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Effective Troubleshooting of Shell-and-Tube Heat Exchangers Using CFD

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174 - Design, Optimization of Heat Exchangers
Topical 11: 2nd Topical Conference on Heat Exchangers

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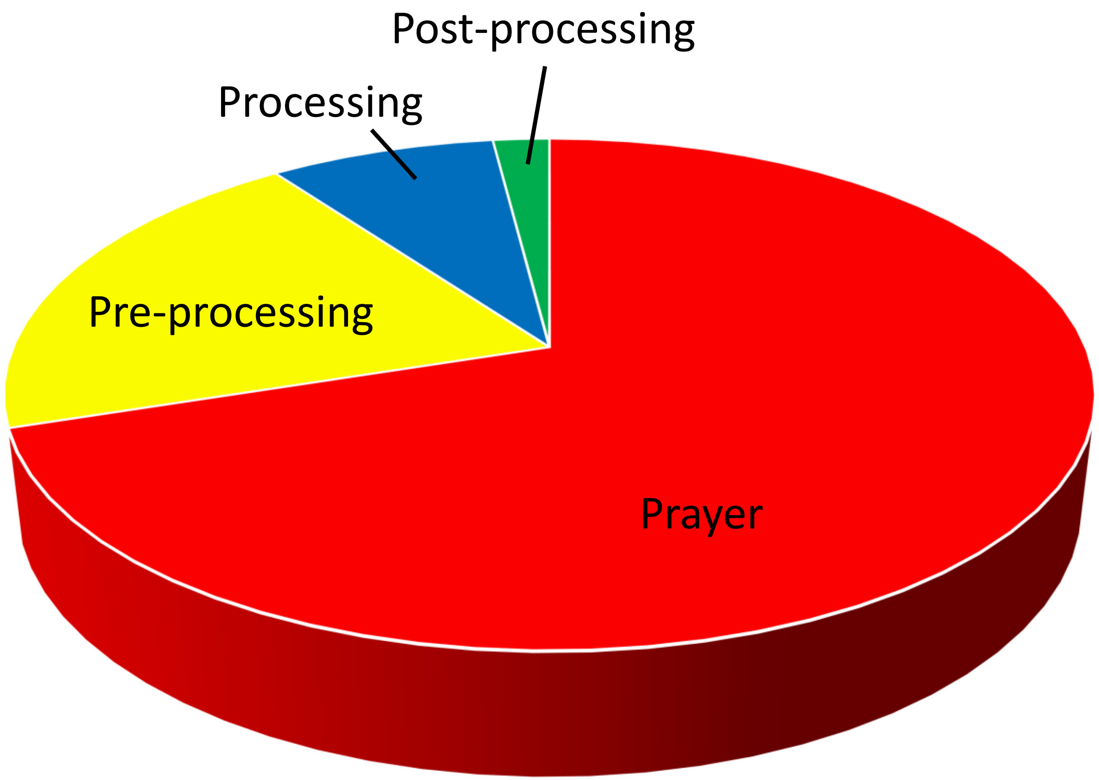
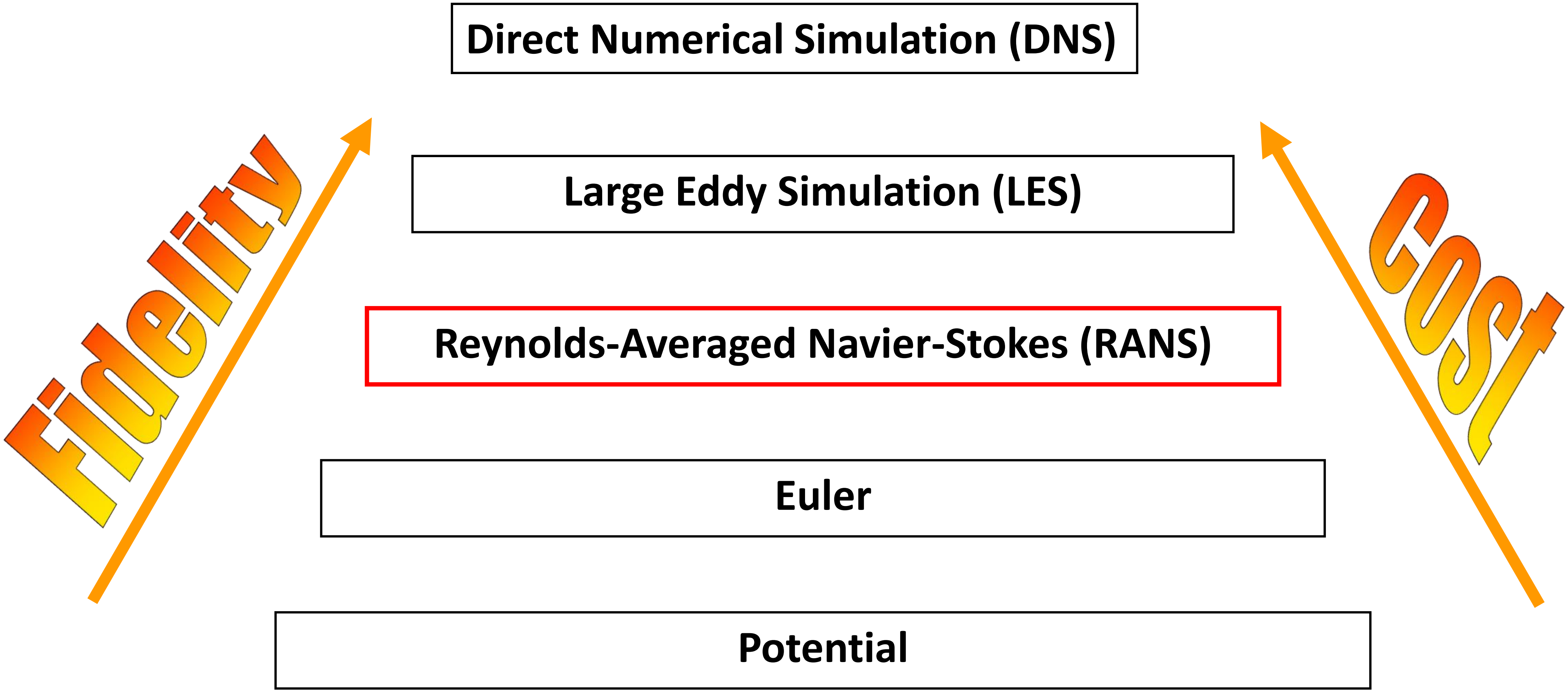
What exactly is CFD?

- Continuous frustrations and divergence
- Colors for directors
- Catastrophic failures and disappointments
- Compelling fluent disillusionment
- Confusion, flailing, and denial



Content courtesy of Prof. Wayne Strasser, Liberty University

Hierarchy of fluid flow models solved by CFD



Viewing RANS equation set conveys power of CFD

- Continuity

$$\frac{D\rho}{Dt} + \rho\vec{\nabla}\bullet\vec{V} = 0$$

- Momentum

$$\rho\frac{D\vec{V}}{Dt} = \vec{f}_{vol} - \vec{\nabla}p + \vec{\nabla}\bullet\overline{\overline{\tau}}$$

$$\overline{\overline{\tau}} = \begin{bmatrix} 0 & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & 0 & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & 0 \end{bmatrix}$$

- Energy

$$\rho\frac{Du}{Dt} = -\vec{\nabla}\bullet\vec{q} - P\left(\vec{\nabla}\bullet\vec{V}\right) + \Phi$$

- Constitutive relations
  (Stress-velocity gradient equations)

$$\tau_{xy} = \tau_{yx} = \mu\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) \qquad \tau_{xz} = \tau_{zx} = \mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) \qquad \tau_{yz} = \tau_{zy} = \mu\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)$$

- Turbulence closure
  (Two-equation model)

$$\frac{D(\rho\kappa)}{Dt} = \vec{\nabla}\bullet\left(\mu + \frac{\mu_t}{\sigma_\kappa}\right)\vec{\nabla}\kappa + G_\kappa + G_b - \rho\varepsilon_t$$

$$\frac{D(\rho\varepsilon_t)}{Dt} = \vec{\nabla}\bullet\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\vec{\nabla}\varepsilon_t - C_{2\varepsilon}\rho\frac{\varepsilon_t^2}{\kappa}$$

