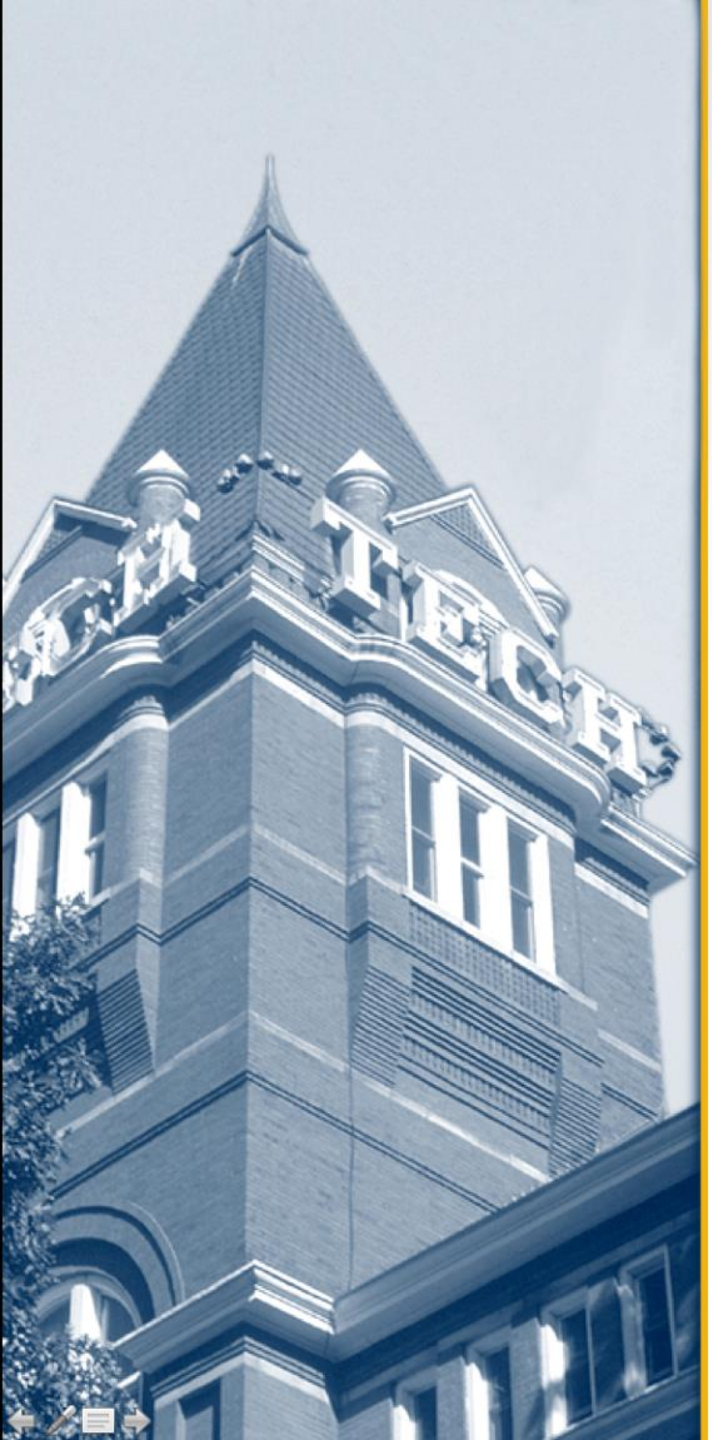

Experimental investigation of effect of buoyancy on supercritical carbon dioxide heat transfer in round tubes

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The 4th International Symposium – Supercritical CO_2 power cycles

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Contents

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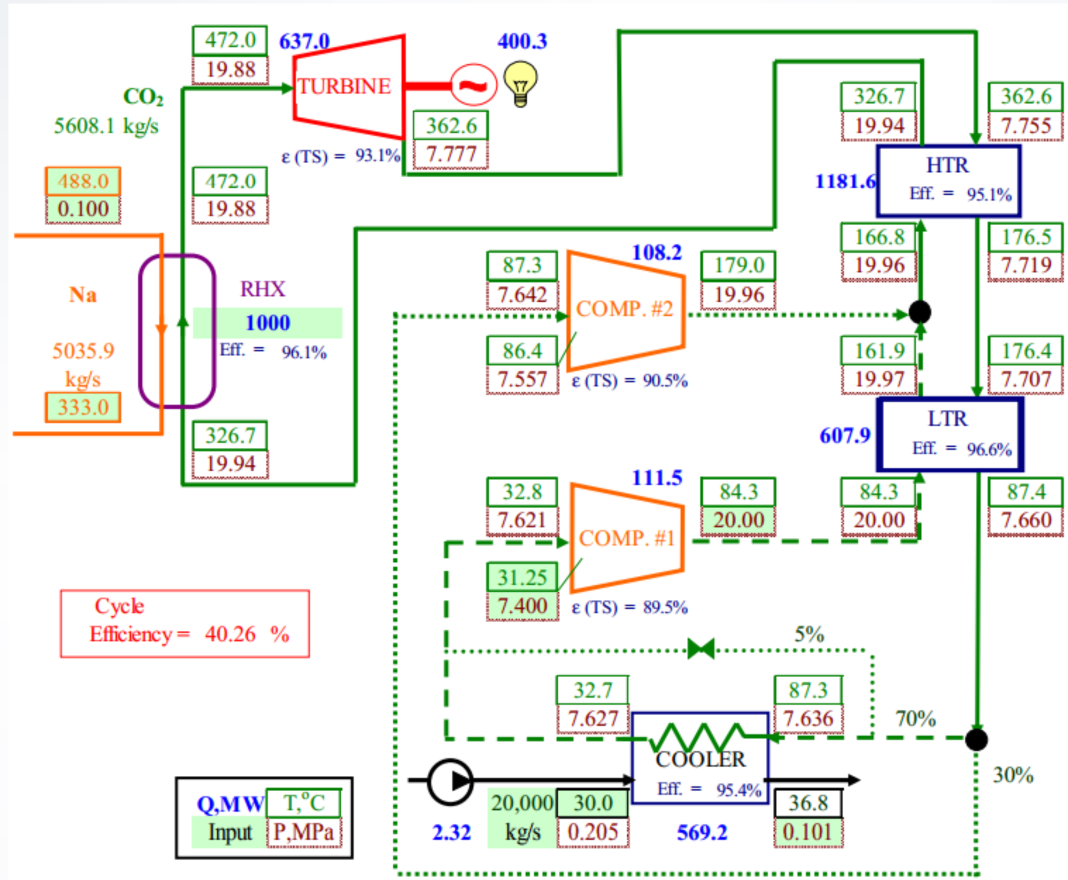
Motivation for the study

