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Heat Transfer of Gas Upflow in a Deteriorated Heat Transfer Regime

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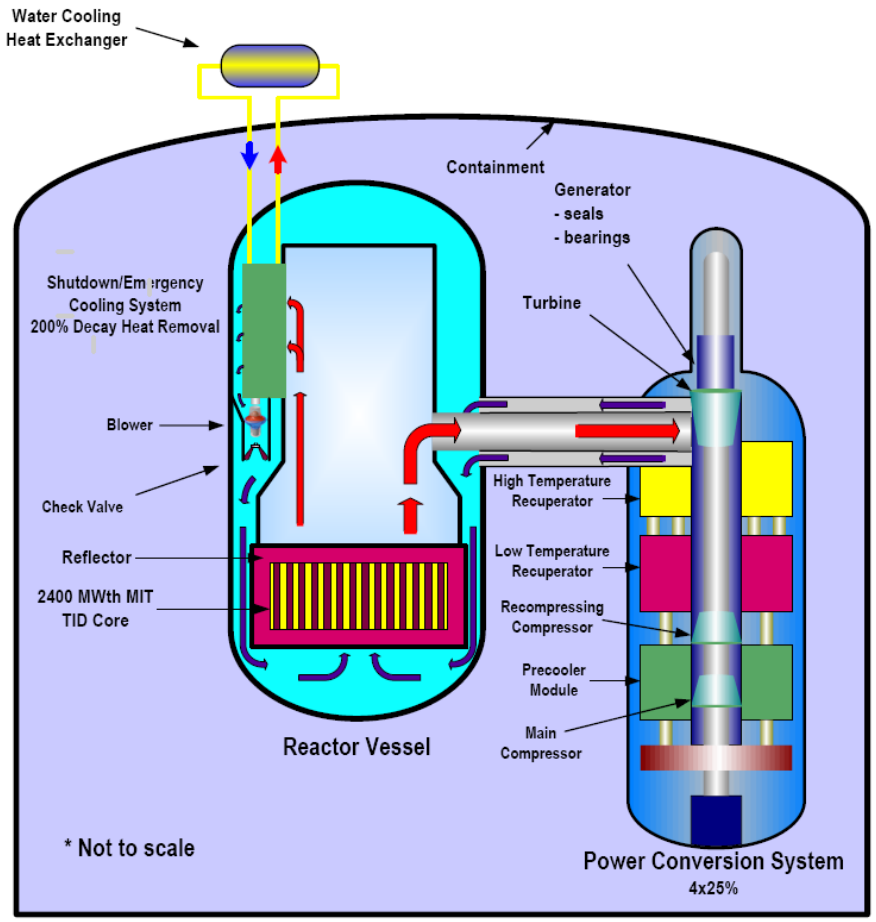
Motivation

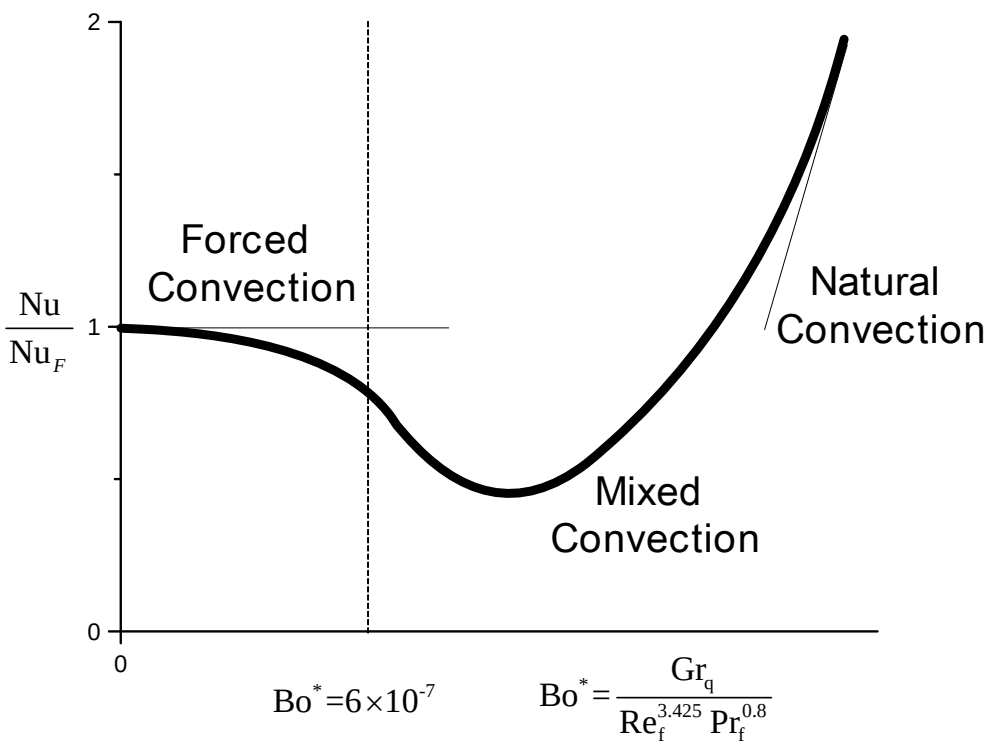


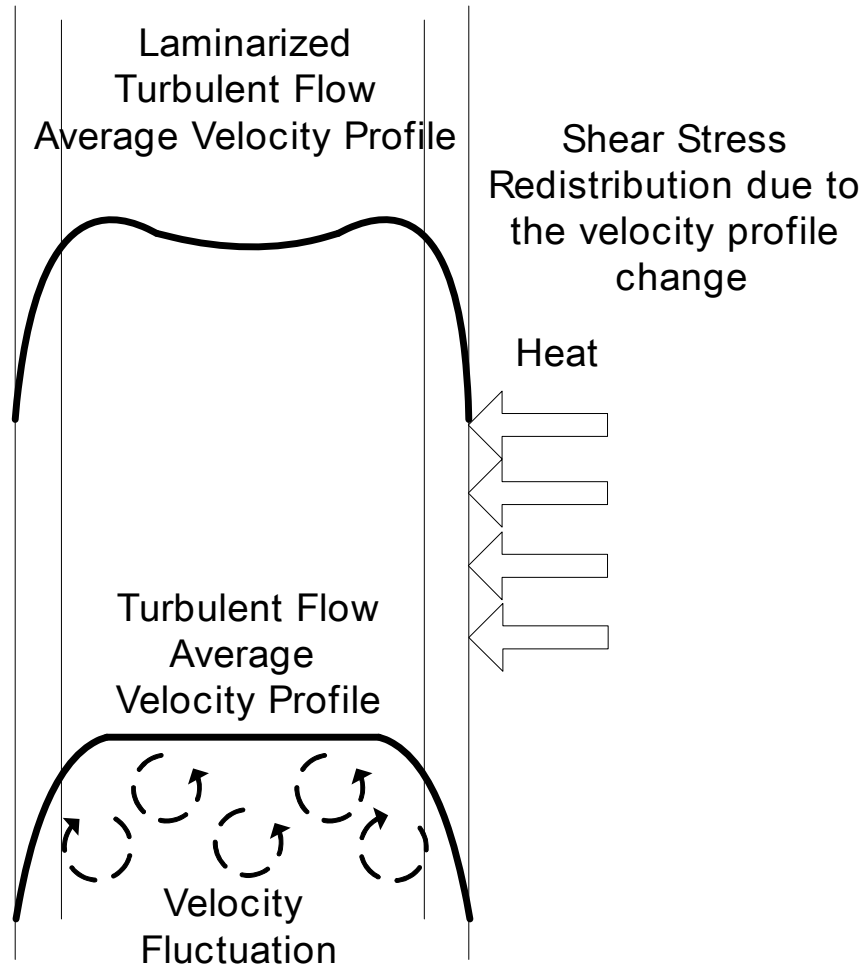
S-CO_2 GFR Layout

- Heat Transfer Regime Map for single phase in system analysis codes (e.g. RELAP5-3D) is insufficient to analyze GFR post-LOCA conditions.
- GFR preliminary analyses indicate that the flow during post–LOCA may be in the Deteriorated Turbulent Heat Transfer (DTHT) regime.
- For a reliable GFR system design, validation of heat transfer correlations with experimental data is necessary.