$$+C_{1\varepsilon}\frac{\varepsilon_t}{\kappa}\left(G_\kappa + G_b\right)$$

- Property relations
  EoS, $\rho\,(T)$, $\mu\,(T)$, $C_p\,(T)$, $k_t\,(T)$

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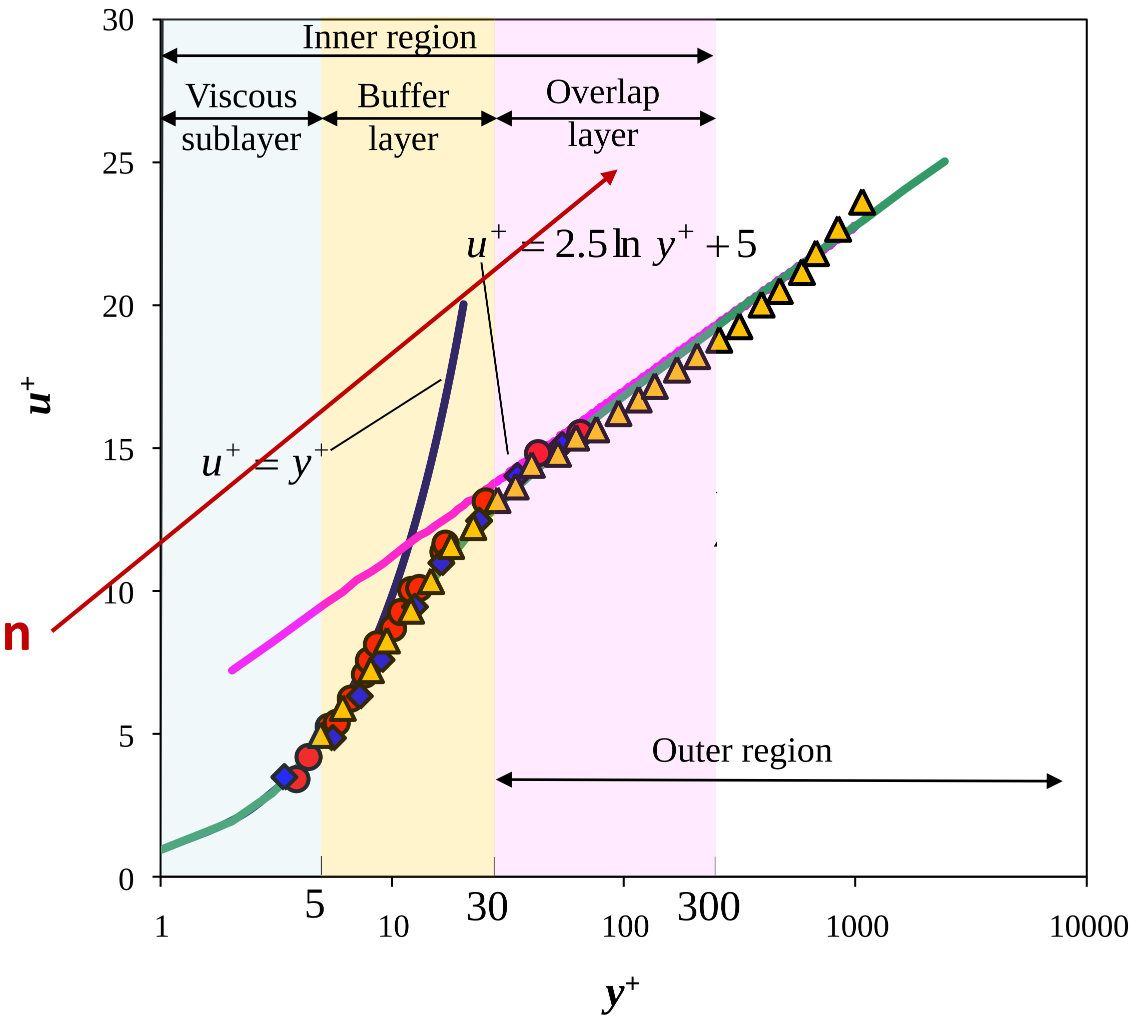
Does CFD compute drag and heat transfer from first principles?

- For laminar flows, **YES**
- For turbulent flows, two options
  1. Fine mesh spacing must be such that $y^+ \leq 1$ for wall adjacent cell, **YES**
  2. Coarser mesh with "universal" character of boundary layer captured by wall functions

     YES, with some empiricism mixed in

     - Centroid of first grid cell located in overlap layer or "log-law" region
     - Popular "scalable" options overcome this limitation
     - Usually wall functions are fine for engineering calculations



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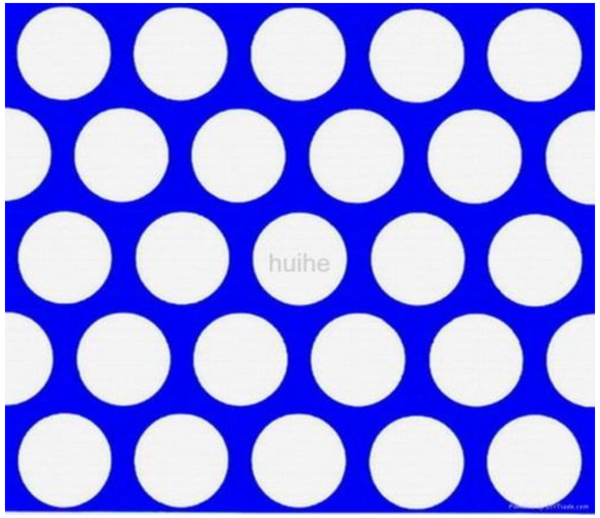
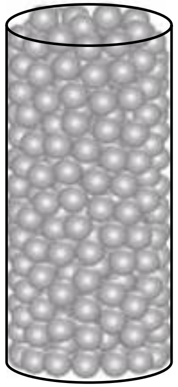
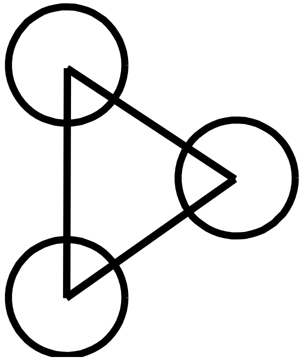
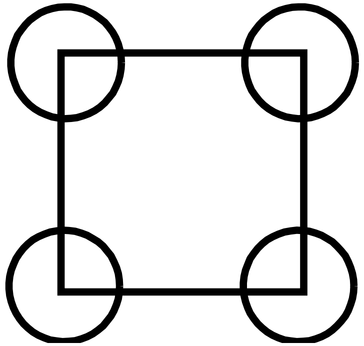
Porous media can simplify CFD models

- Can be used for single- and multiphase
- 2D: Perforated plates and distributors
- 3D: Packed beds and tube banks
- Resistance determined *a priori* via j- and f-factor relationships vs. pitch ratio and Re
- Heat transfer represented with or without thermal equilibrium between medium and fluid flow









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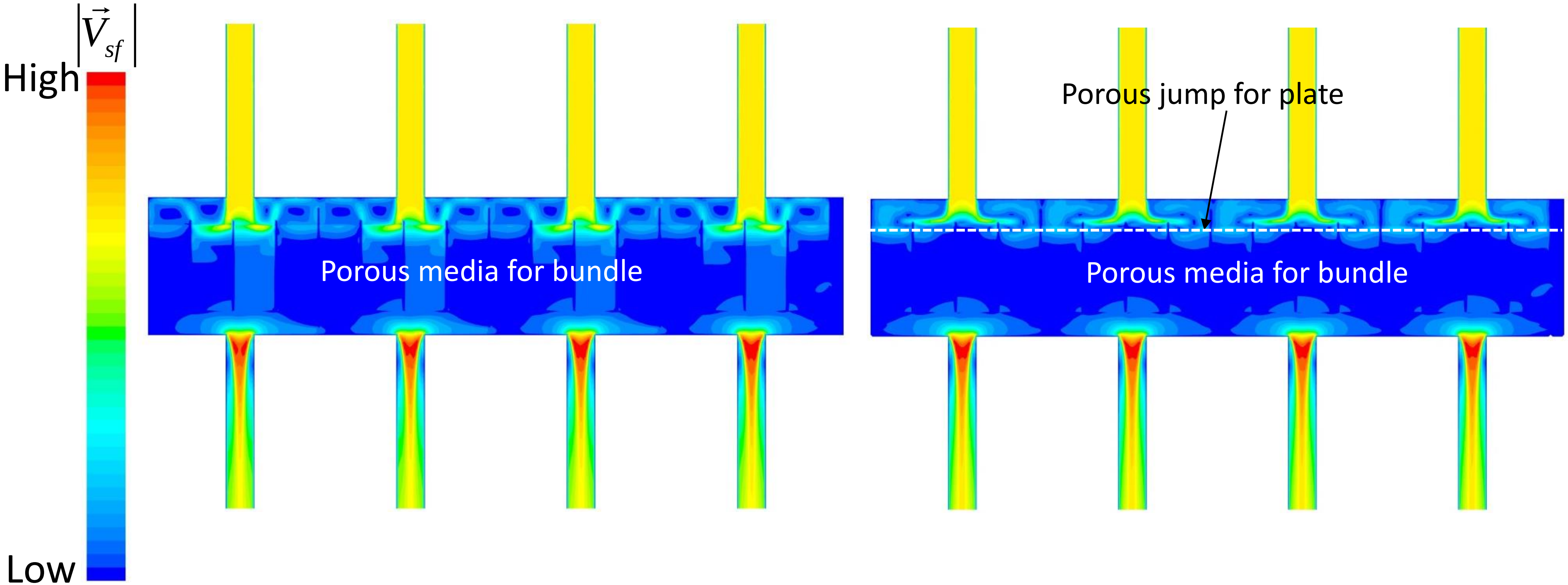
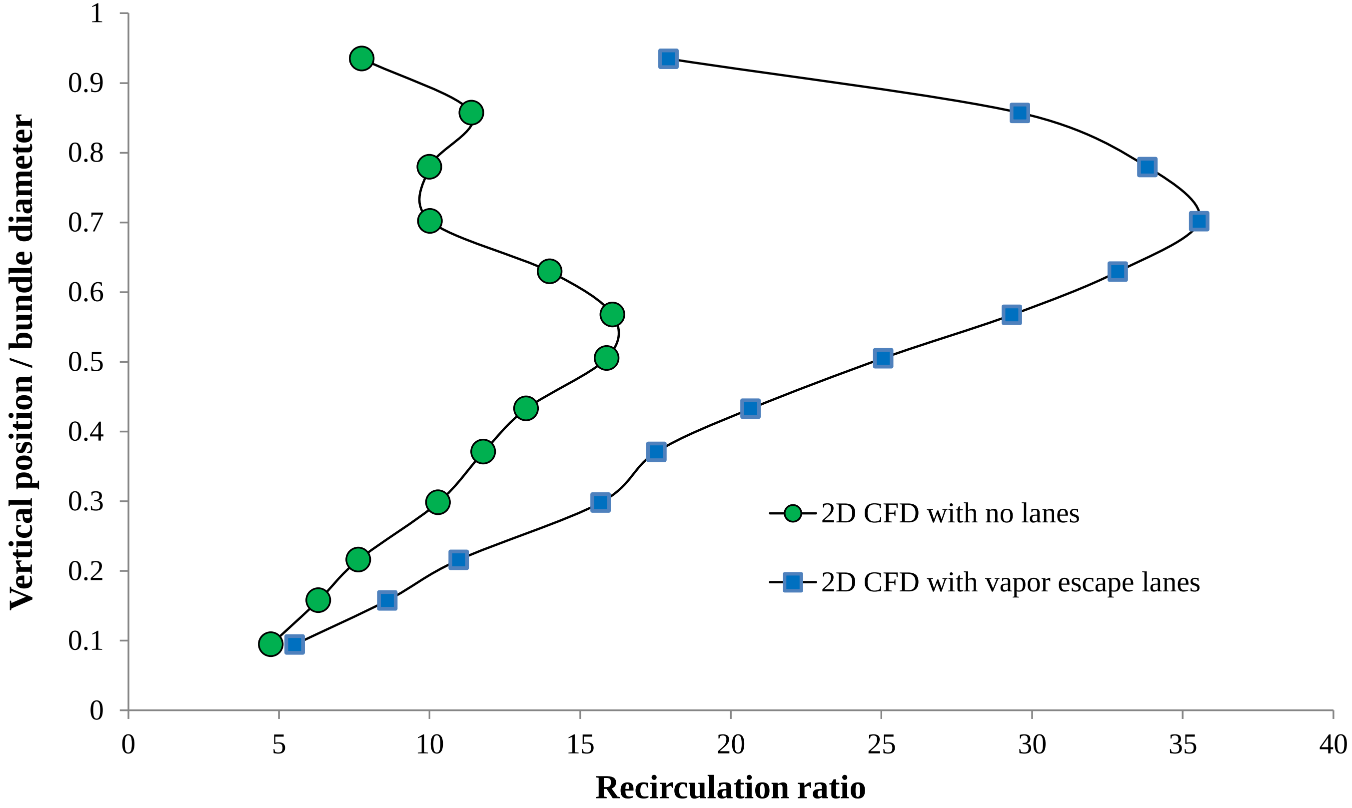
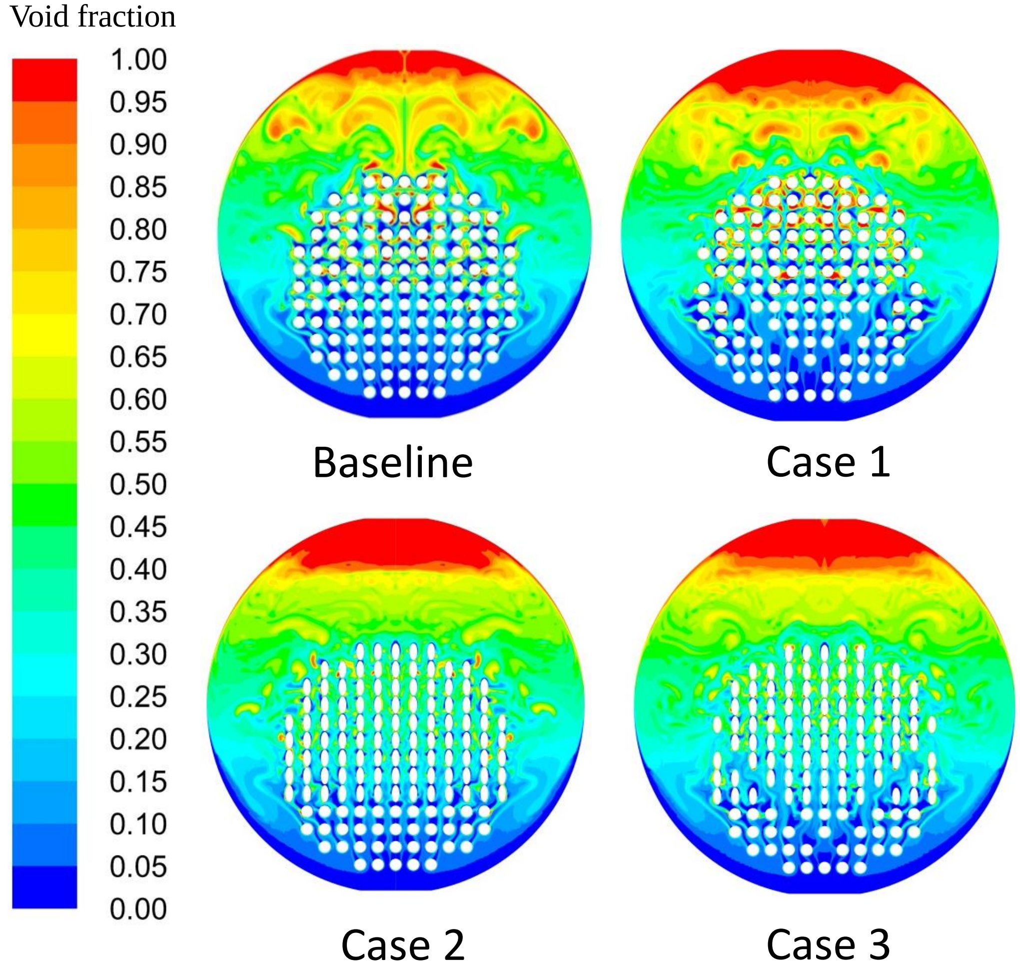
Is distribution plate beneficial?



