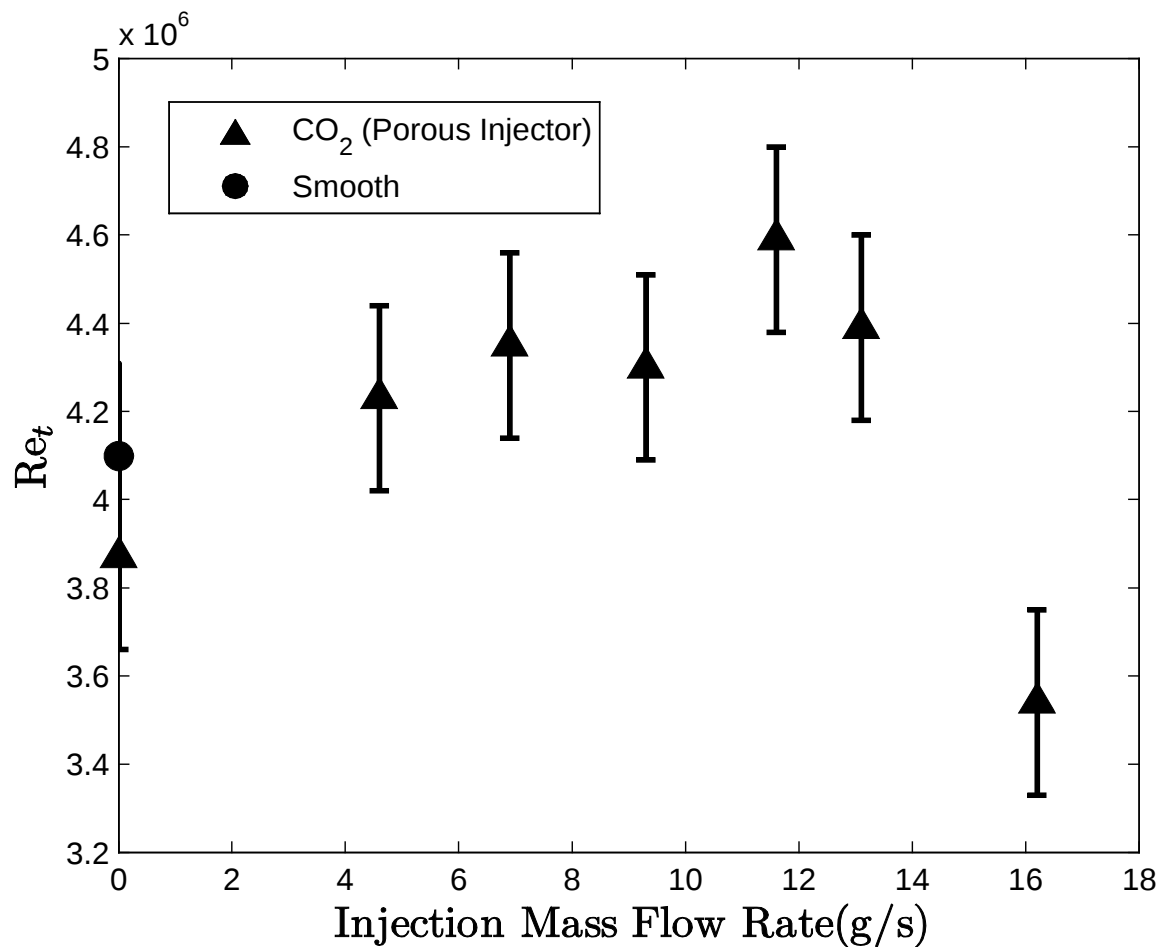


T : solid line
M : dash dot line



Gas inj into N2 @ ~10 MJ/kg, ~50 MPa





**Summary of results
(intermittency method)**

Re vs. injection @ ~10 MJ/kg, ~55 MPa