- Heat exchangers in the cycle
  - High temperature recuperator (HTR)
  - Low temperature recuperator (LTR)
  - Cooler
- Expected operating conditions
  - 7.6 – 20 *MPa*
  - 20 – 50 *KW/m*^{2}
  - 200 – 300 *Kg/m*^{2}*s*
- For these conditions, there is a need for fundamental understanding of effects of buoyancy on heat transfer
  - Various channel sizes



From ANL Plant Dynamics Code [Moisseytsev *et al*]

Experimental facility

- Heat transfer deterioration due to buoyancy effects and flow acceleration
- Key components of the test facility – A high pressure CO_2 supply pump, circulation pump, flow meter, precooler, preheater, and DC power supply
- Test section orientation can be changed with minor tubing modifications

Component	Capabilities
HPLC pump	Up to ~ 10,000 *psi*
Circulation pump	0.6 – 7.0 *GPM*
Coriolis flow meter	0 – 0.27 *Kg/sec*
Pre-heater	Maximum 5.5 *KW*
Water chiller	Maximum 5.28 *KW*
Pre-cooler	Double tube HEX
DC power supply	0 – 5 *KW*
Buffer Tank	~ 0.5 m^3

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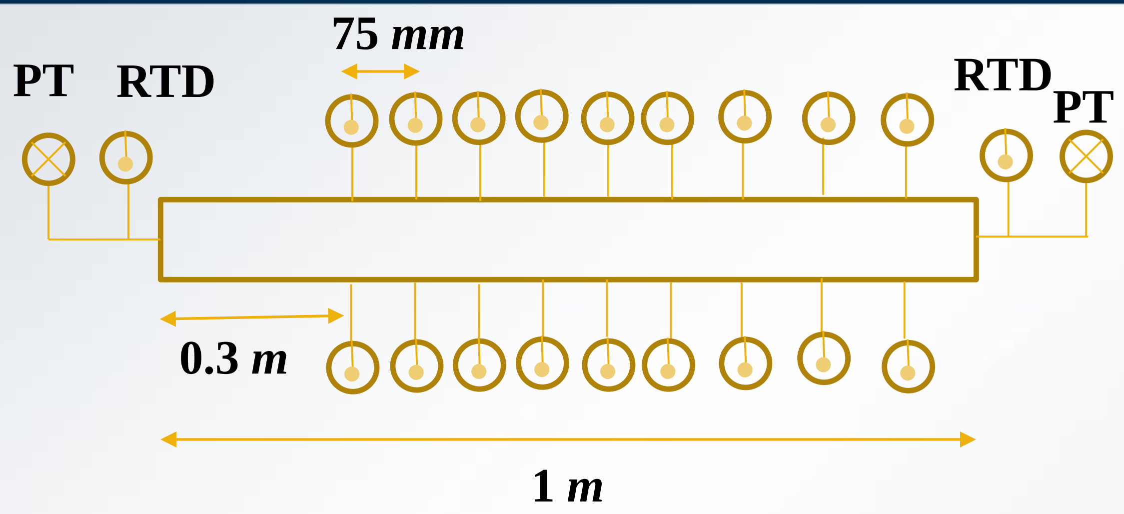
Test section



- Direct current volumetric heating
  - 10 *V*, 500 *A* power supply

- $L = 1m$, $D_{in} \sim 10.9mm$, $D_{out} \sim 12.7mm$

- RTD probes are calibrated against boiling water and ice bath

- Wall temperatures are measured using 20 E type thermocouples
  - Calibrated against RTDs under no heat flux conditions

Data analysis procedure

- Data recorded for 500 s @ 1Hz

$$Q"_{PS} = \frac{V_{PS} I_{PS}}{\pi D_i L} \quad \text{[PS – power supply]}$$

$$T_{wi} = T_{wo} + \frac{\dot{q}}{4k_{ss}}\left[\left(\frac{D_{out}}{2}\right)^2 - \left(\frac{D_{in}}{2}\right)^2\right] - \frac{\dot{q}}{2k_{ss}}\left(\frac{D_{out}}{2}\right)^2 \ln\left(\frac{D_{out}}{D_{in}}\right)$$

$$\dot{q} = \frac{V_{PS} I_{PS}}{\left[\frac{\pi}{4}(D_{out}^2 - D_{in}^2)L\right]}$$

Where, k_{ss} is the thermal conductivity of stainless steel 316

$$T_{b+1} = T_b + \frac{Q"_{PS}}{\dot{m}C_p}\pi Dx$$

- Local heat transfer coefficients and Nusselt numbers are calculated as,

$$h = \frac{Q"_{PS}}{A(T_{wi} - T_b)}$$

$$Nu_b = \frac{hD}{k_b}$$

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Results

- Effect of
  - Operating pressure
  - Flow direction
  - Inlet temperature
  - Heat flux

Control Parameters	Range of Study
Inlet Temperature	20 – 55^0 *C*
Operating pressure	7.5, 8.1, and 10.2 *MPa*
Mass flux	195, 320 Kg/m^2sec
Heat flux	0 - 65 KW/m^2
Flow direction	Horizontal, Upward, and Downward