Applications to Kettle Reboilers

Vapor escape lanes can increase recirculation





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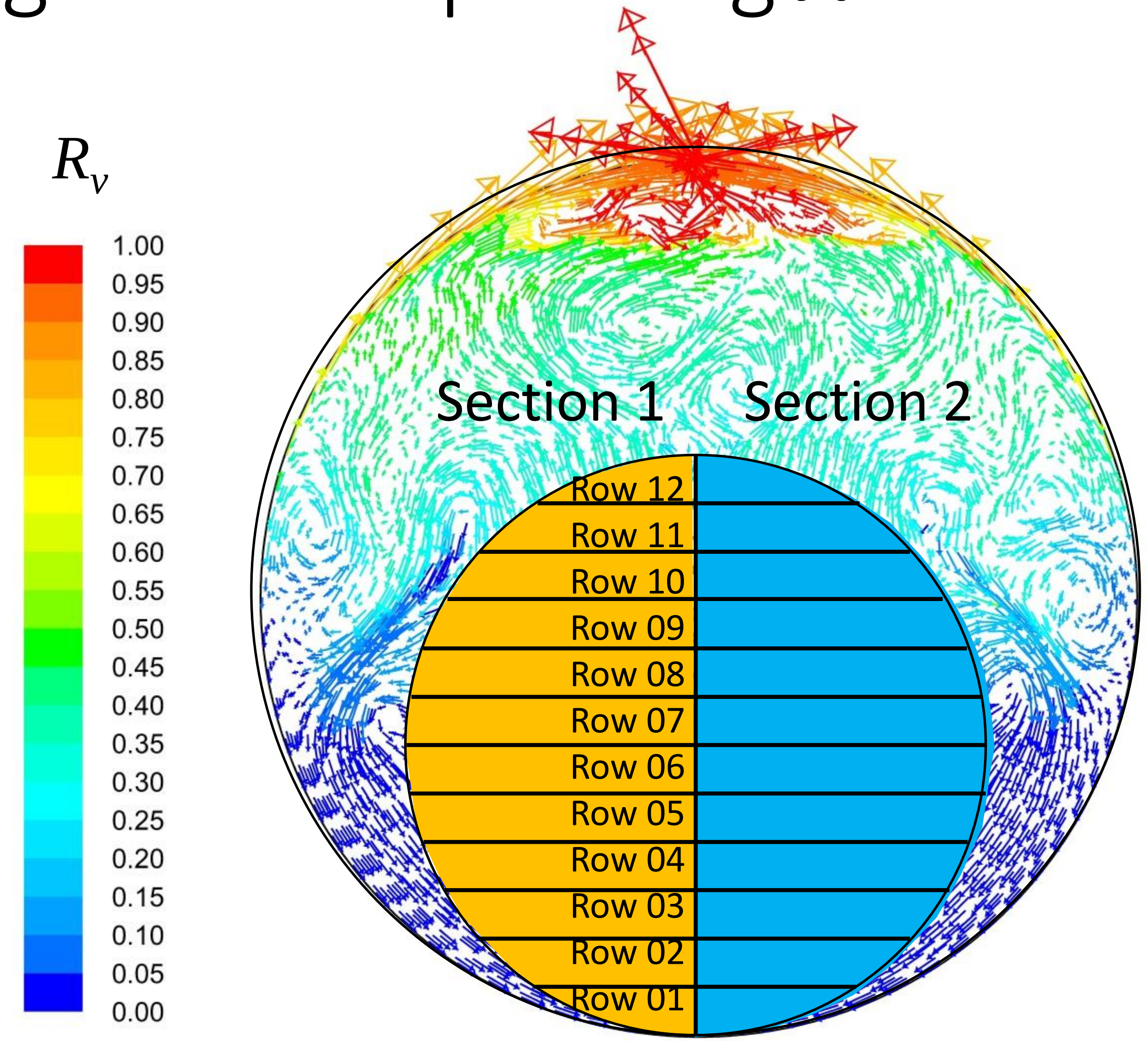
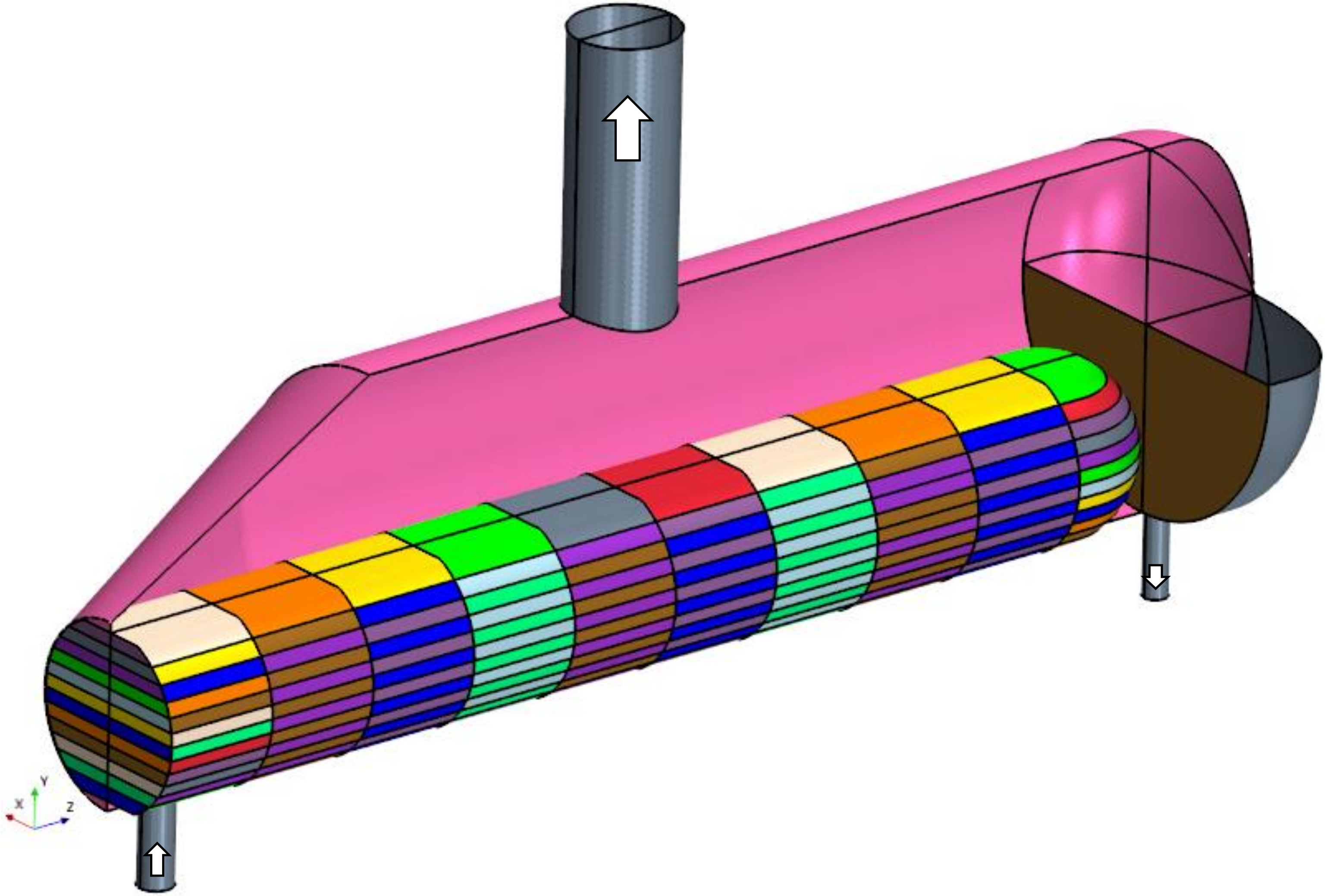
Vaporization rates in porous volumes specified according to corresponding *Xist*® increment