Objective: Obtain data in DHTH regime and develop HT correlations

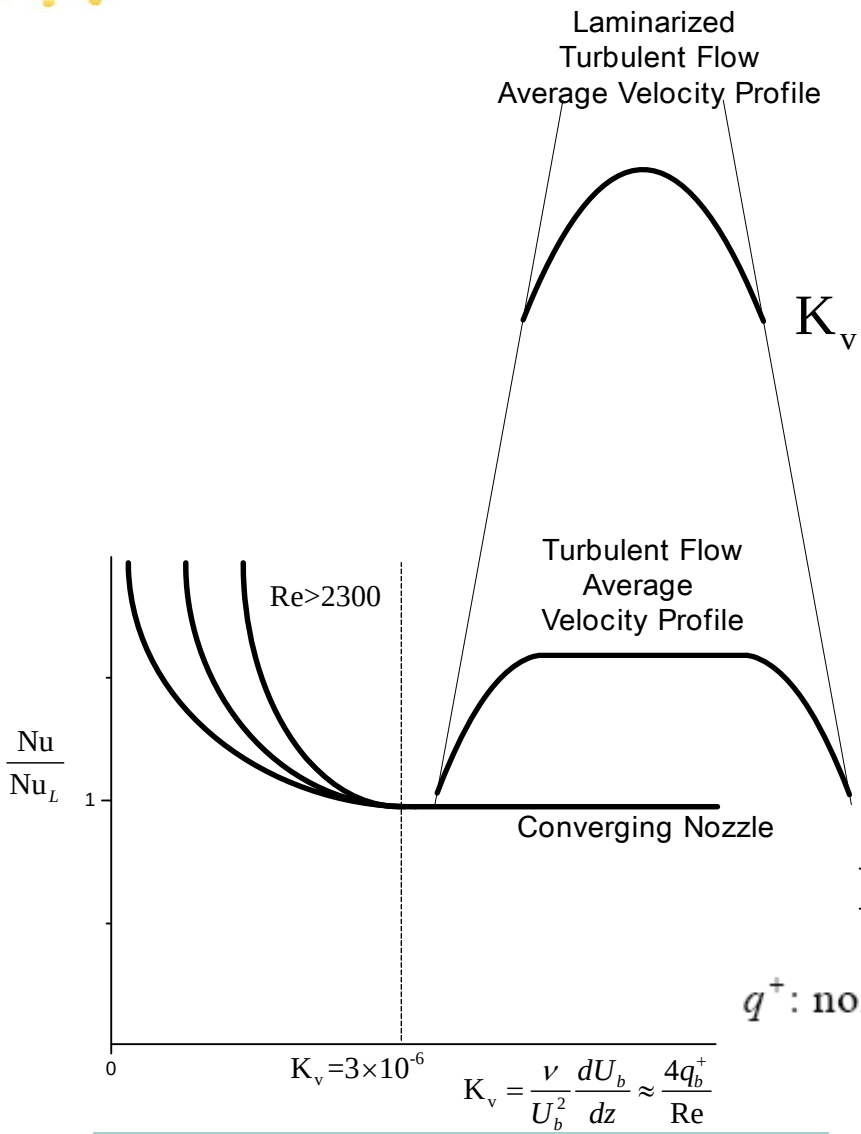
HT Deterioration due to Buoyancy Effect





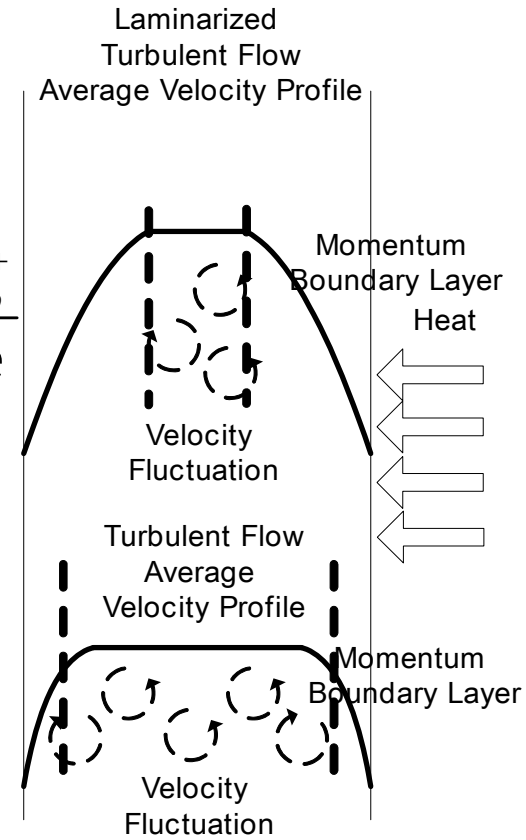
Hall & Jackson (1969)