- Buoyancy factor calculations

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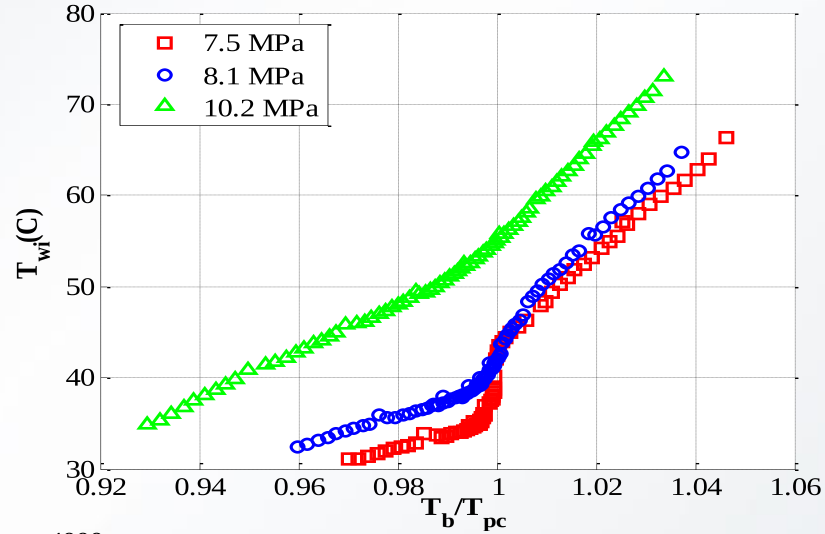
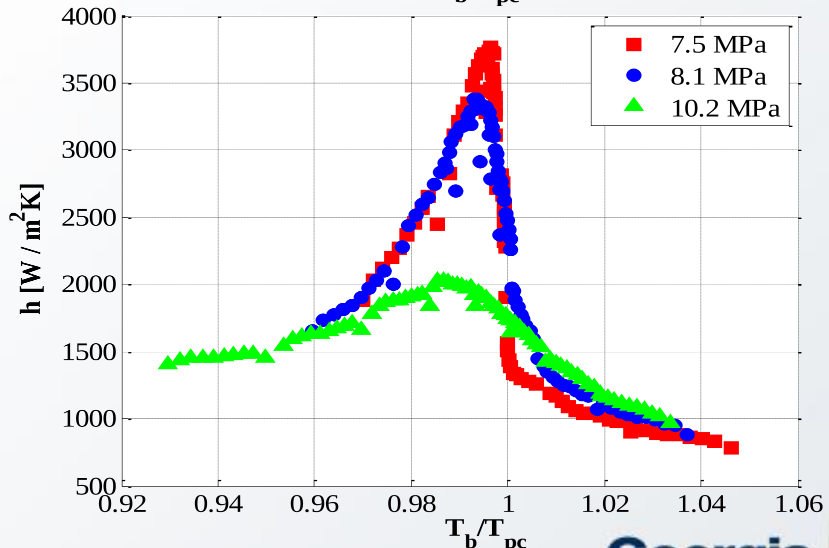
Effect of operating pressure

- Test conditions
  - Mass flux, 195 Kg/m^{2}sec
  - Heat flux, 13.5 KW/m^2
  - Downward flow
- Heat transfer enhancement close to the pseudo-critical point
- $T_b < T_{pc}$, lower operating pressure results in higher HTC's
- $T_b > T_{pc}$, higher operating pressure results in higher HTC's
- Attributed to variation of isobaric Prandtl number





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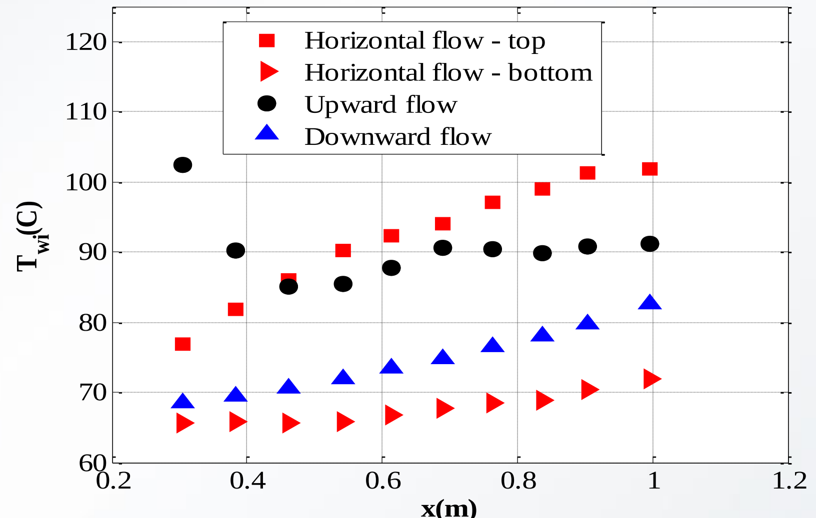
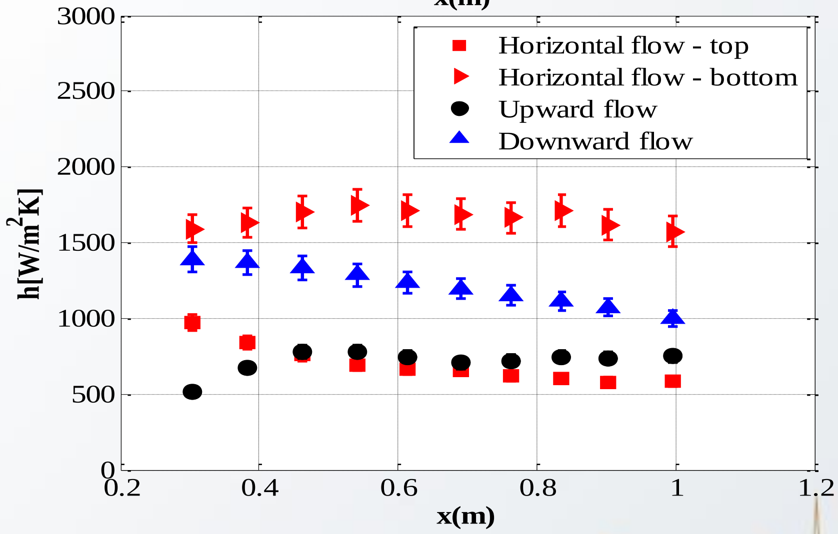
Effect of flow direction

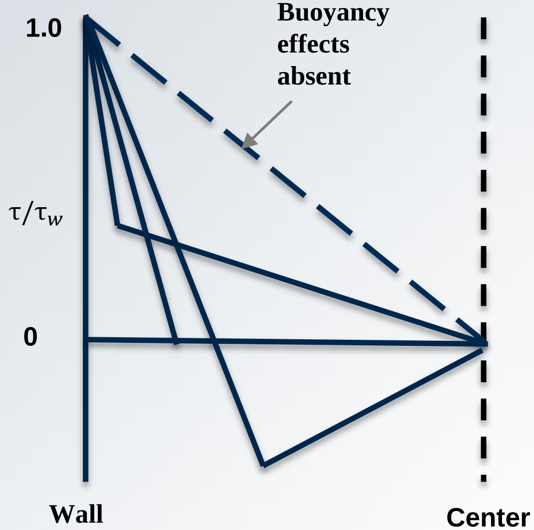
- Test conditions
  - Mass flux, 195 Kg/m^2sec
  - Heat flux, 24 KW/m^2
  - Operating pressure, 10.2 MPa
  - Bulk inlet temperature, 46^0 C
- Horizontal flow – Circumferential variation in wall temperature
- Upward flow – Localized spikes in wall temperature
- Downward flow – Wall temperatures are significantly lower than upward flow