Value synergy using CFD and *Xist* together



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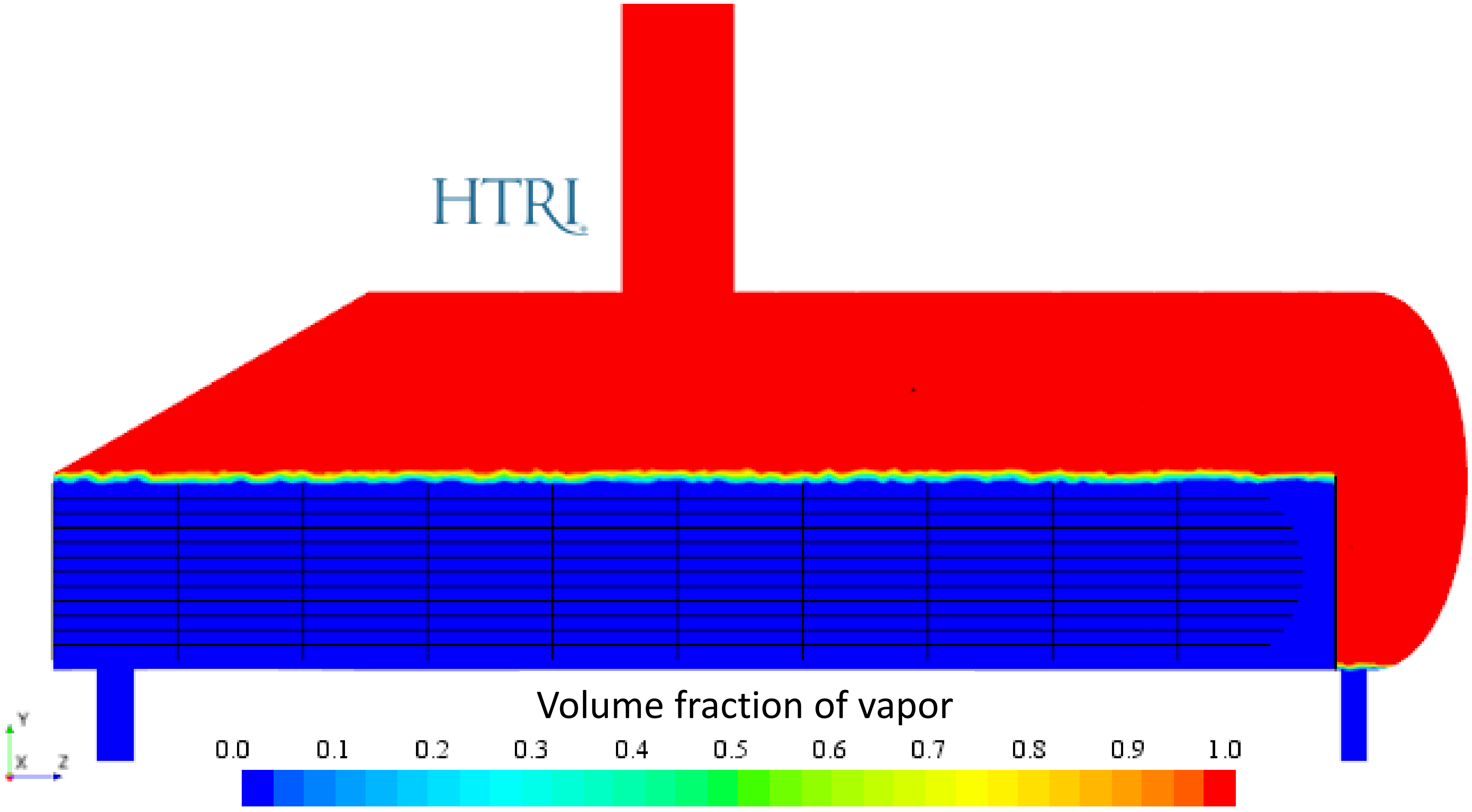
Void fraction on center plane $t^* = 0$ (initial condition)