HT Deterioration due to Acceleration Effect



$$K_v = \frac{\nu}{U_b^2}\frac{dU_b}{dz} \approx \frac{4q_b^+}{\mathrm{Re}}$$

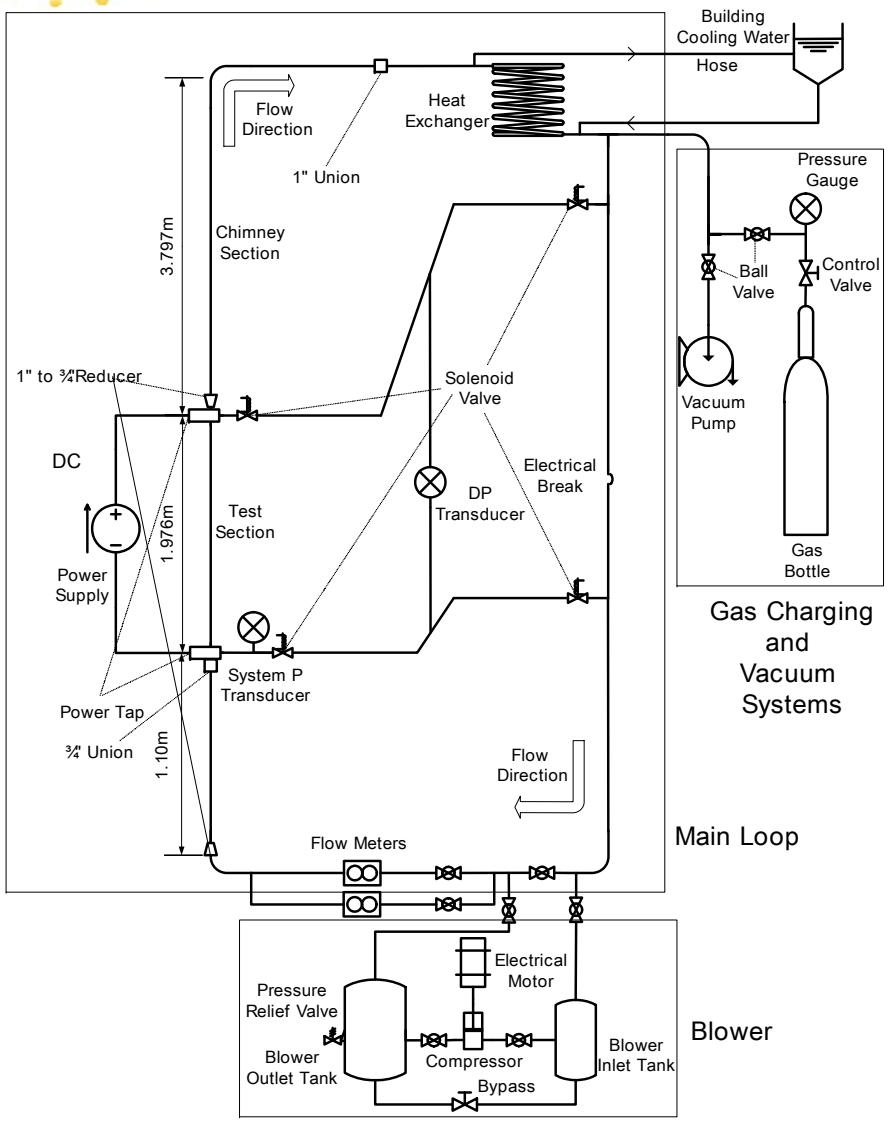
$$\approx$$



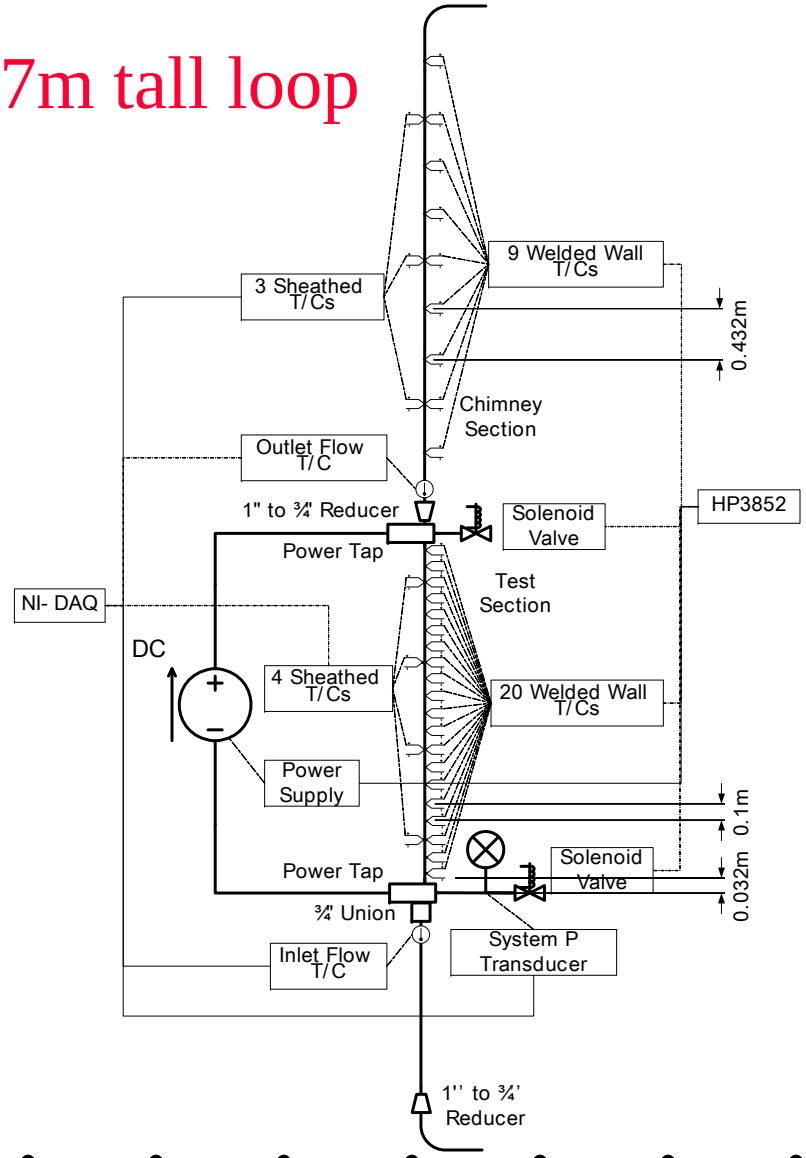
McEligot et al. (1969)

$$q^+ : \text{nondimensional heat flux} = \frac{q''_w}{GH_b} \approx \frac{q''_w}{Gc_pT_b} \approx \frac{\beta q''_w}{Gc_p}$$

Experimental Facility (1)

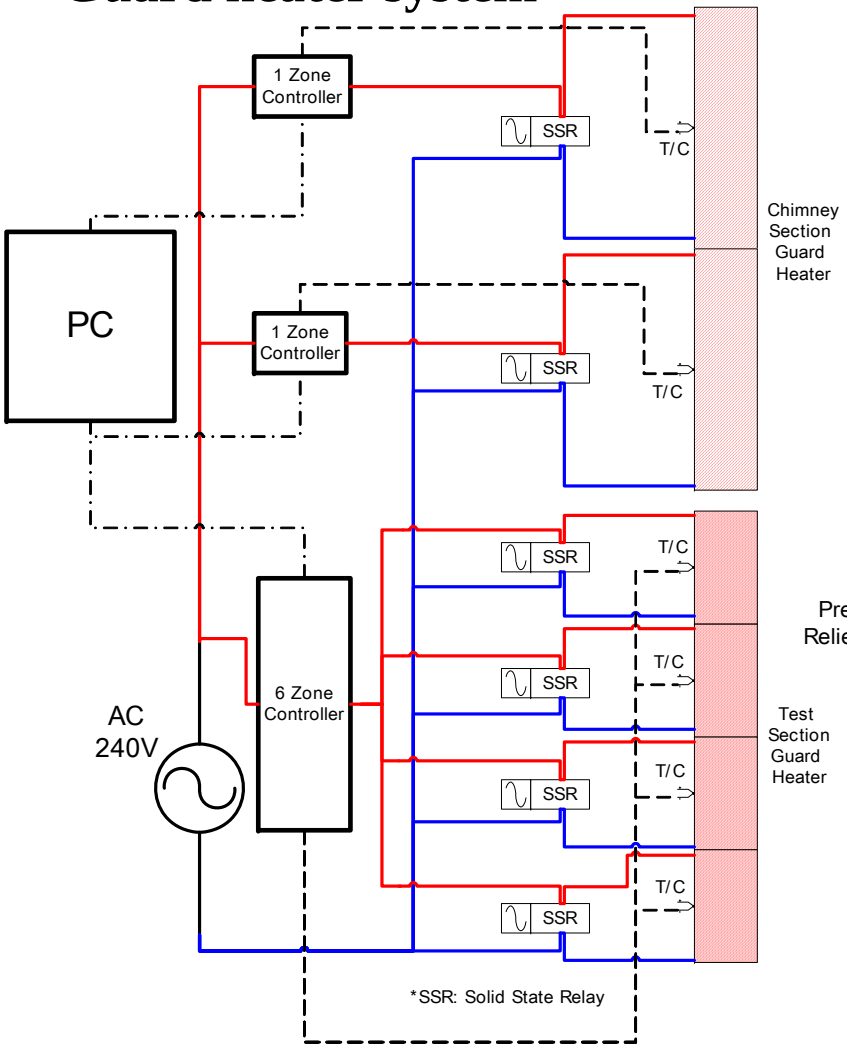


7m tall loop

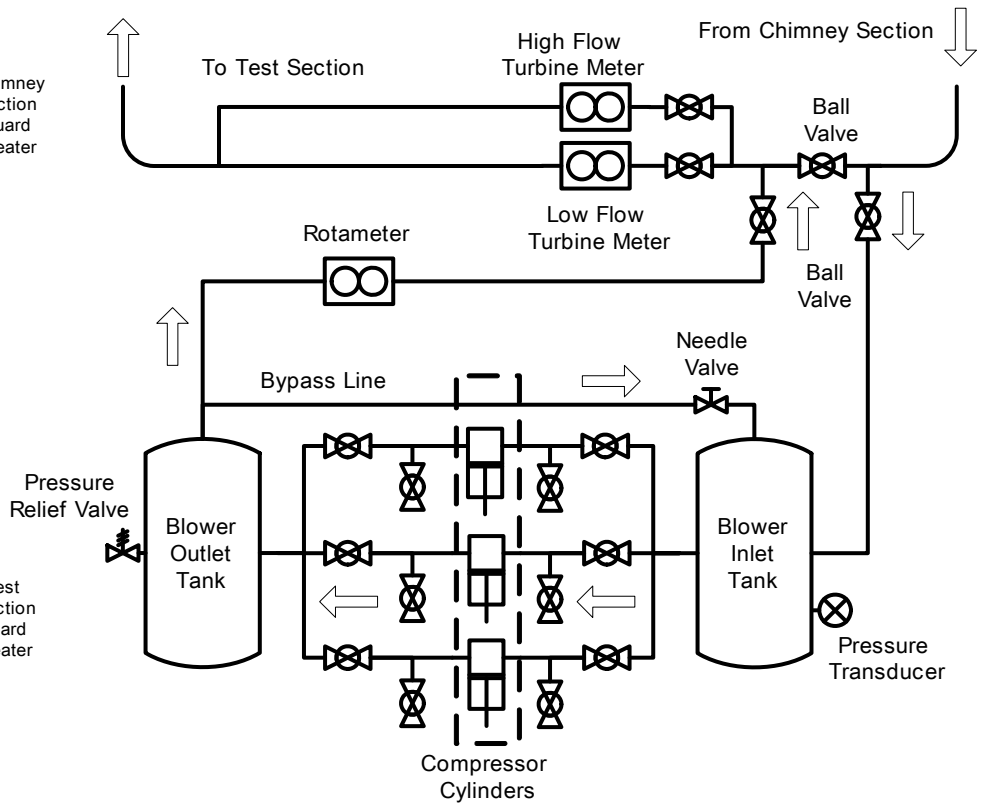


Experimental Facility (2)