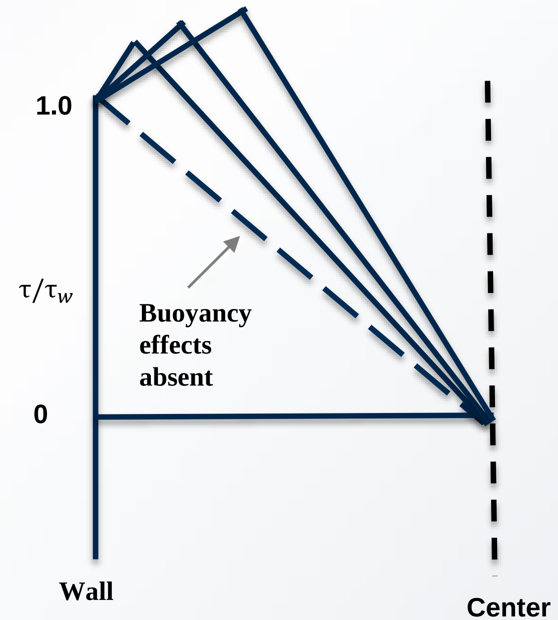


Effect of flow direction

Upward flow



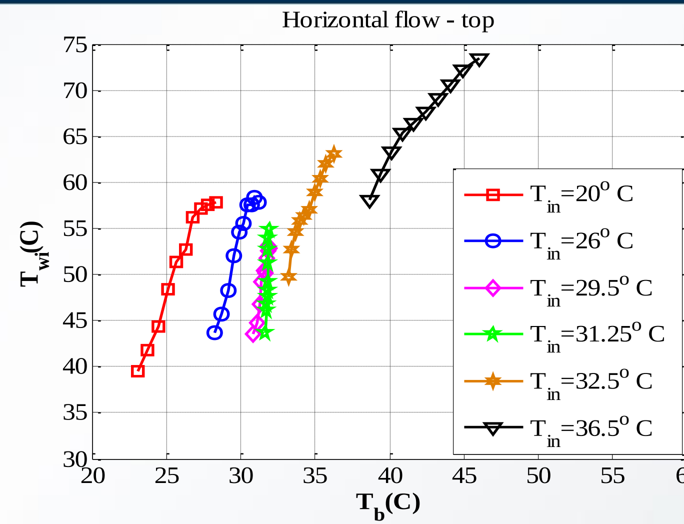
Downward flow

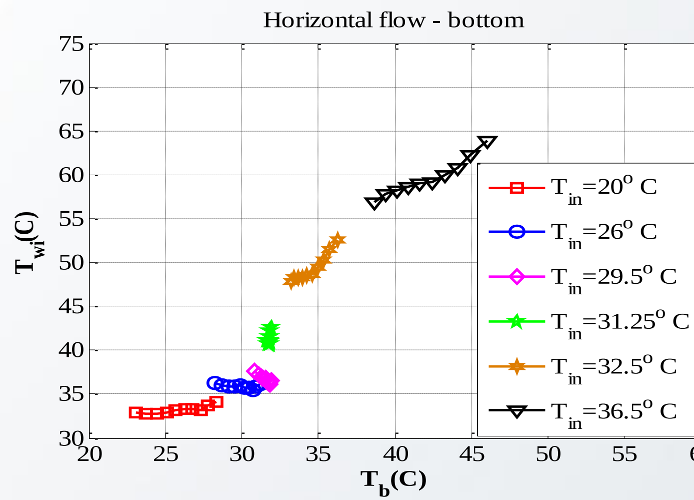


- Upward flow – Turbulent shear stress is reduced by buoyancy force
- Downward flow – Turbulent shear stress is enhanced by buoyancy force

Effect of inlet temperature

- Test conditions
  - Mass flux, 320 Kg/m²sec
  - Heat flux, 24 KW/m²
  - Operating pressure, 7.5 MPa
  - Horizontal, upward and downward flow
- Horizontal flow – Severe discontinuity in the wall temperature as the inlet temperature is changed
- Thermal entrance length effects
- Temperature differences between top and bottom sides reduce for $T_b > T_{pc}$





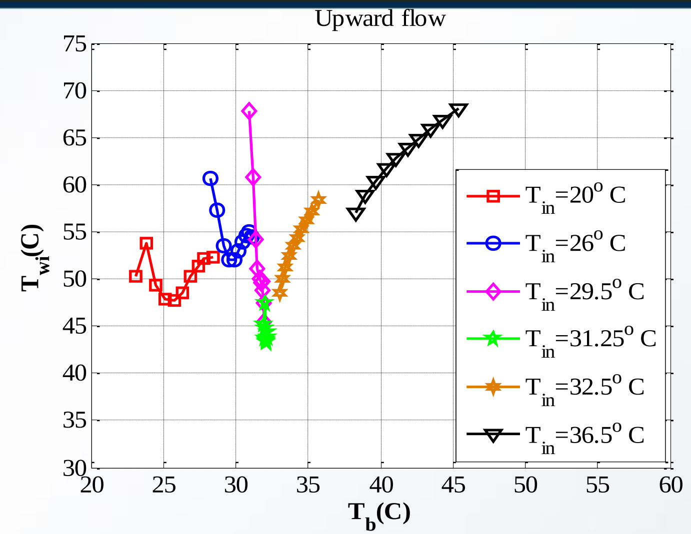
Effect of inlet temperature

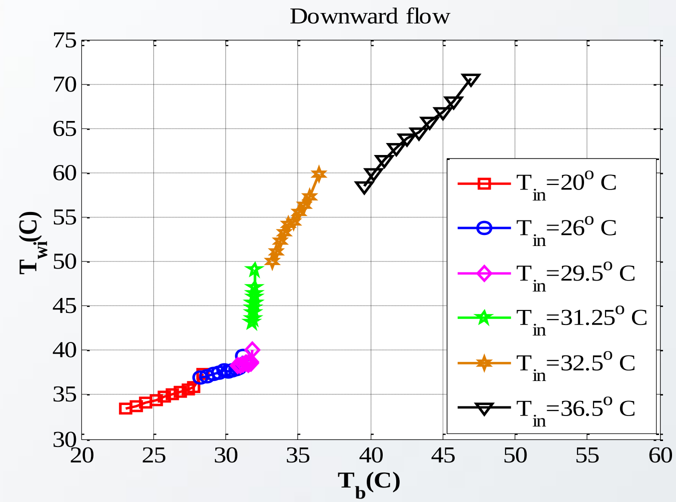
- Upward flow – Location of spikes can be readily be changed by changing the inlet temperature