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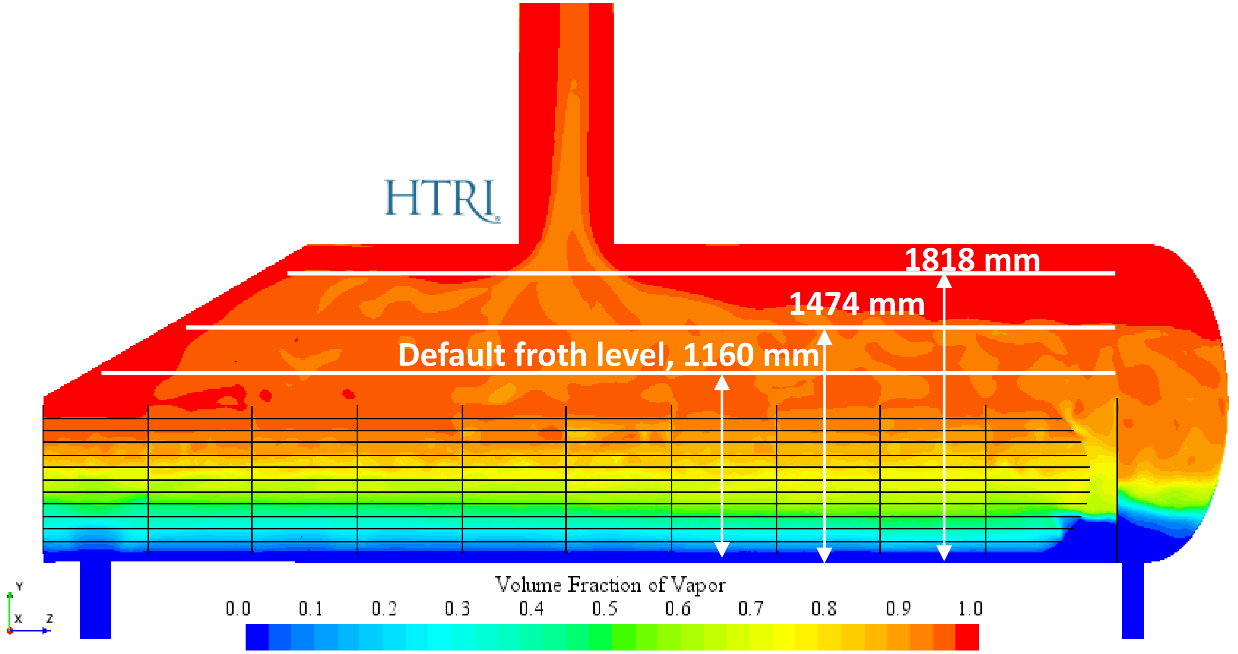
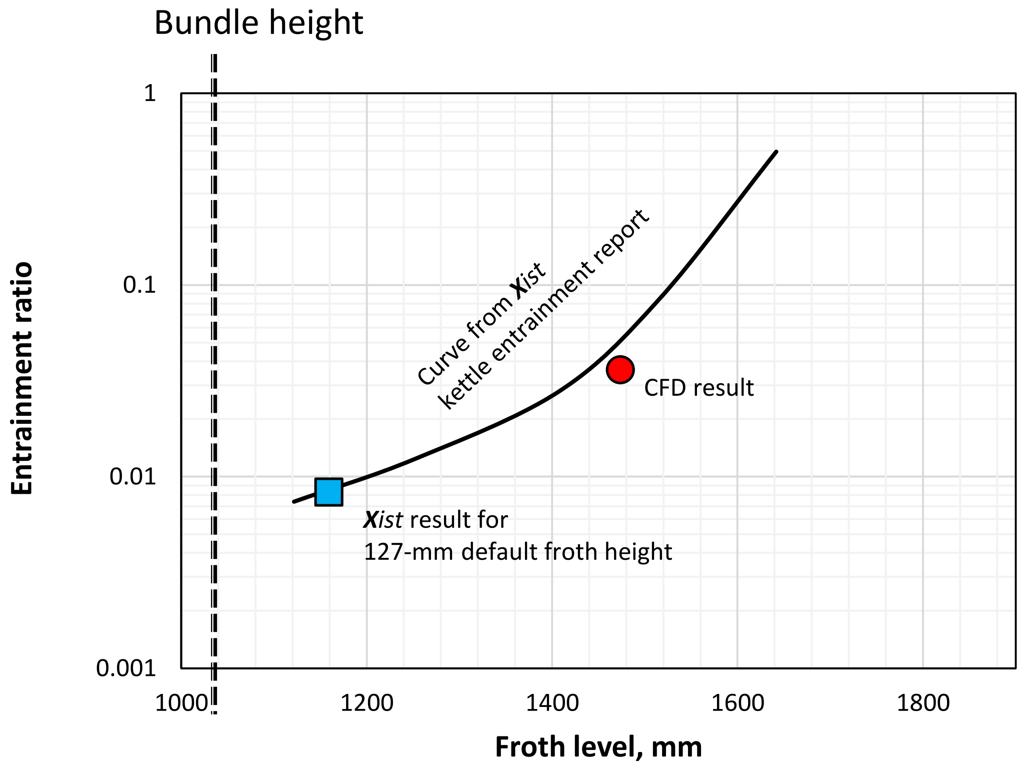
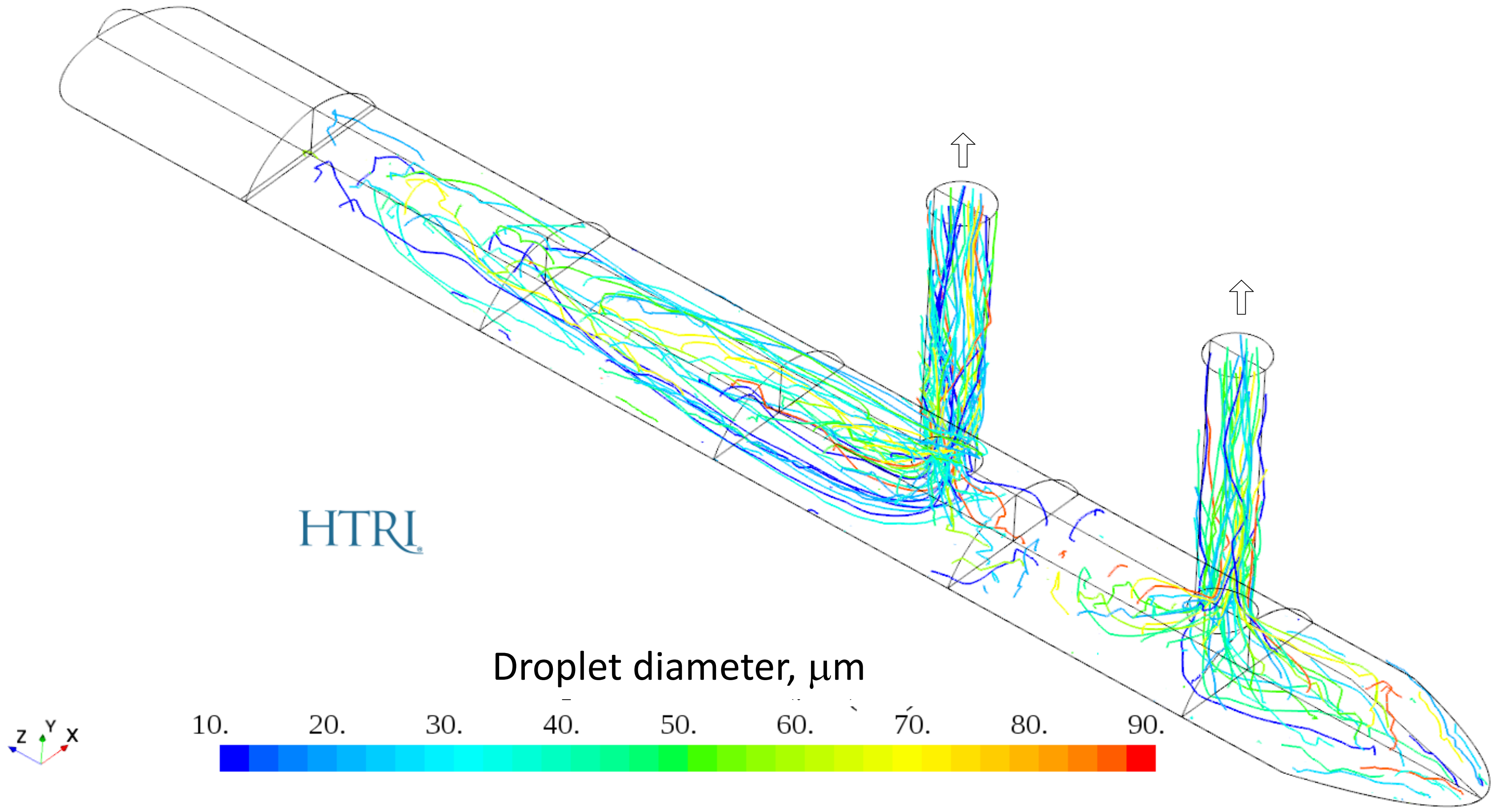
Entrainment vs. froth height relationship in *Xist* is in agreement with Eulerian multiphase CFD results





Eulerian-Lagrangian approaches to entrainment are straightforward, but boundary conditions are elusive