Guard heater system

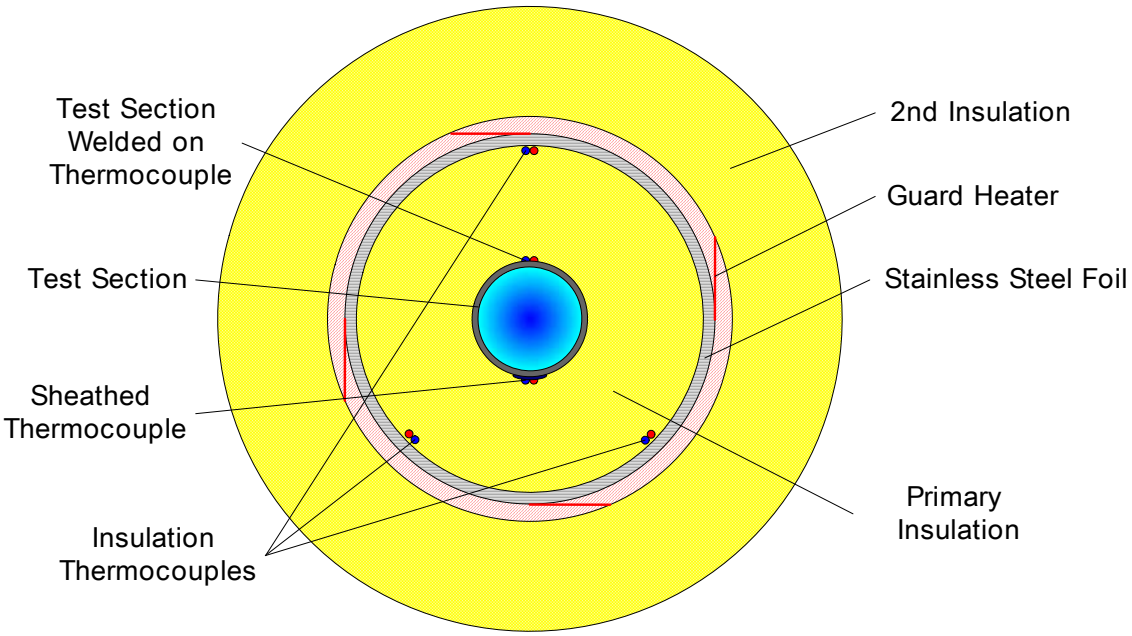


Blower system



Experimental Facility (3)