- Downward flow – Sharp increase in wall temperature for $T_{in} \sim T_{pc}$

- Pseudo-film boiling phenomenon similar to film boiling at subcritical pressures

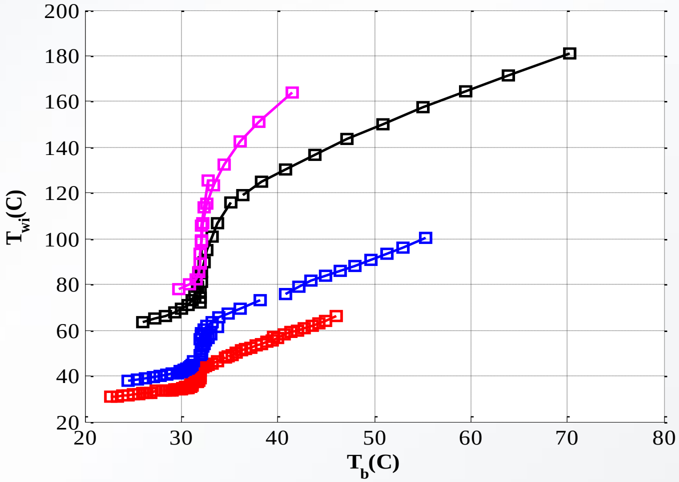
- For $T_b > T_{pc}$, wall temperatures similar for both upward and downward flows

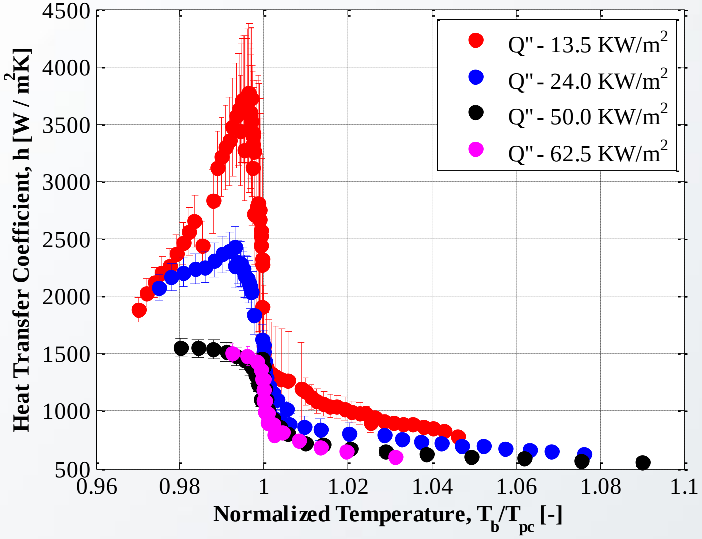




Effect of heat flux

- Test conditions
  - Mass flux, 195 Kg/m^{2}sec
  - Operating pressure, 7.5 MPa
  - Downward flow
- Heat transfer enhancement reduces with heat flux
- Area integrated values of C_p reduces
- Pseudo-film boiling phenomenon is evident for all heat fluxes





Buoyancy criteria – Vertical flows

- Experimental Nusselt numbers normalized with Jackson correlation (developed for forced convection)

$$Nu_{jackson} = 0.0183 Re_b^{0.82} Pr_b^{0.5} \left(\frac{\rho_w}{\rho_b}\right)^{0.3} \left(\frac{C_{av}}{C_{pb}}\right)^{n}$$