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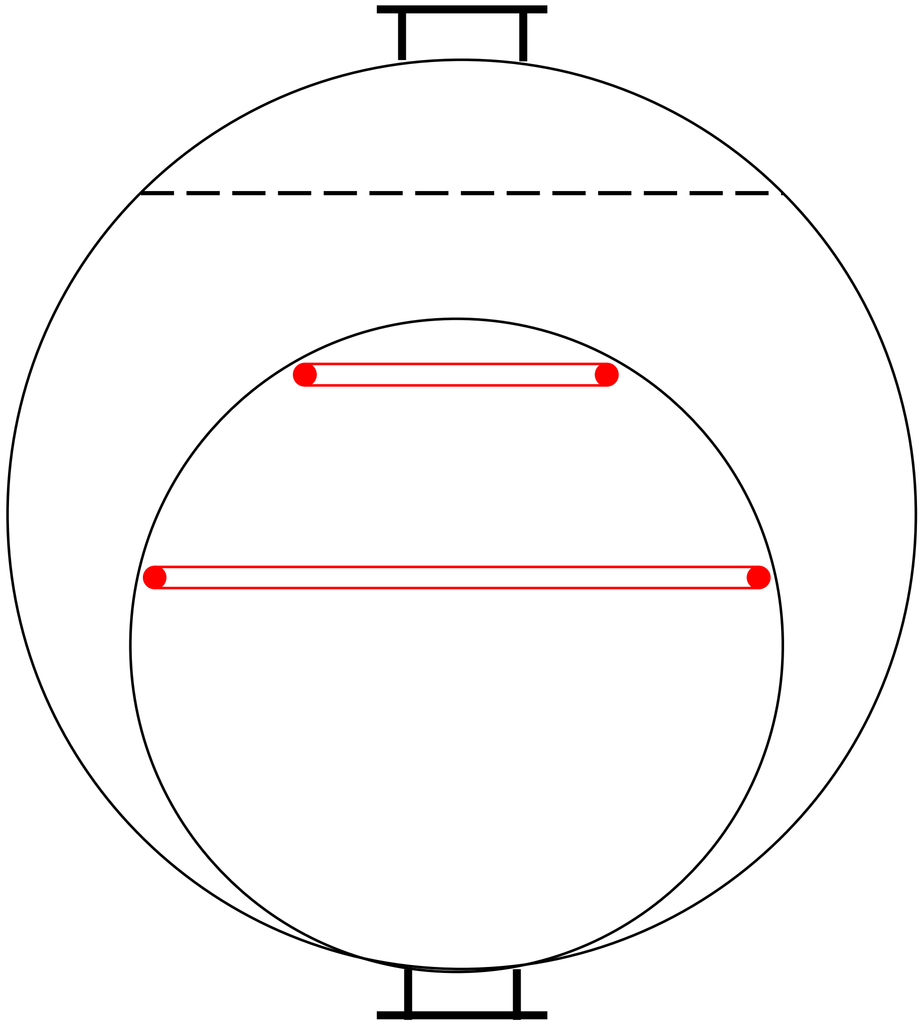
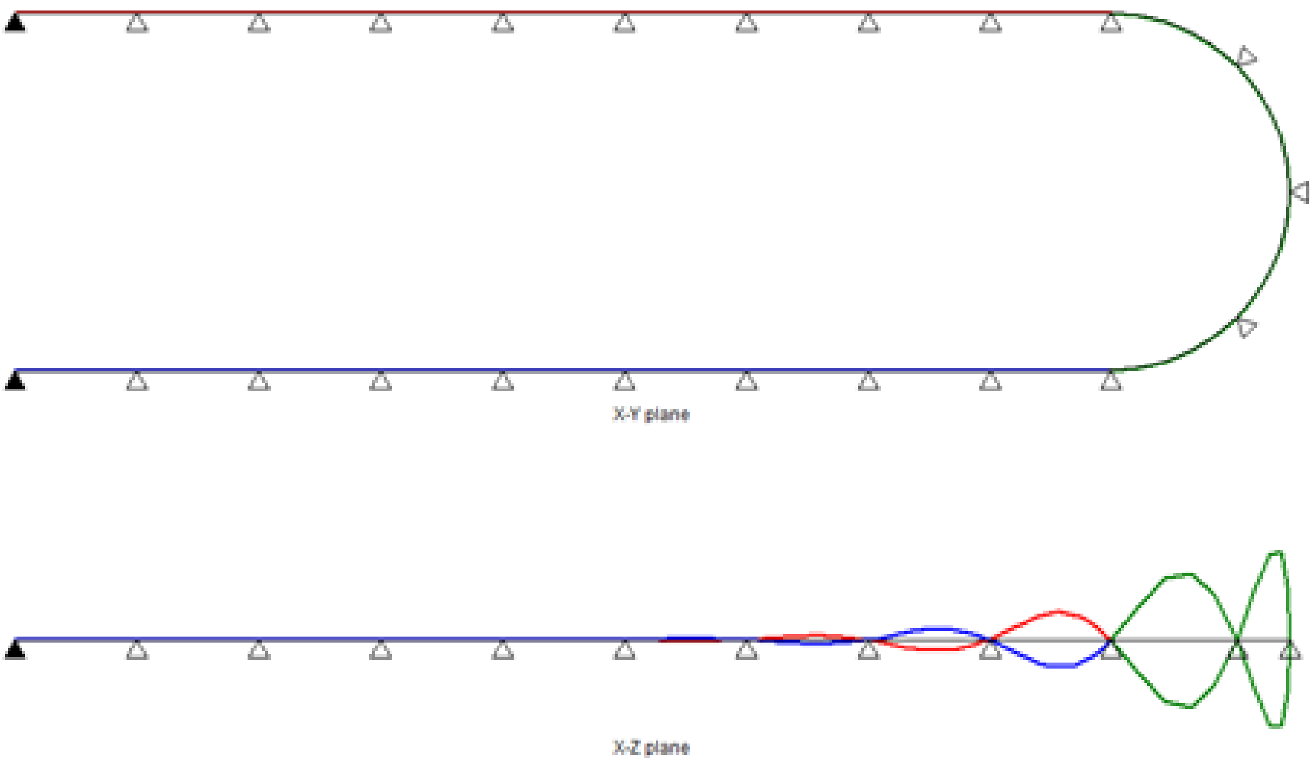
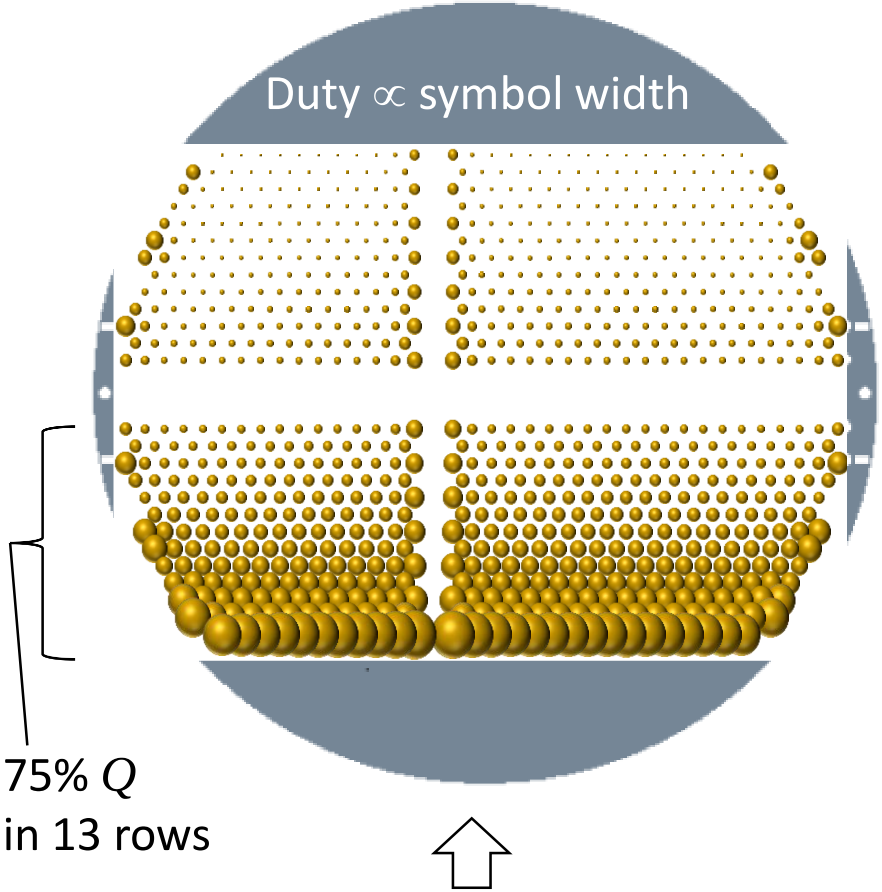
Extract velocity profiles from simulation for accurate vibration analyses