Double insulation

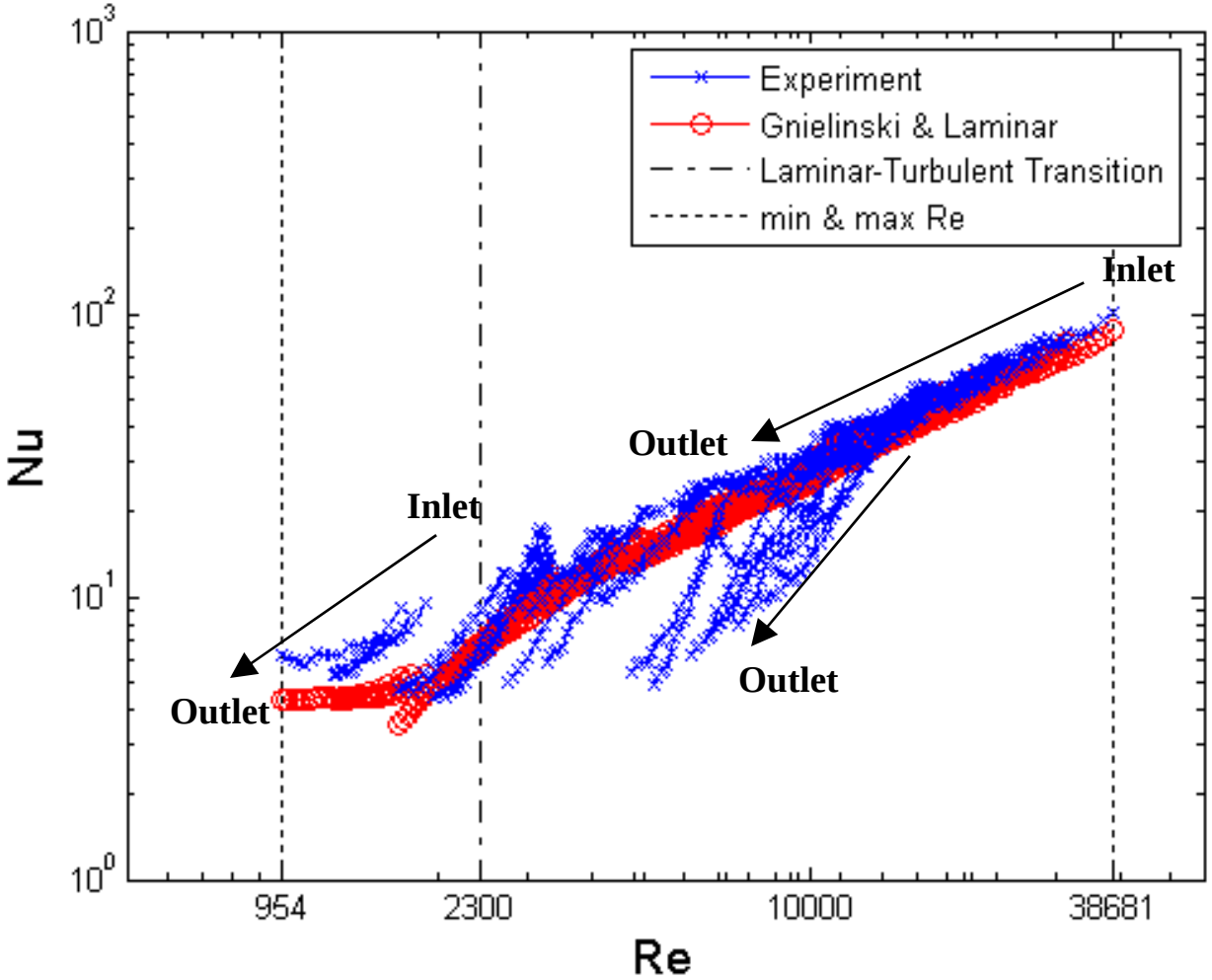


Experimental Conditions

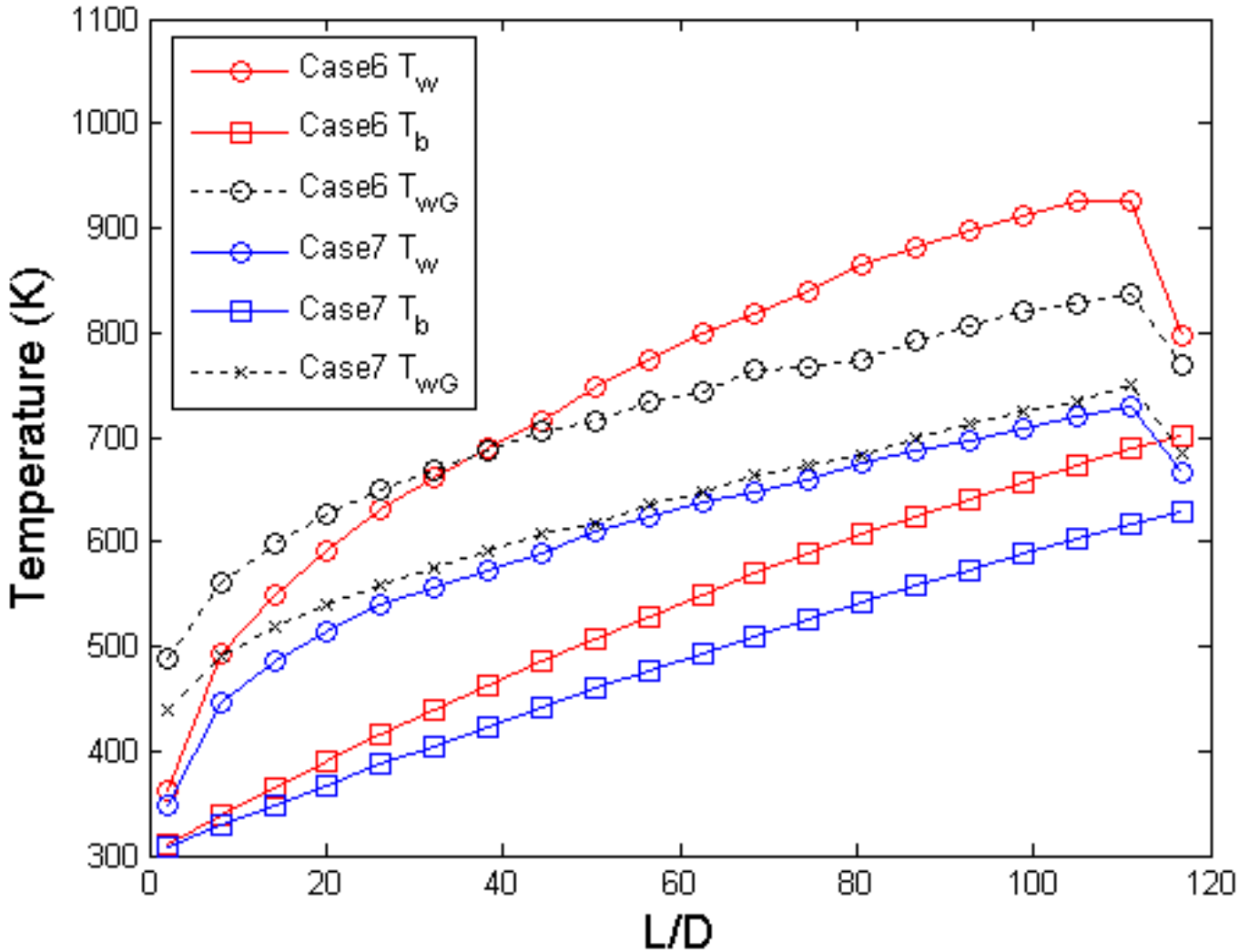
	All	N_2	He	CO_2
Total number of Runs	58 (N_2, He, CO_2)	20	15	23
Pressure Range (MPa)	0.13 – 0.67	0.13 – 0.59	0.17 – 0.40	0.13 – 0.67
Power Range (W)	200 – 2690	291 – 1989	200– 2630	720 – 2690
Volumetric Flow Rate Range (m3/sec)	$0.19 – 2.88\times10^{-3}$	$0.24 – 2.88\times10^{-3}$	$1.17 – 2.88\times10^{-3}$	$0.19 – 2.83\times10^{-3}$
Inlet Temperature (K)	302 – 304	~302	~304	~303
Inlet Re Range	1800 – 42,700	5300 – 23,600	1800 – 4,500	12,000 – 42,700
Inlet q^+ Range	0.0003 – 0.0039	0.0003 – 0.0036	0.0003 – 0.0039	0.0006 – 0.0022
Inlet Bo^* Range	$3\times10^{-9} – 1\times10^{-5}$	$3\times10^{-9} – 6\times10^{-6}$	$7\times10^{-9} – 4\times10^{-7}$	$1\times10^{-8} – 1\times10^{-5}$
Inlet K_v Range	$6\times10^{-8} – 5\times10^{-6}$	$6\times10^{-8} – 3\times10^{-6}$	$4\times10^{-7} – 5\times10^{-6}$	$8\times10^{-8} – 8.5\times10^{-7}$