Where, n is defined as

$n = 0.4$ for $T_b < T_w < T_{pc}$ and $1.2T_{pc} < T_b < T_w$

$n = 0.4 + 0.2\left(\frac{T_w}{T_{pc}} - 1\right)$ for $T_b < T_w < T_{pc}$

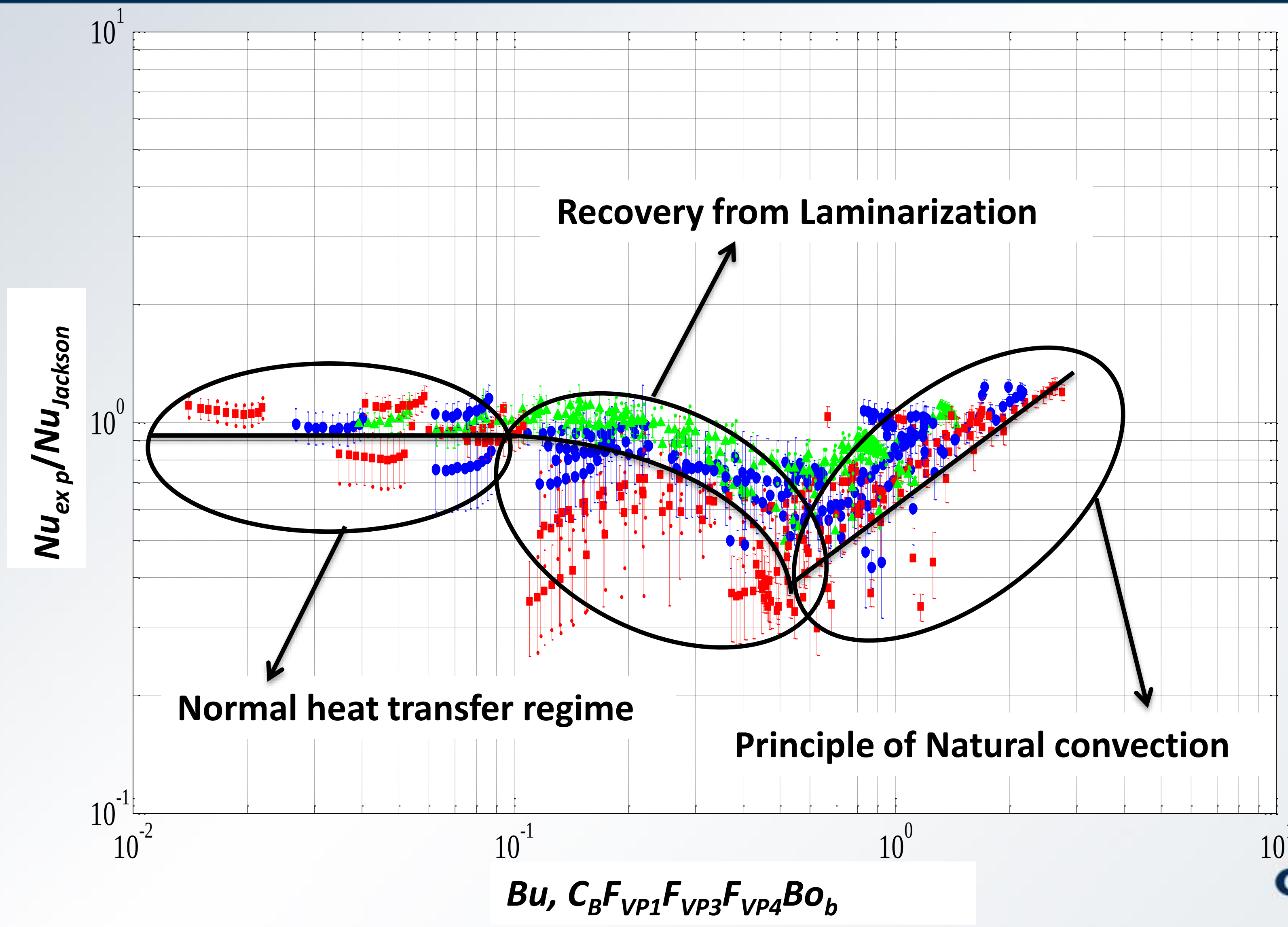
$n = 0.4 + 0.2\left(\frac{T_w}{T_{pc}} - 1\right)\left(1 - 5\left(\frac{T_b}{T_{pc}} - 1\right)\right)$ for $T_{pc} < T_b < 1.2T_{pc}$

- Jackson, 2013 buoyancy criteria

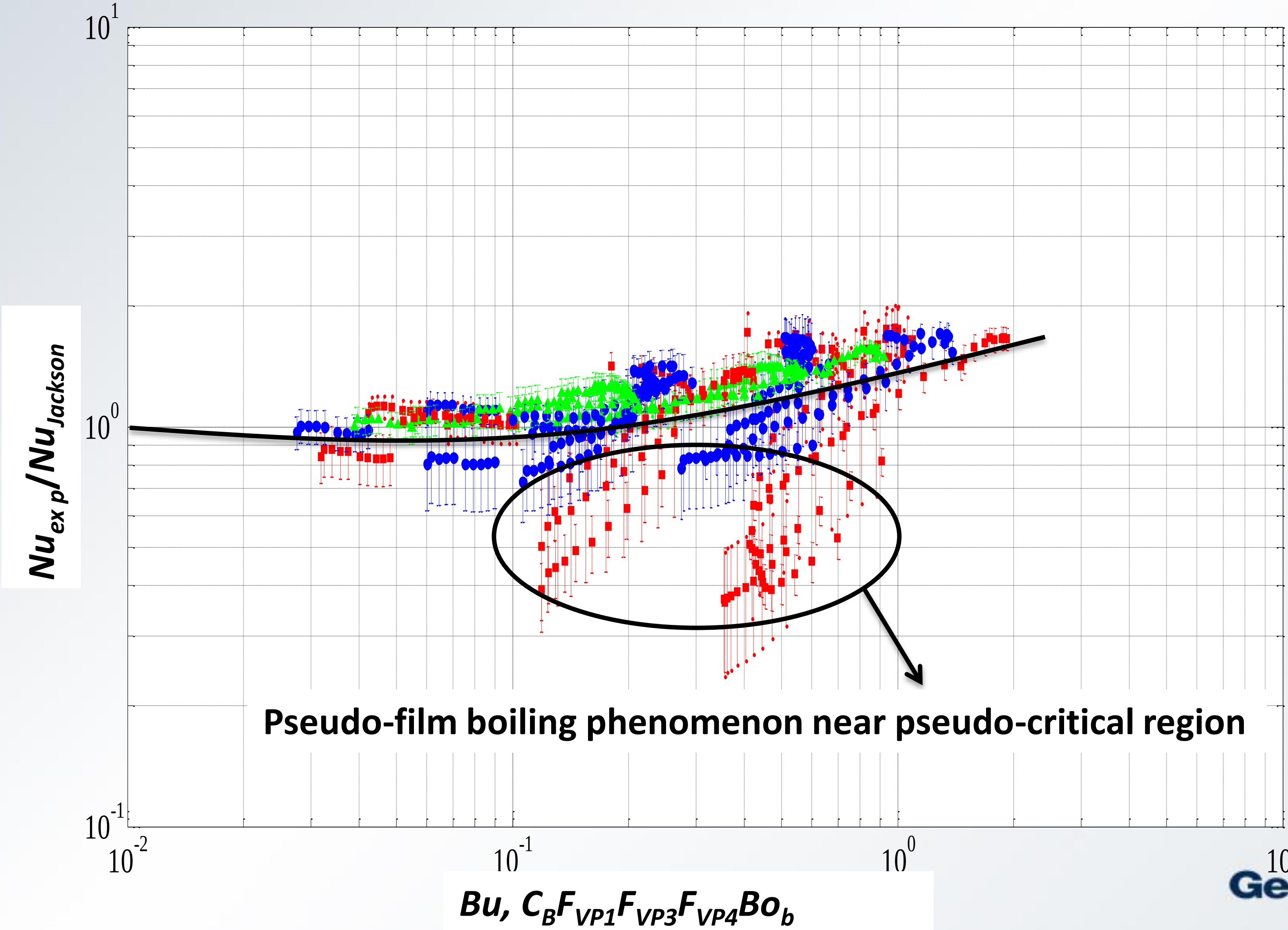
$$Bu = C_B Bo_b F_{VP1} F_{VP3} F_{VP4} < 0.04$$