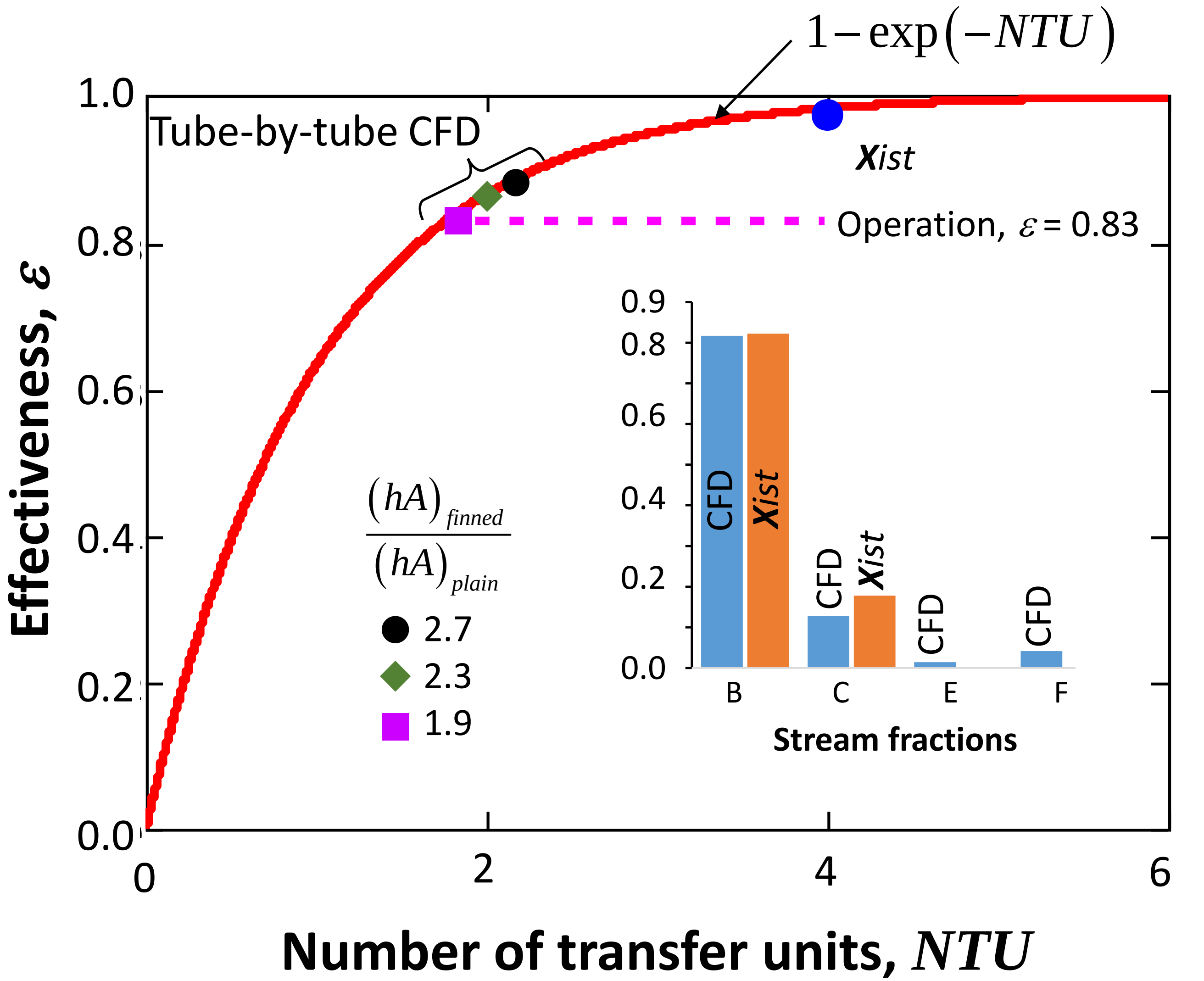




Applications to High Effectiveness X Shells

Example: Underperforming BXU heating gas with steam





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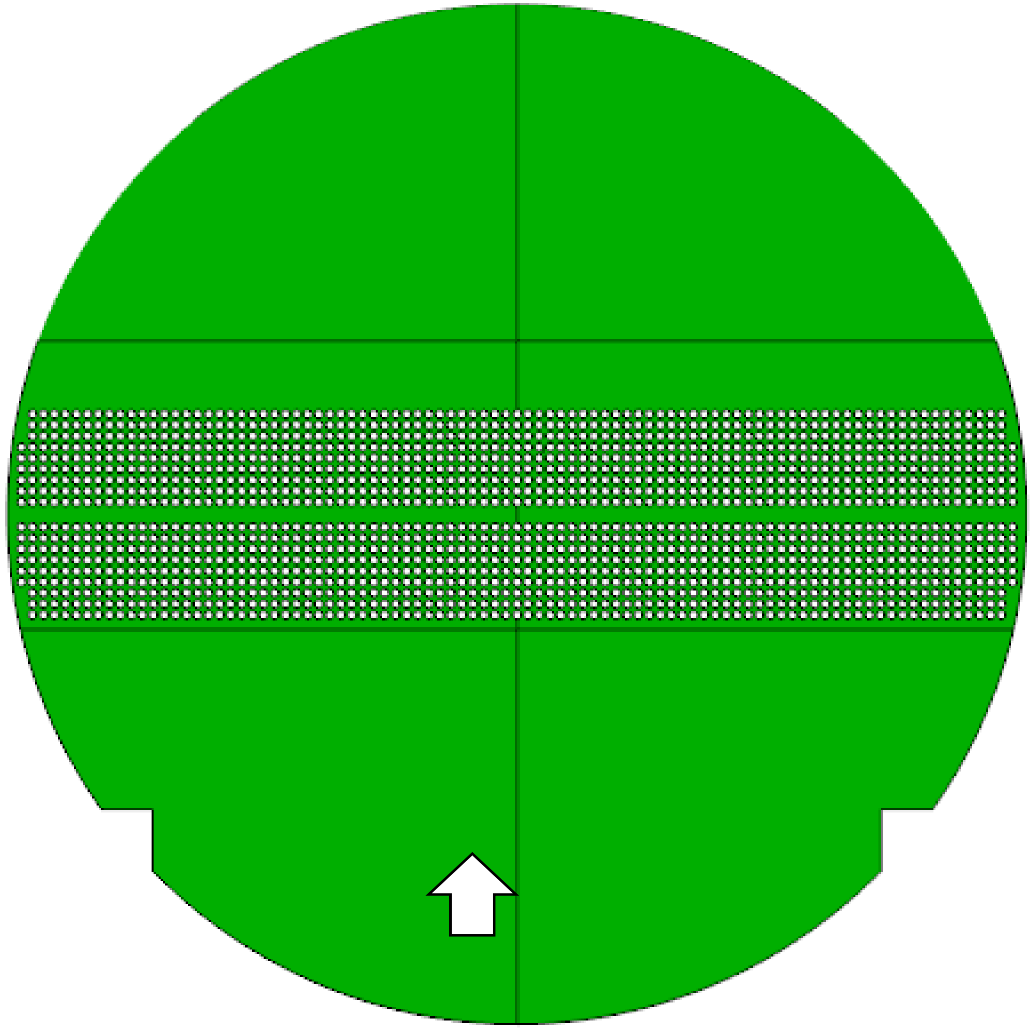
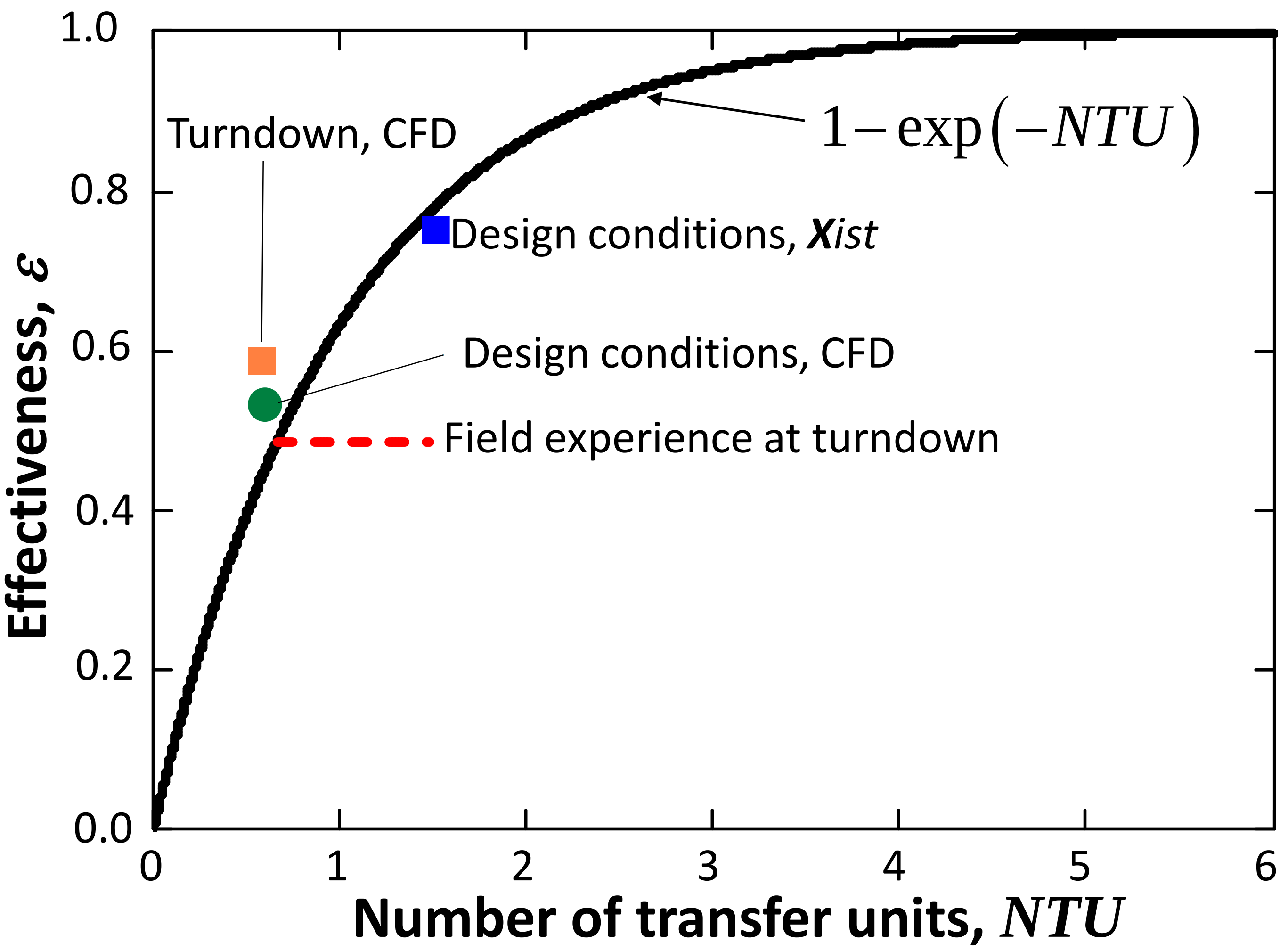
High-effectiveness BXU gas heater underperformed