Unique loop – both Kv and Bo DTHT possible

Experimental data in Nu vs. Re space

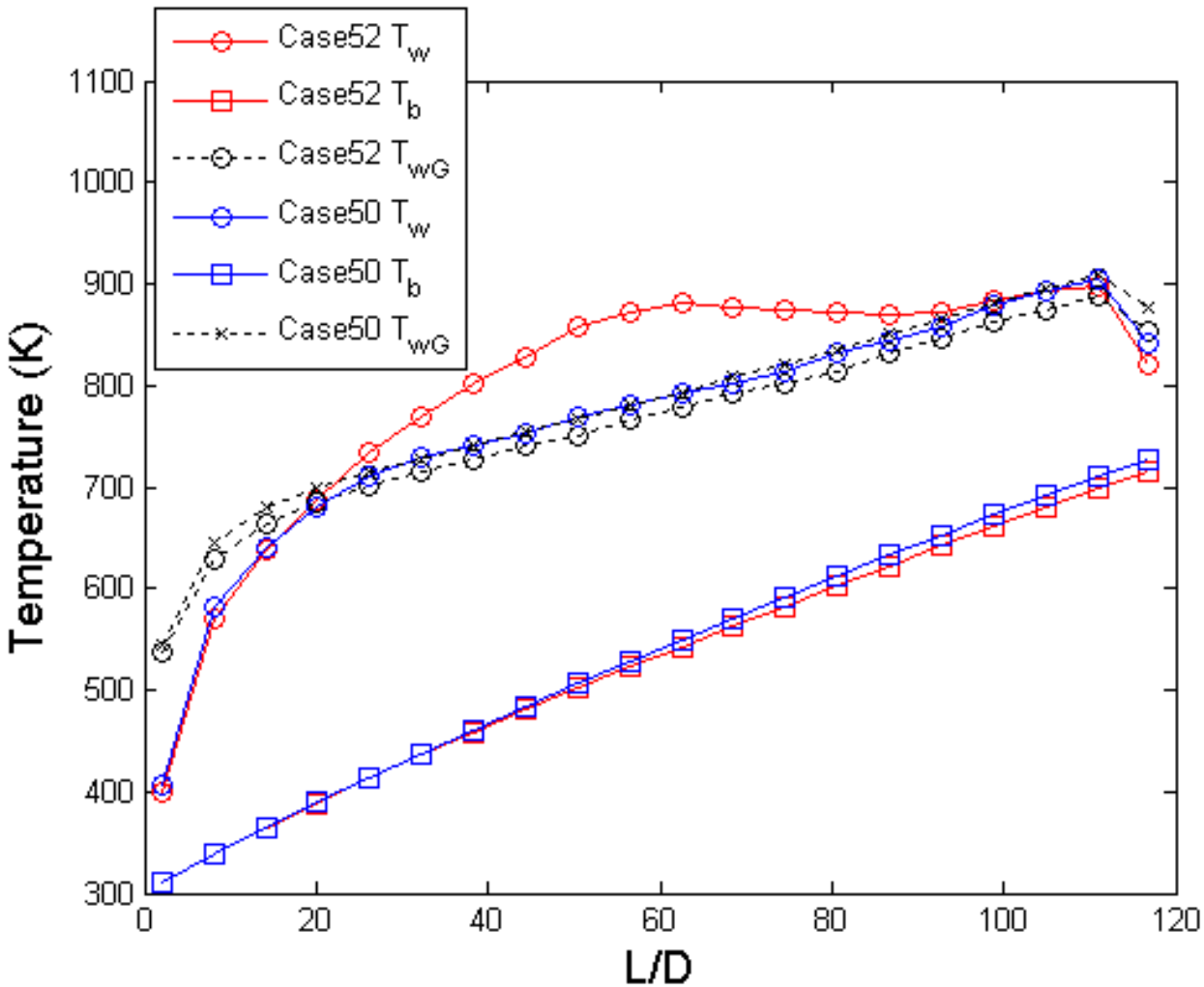


Temperature Profile - Acceleration DTHT



Run 6: Kv ~ 3×10^{-6}

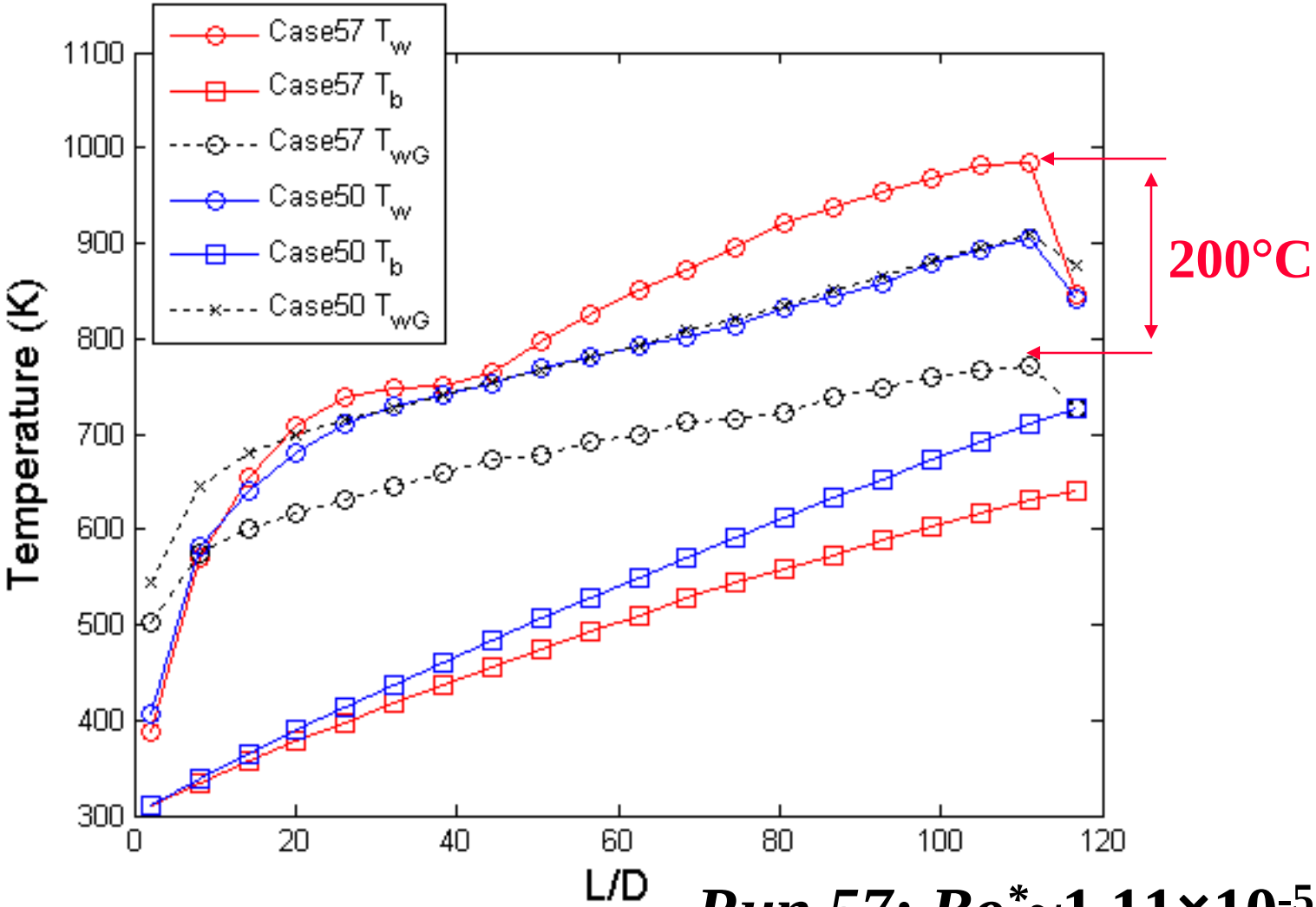
Temperature Profile - Returbulizing Buoyancy DTHT