$C_B = 4600$, $Bo_b = \frac{Gr_b}{Re_b^{2.625} Pr_b^{0.4}}$, $F_{VP1} = \left(\frac{\mu_{av}}{\mu_b}\right)\left(\frac{\rho_{av}}{\rho_b}\right)^{-0.5}$, $F_{VP3} = \left(\frac{Pr_{av}}{Pr_b}\right)^{-0.4}$, $F_{VP4} = \frac{\rho_b - \rho_{av}}{\rho_b - \rho_w}$

Buoyancy criteria – Upward flow

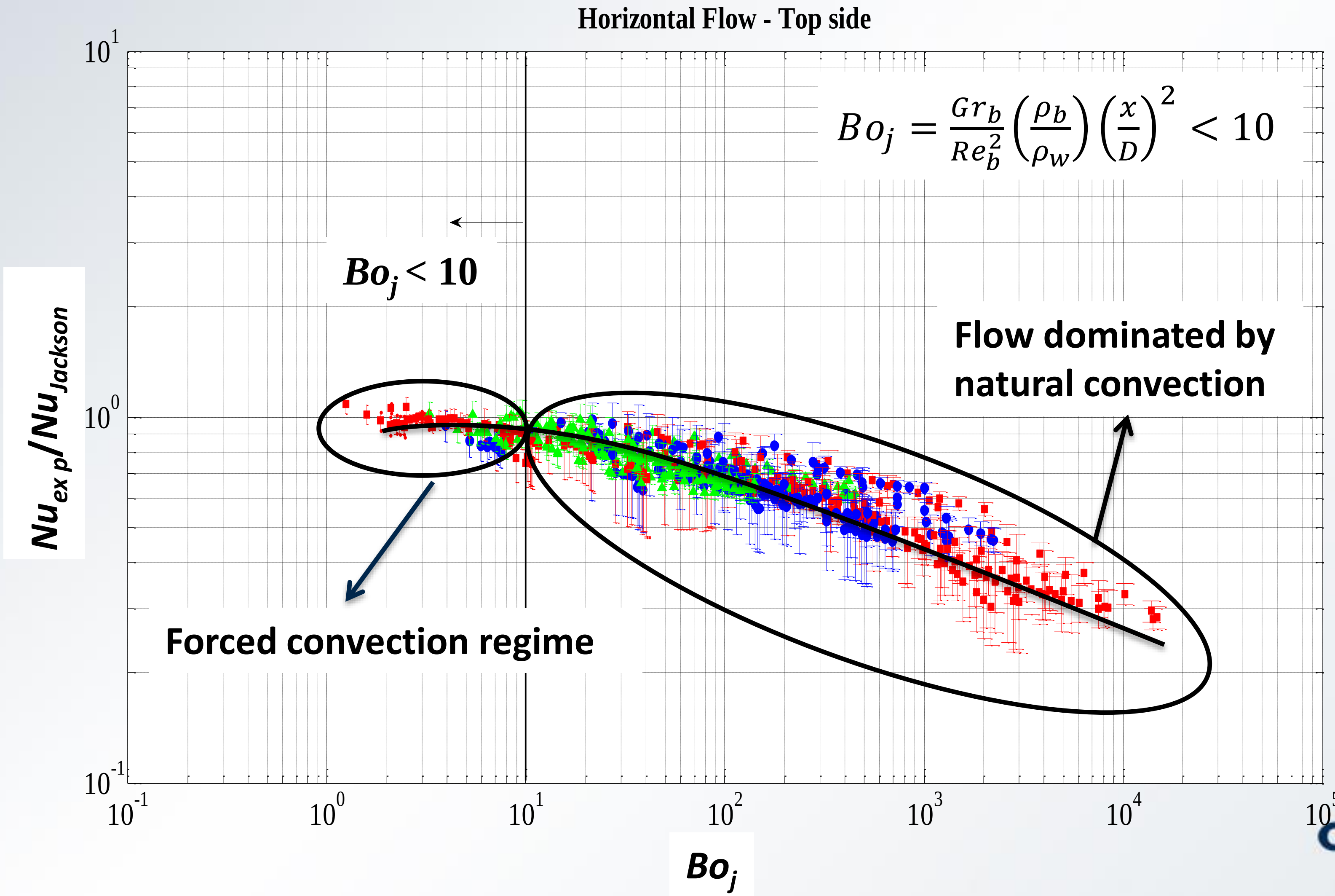


Buoyancy criteria – Downward flow



Buoyancy criteria – Horizontal flow

- Jackson, 1976 suggested a criteria to neglect buoyancy effects for horizontal flows



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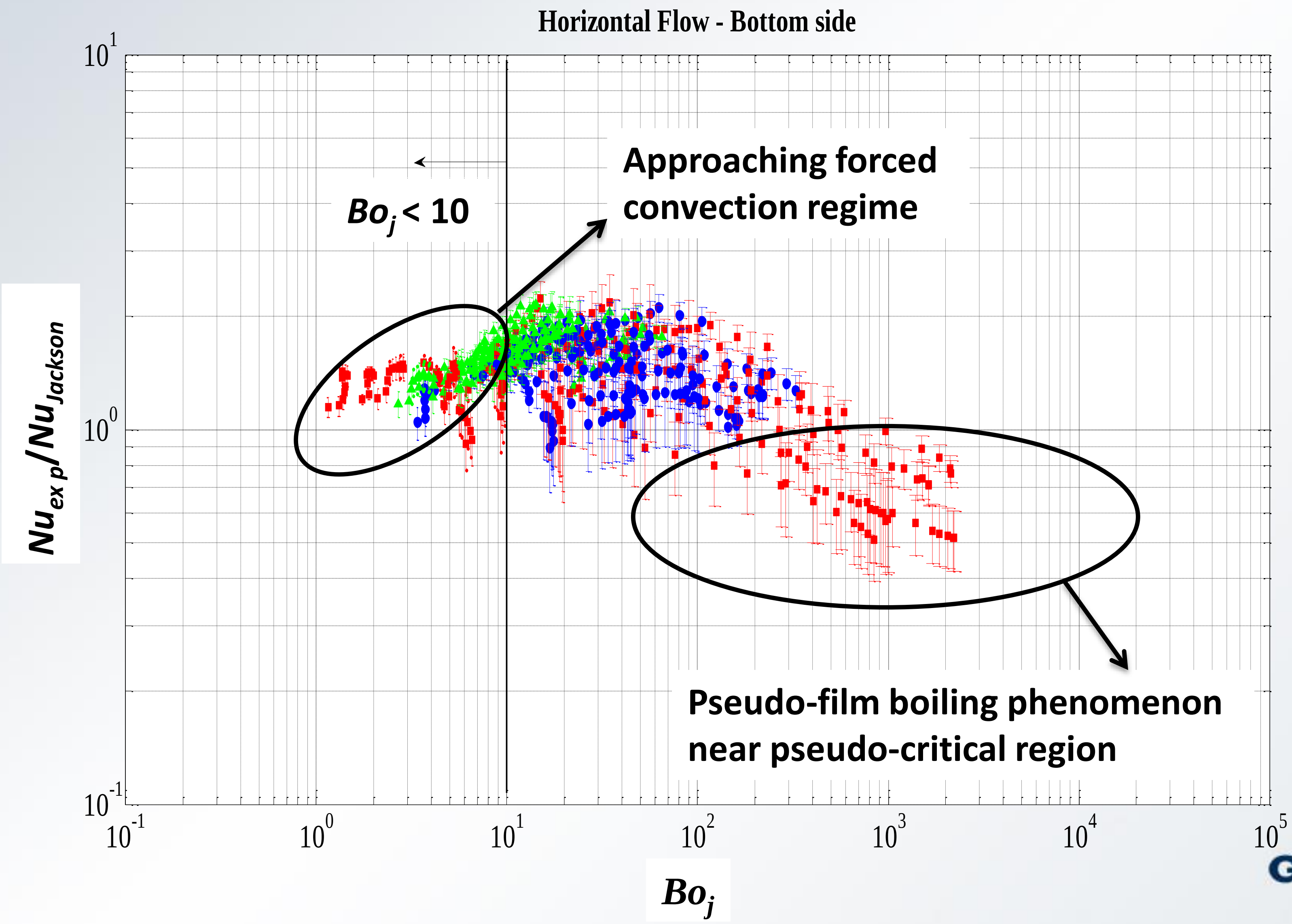
Buoyancy criteria – Horizontal flow



Summary

- Effect of buoyancy on heat transfer was investigated

- For $T_b < T_{pc}$, effect of buoyancy was significant resulting in
  - Circumferential variation of wall temperature for horizontal flow
  - Localized peaks in wall temperature for upward flow
  - Enhancement in heat transfer for downward flow

- For $T_b > T_{pc}$, effect of buoyancy was minimum leading to similar wall temperature profiles for all the flow orientations

- Buoyancy criteria suggested by Jackson can be used to predict the effect of buoyancy for both horizontal and vertical flows

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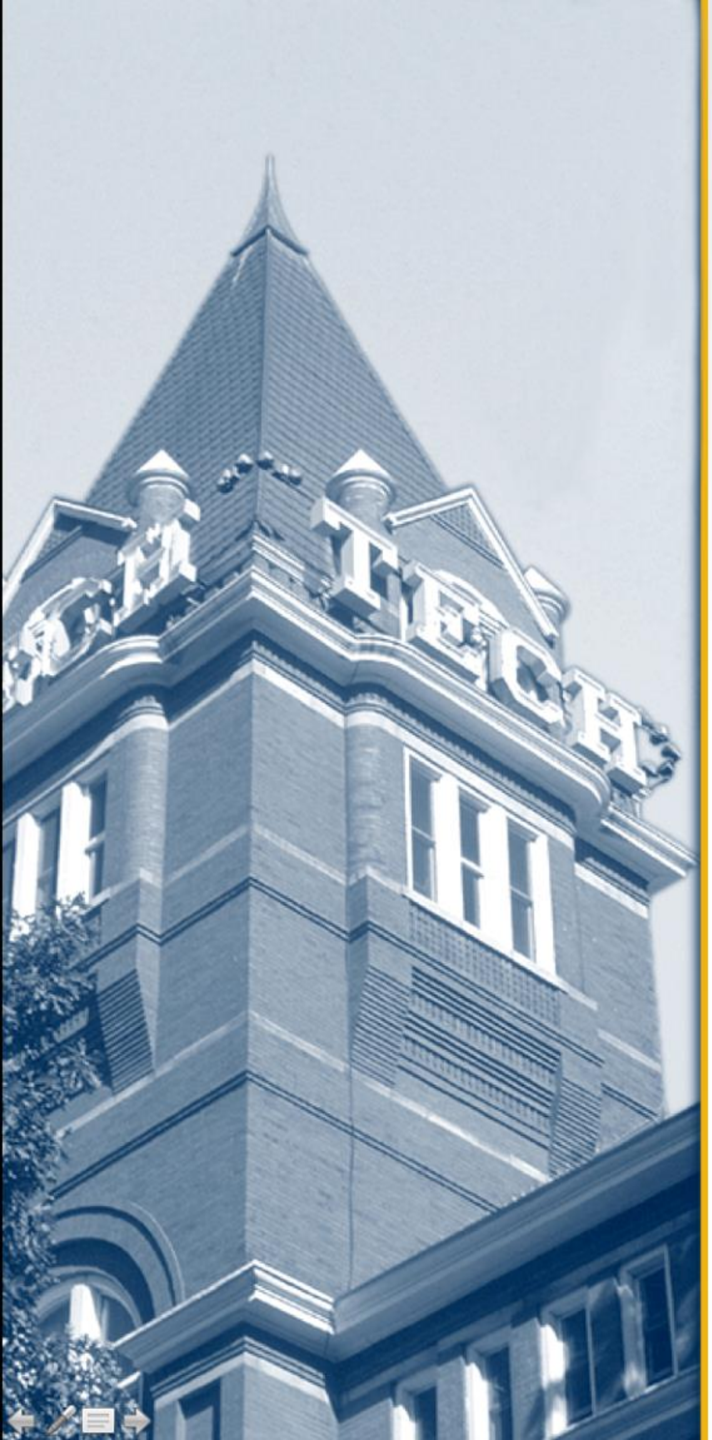

Thank you for your time!

Questions?

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