New HT regime not see before

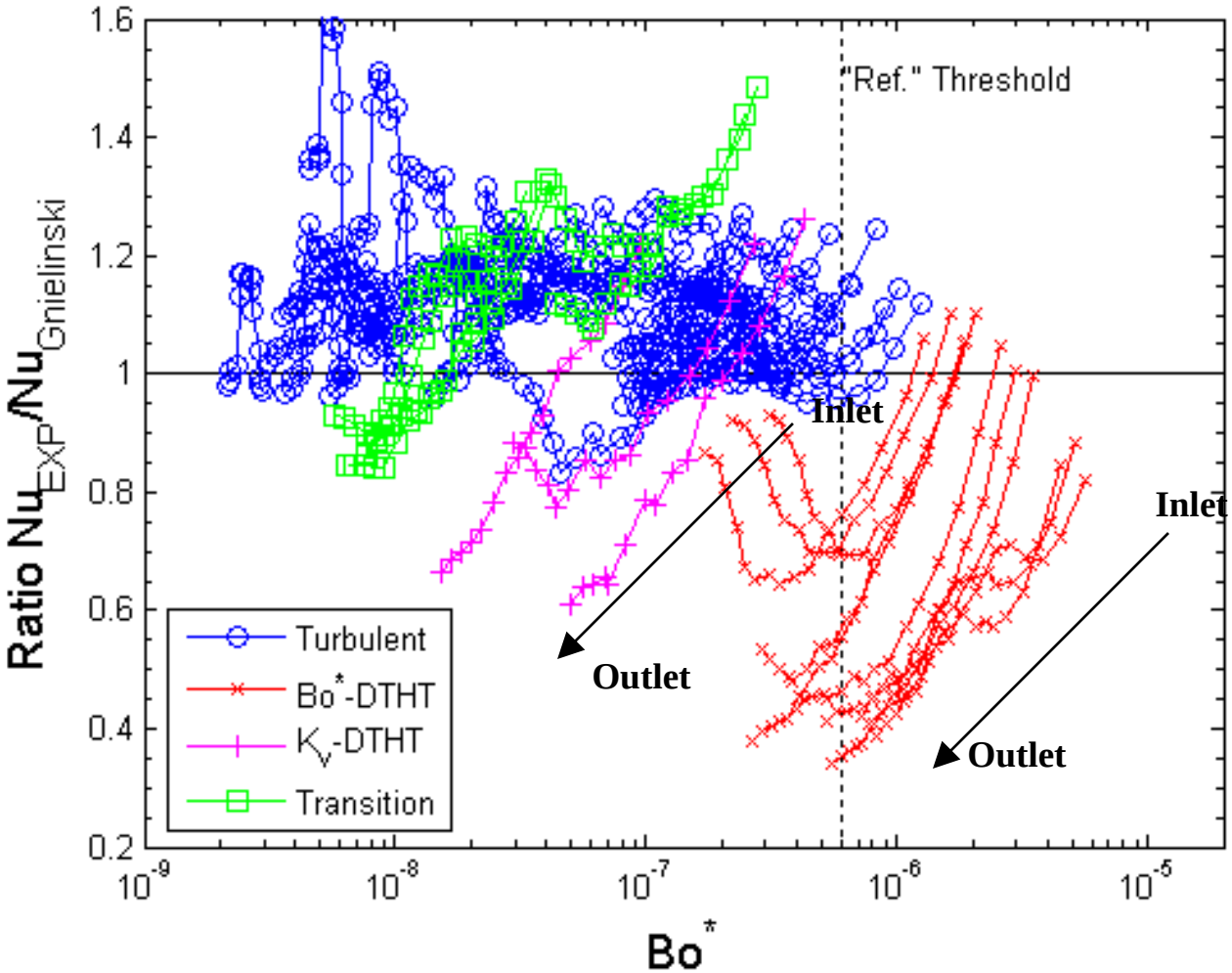
Run 52:Bo*~2.95×10^{-6}

Temperature Profile
Non-Returbulizing Buoyancy DTHT



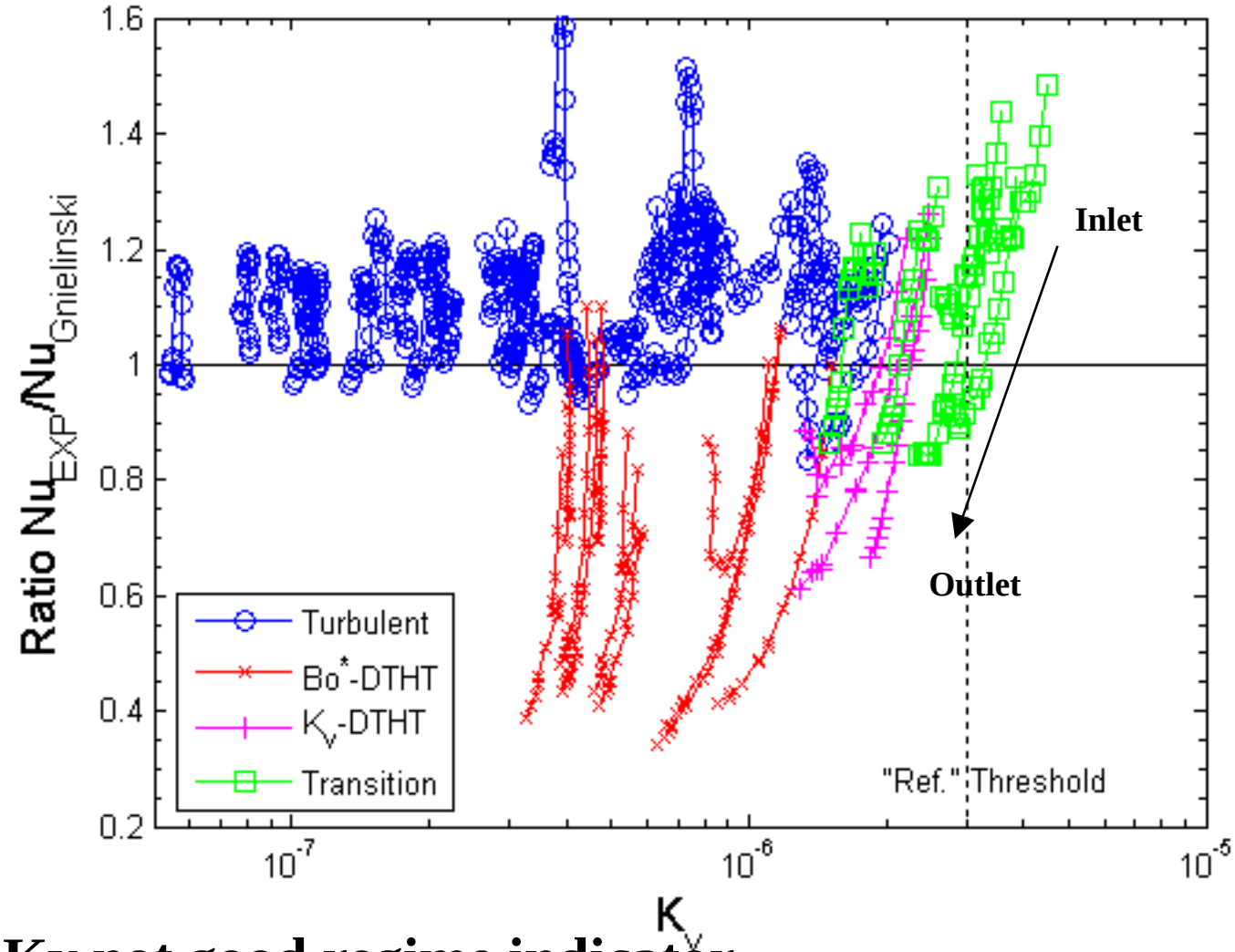
Run 57: Bo*~1.11×10^{-5}

Ratio Nu_{EXP}/Nu_G vs. Bo*



Local Bo not good regime indicator

Ratio Nu_{EXP}/Nu_G vs. Kv

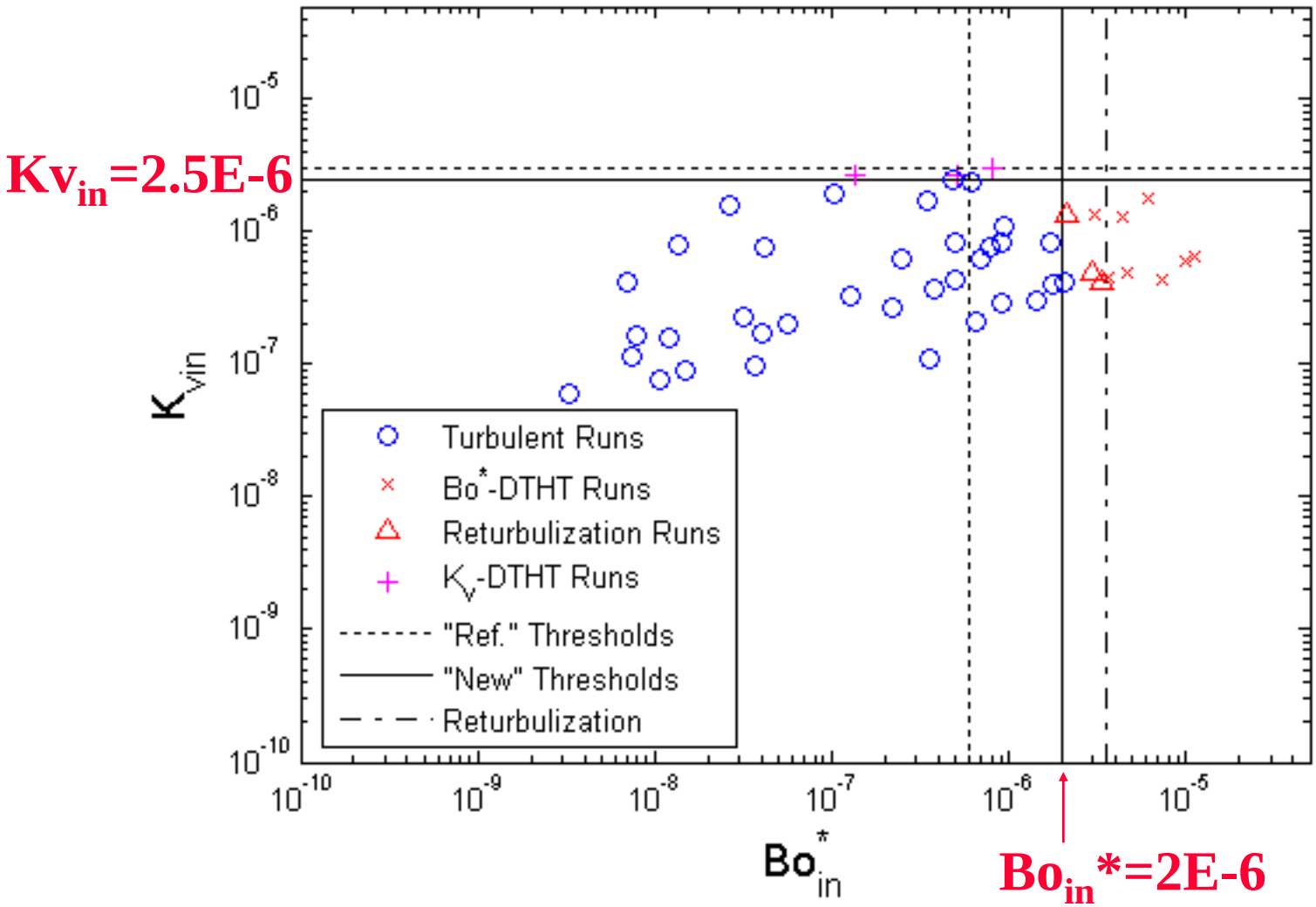


Local Kv not good regime indicator

How to determine threshold?

DTHT Threshold

Based on Inlet Kv and Bo*



One of MIT new HT correlations

If $\mathrm{Re}_{in} \le 2300$ (Mixed Convection Laminar and Forced Convection Laminar)

$$\mathrm{Nu}_{\mathrm{TYPE3-Laminar}} = \max\left(1, 3.0\left(\frac{\mathrm{Gr}_q}{\mathrm{Re}^2}\right)^{0.11}\right)\mathrm{Nu}_{\mathrm{Laminar}}$$

$$\mathrm{Nu}_{\mathrm{Laminar}} = \left(\frac{1}{\mathrm{Nu}_\infty} - \frac{1}{2}\sum_{m=1}^{10}\frac{\exp\left(-\gamma_m^2 x^+\right)}{A_m \gamma_m^4}\right)^{-1}$$

$$\textit{where}\ \ \mathrm{Nu}_\infty = 4.364, \qquad x^+ = \frac{2x/D}{\mathrm{Re}\,\mathrm{Pr}},$$

$$\gamma_m = 4m + \frac{4}{3}, \qquad A_m = 0.4165\gamma_m^{-7/3}$$

If $K_{v,in} < 2.5\times10^{-6}$, $Bo^*_{in} < 2\times10^{-6}$ and $\mathrm{Re}_{in} > 2300$ (Turbulent)

$$\mathrm{Nu}_{\mathrm{TYPE3}} = \frac{\left(f/8\right)\left(\mathrm{Re}-1000\right)\mathrm{Pr}}{1+12.7\sqrt{f/8}\left(\mathrm{Pr}^{2/3}-1\right)}\left(\frac{T_w}{T_b}\right)^{-0.5}\left(1+\frac{x}{D}^{-\frac{2}{3}}\right)$$

$$f = \left(1.82\log_{10}\mathrm{Re}-1.64\right)^{-2}$$

If $K_{v,in} \ge 2.5\times10^{-6}$, $Bo^*_{in} \ge 2\times10^{-6}$ and $\mathrm{Re}_{in} > 2300$ (DTHT)

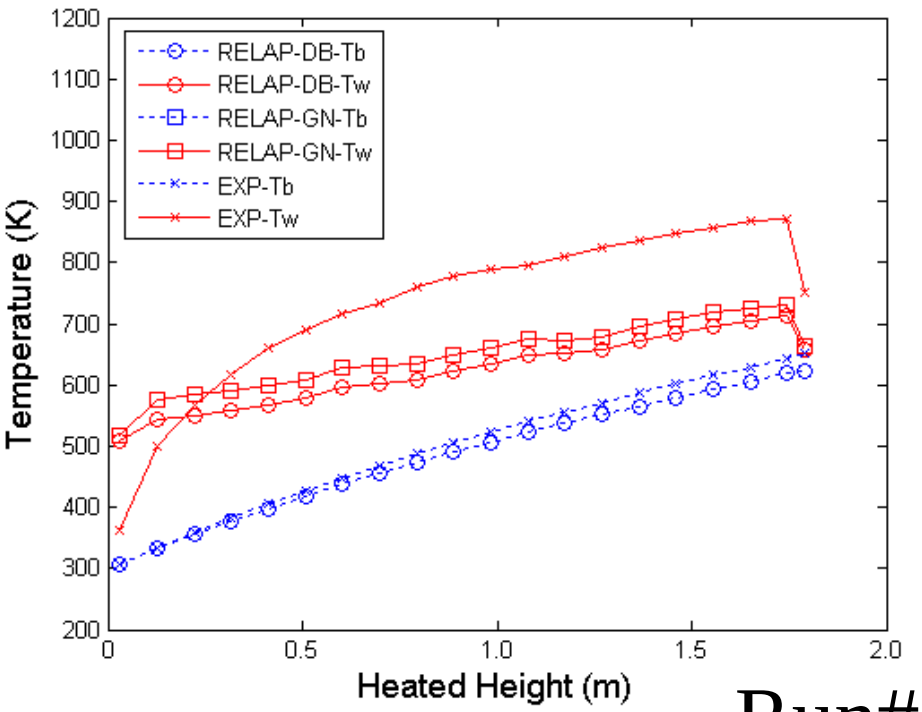
$$\mathrm{Nu}_{\mathrm{TYPE3-}temp} = \frac{\left(f/8\right)\left(\mathrm{Re}-0.011\left(\frac{q^+}{\mathrm{Re}^{0.44}}\right)^{-1.16}\right)\mathrm{Pr}}{1+12.7\sqrt{f/8}\left(\mathrm{Pr}^{2/3}-1\right)}\left(\frac{T_w}{T_b}\right)^{-0.5}\left(1+\frac{x}{D}^{-\frac{2}{3}}\right)$$

$$f = \left(1.82\log_{10}\mathrm{Re}-1.64\right)^{-2}$$

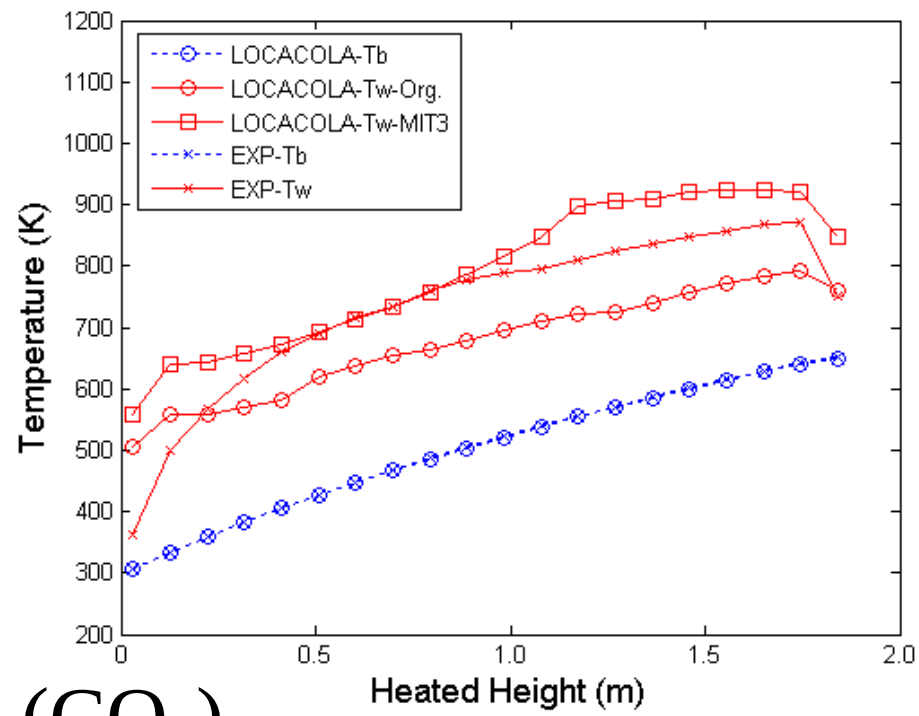
$$\mathrm{Nu}_{\mathrm{TYPE3}} = \max\left(\mathrm{Nu}_{\mathrm{TYPE3-}temp}, \mathrm{Nu}_{\mathrm{Laminar}}\right)$$

Model Comparison with Natural Circulation Data

RELAP5



LOCA-COLA



Run#5 (CO_2)

(P=0.3MPa, Re_{in}=6100, q^+ =0.0023 $Bo^*=1.05\times10^{-5}$, $Kv=5.18\times10^{-6}$)

- Both acceleration and buoyancy driven DTHT regime
- 20% uncertainty band on a correlation can result in a significant wall temperature changes

Conclusions

- Natural circulation gas loops can operate in Bo*, Kv or Mixed DTHT regimes.
- Substantial reduction of heat transfer coefficient by as much as 70% of its forced convection value was observed.
- Most system analysis computer codes will have to update heat transfer regime maps to add the capability to predict better wall temperature in DTHT gas flow regimes.
- But uncertainty on wall temperatures will remain relatively high even for new DTHT correlations (20% uncertainty in small HTC typical of low-Re gas flow results in 100K wall temperature uncertainty versus 1K for natural circulation water flow

Details in 3 Journal Publications

- "Studies of Deteriorated Heat Turbulent Transfer Regime for Gas Cooled Fast Reactor Decay Heat Removal System", Nucl. Eng. Des., Vol. 237 (2007), p. 1033-1045
- "Deteriorated Turbulent Heat Transfer (DTHT) of Gas Up-flow in a Circular Tube: **Experimental Data**", Article in press in Int. J. of Heat and Mass Transfer
- "Deteriorated Turbulent Heat Transfer (DTHT) of Gas Up-flow in a Circular Tube: **Heat Transfer Correlations**", Article in press in Int. J. of Heat and Mass Transfer