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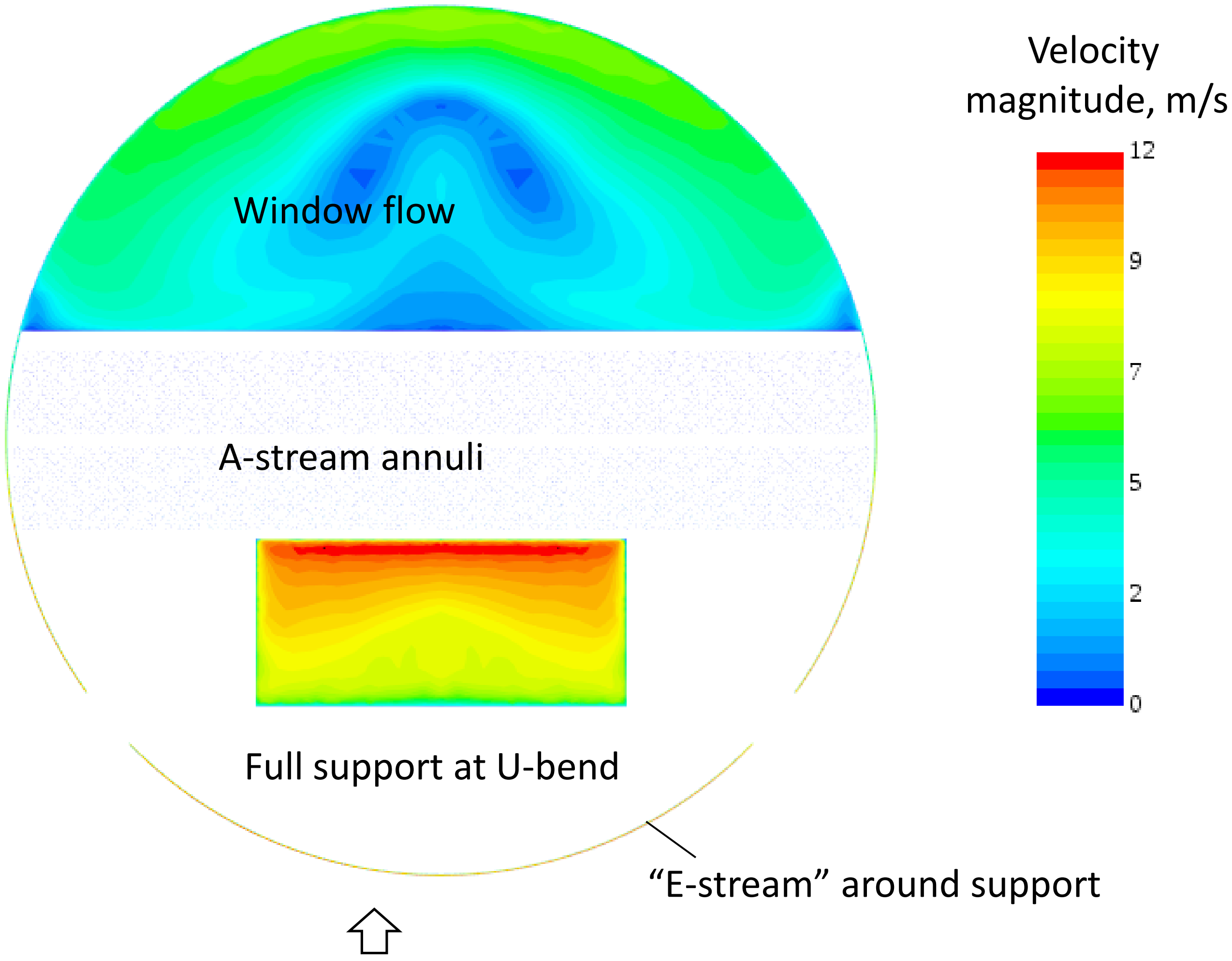
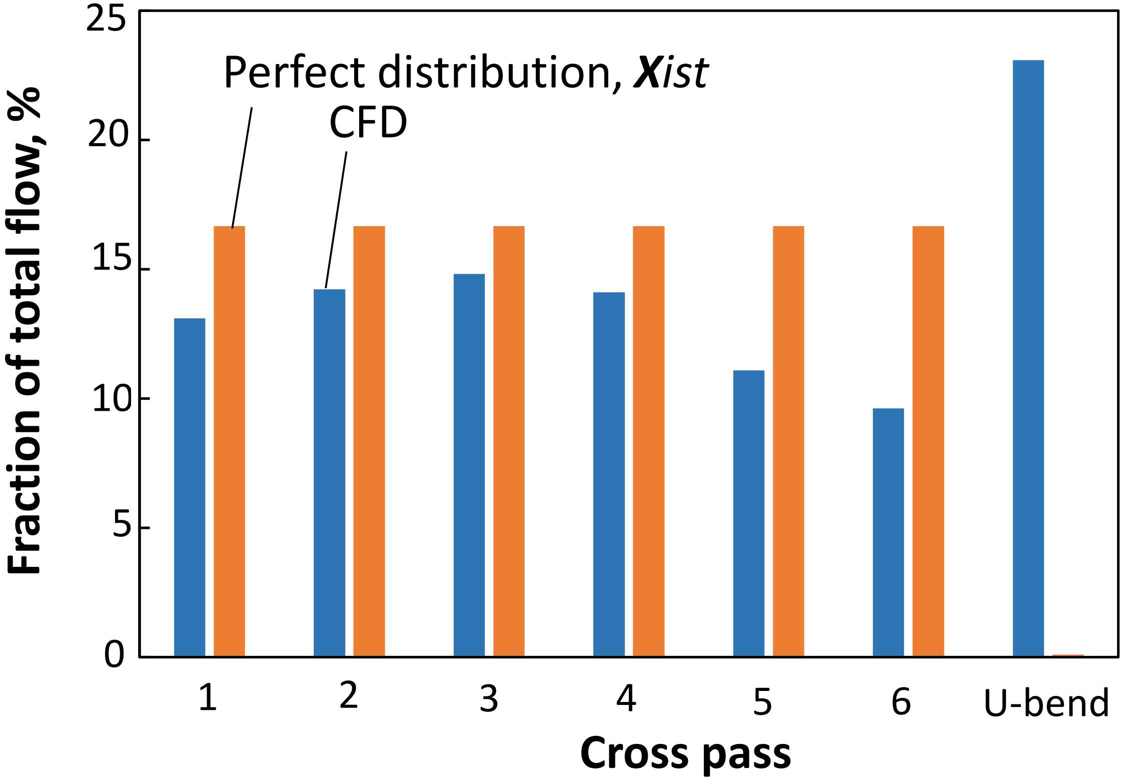
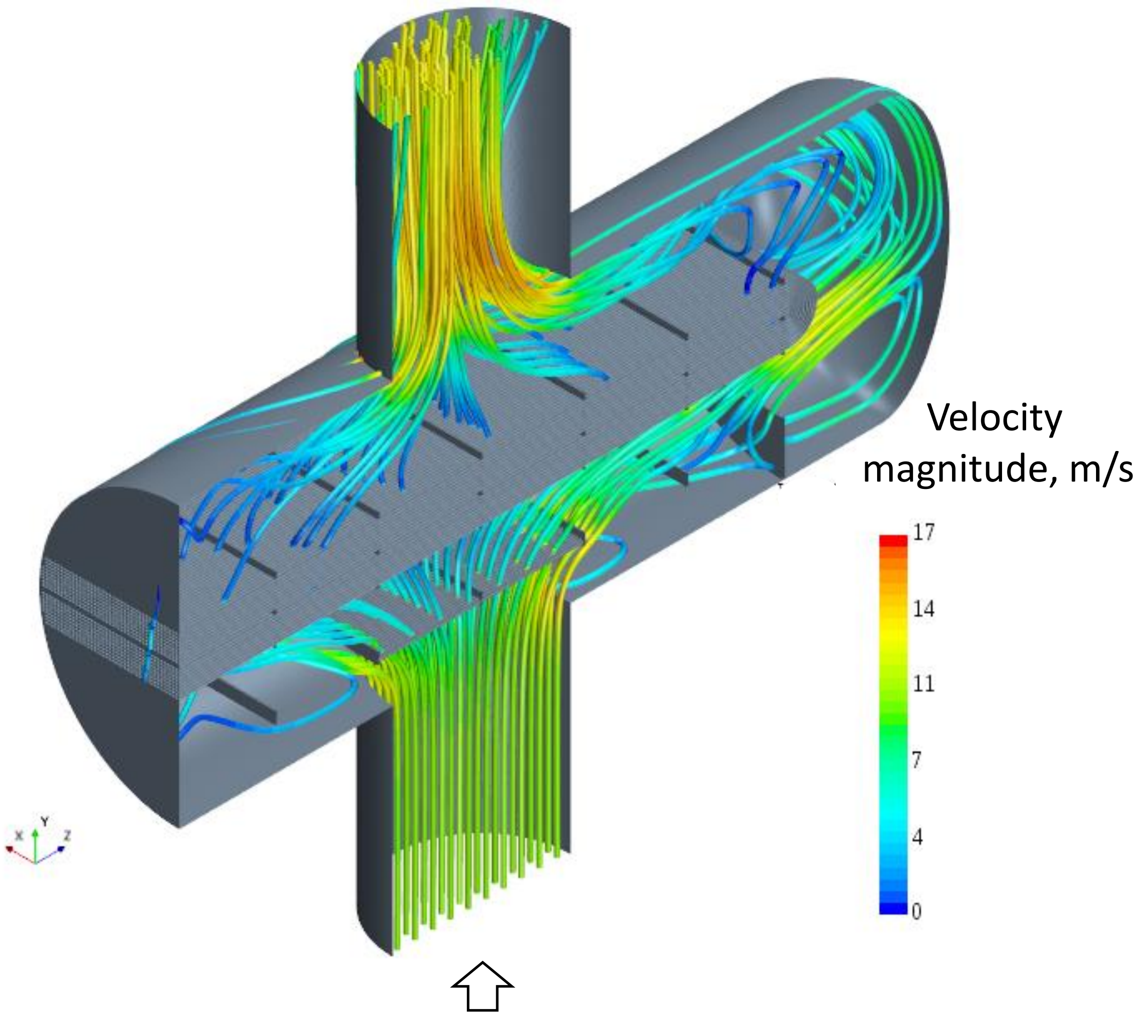
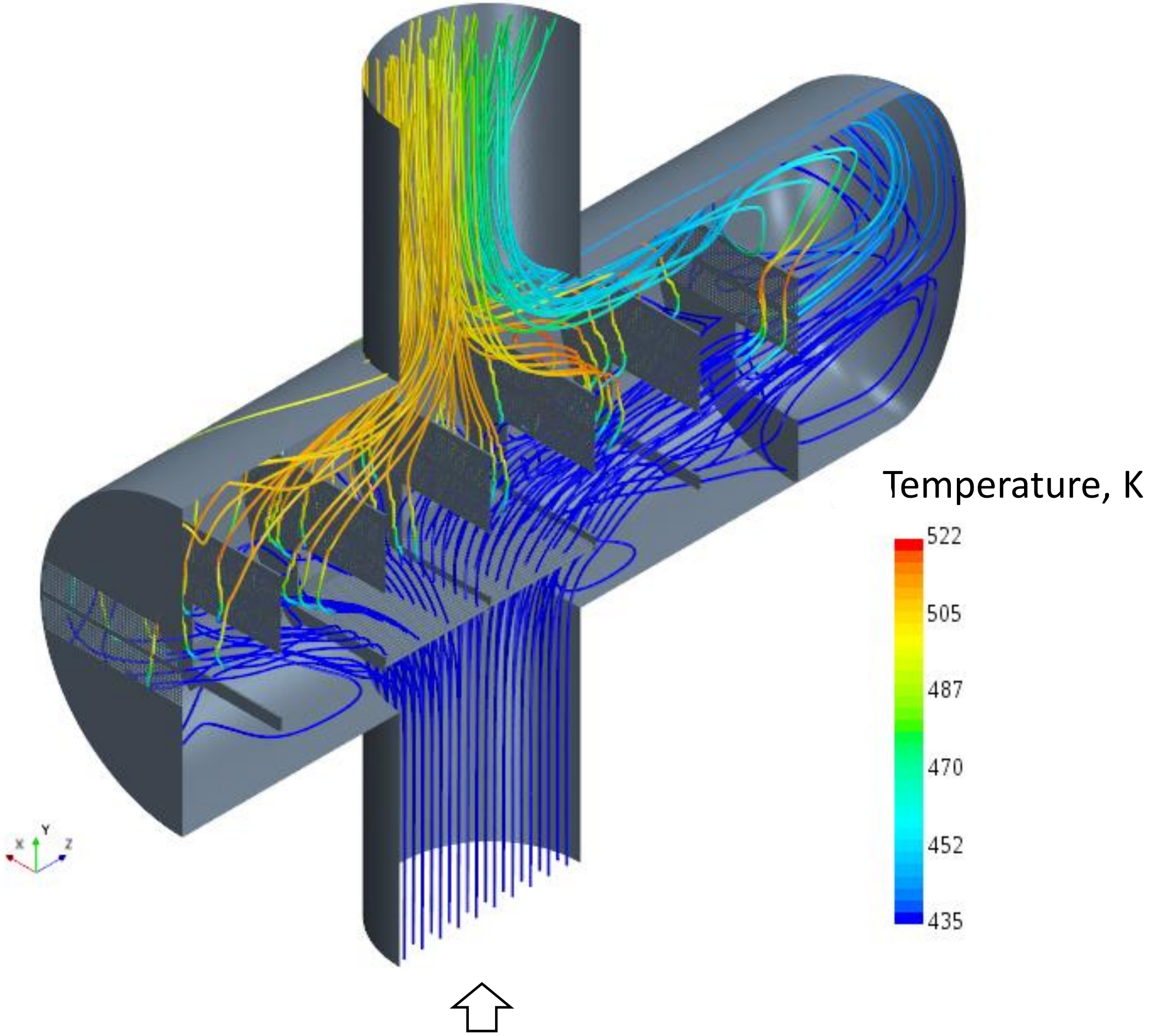
B-stream: 70% instead of design value of 96%





Non-idealities of full support plate with windows





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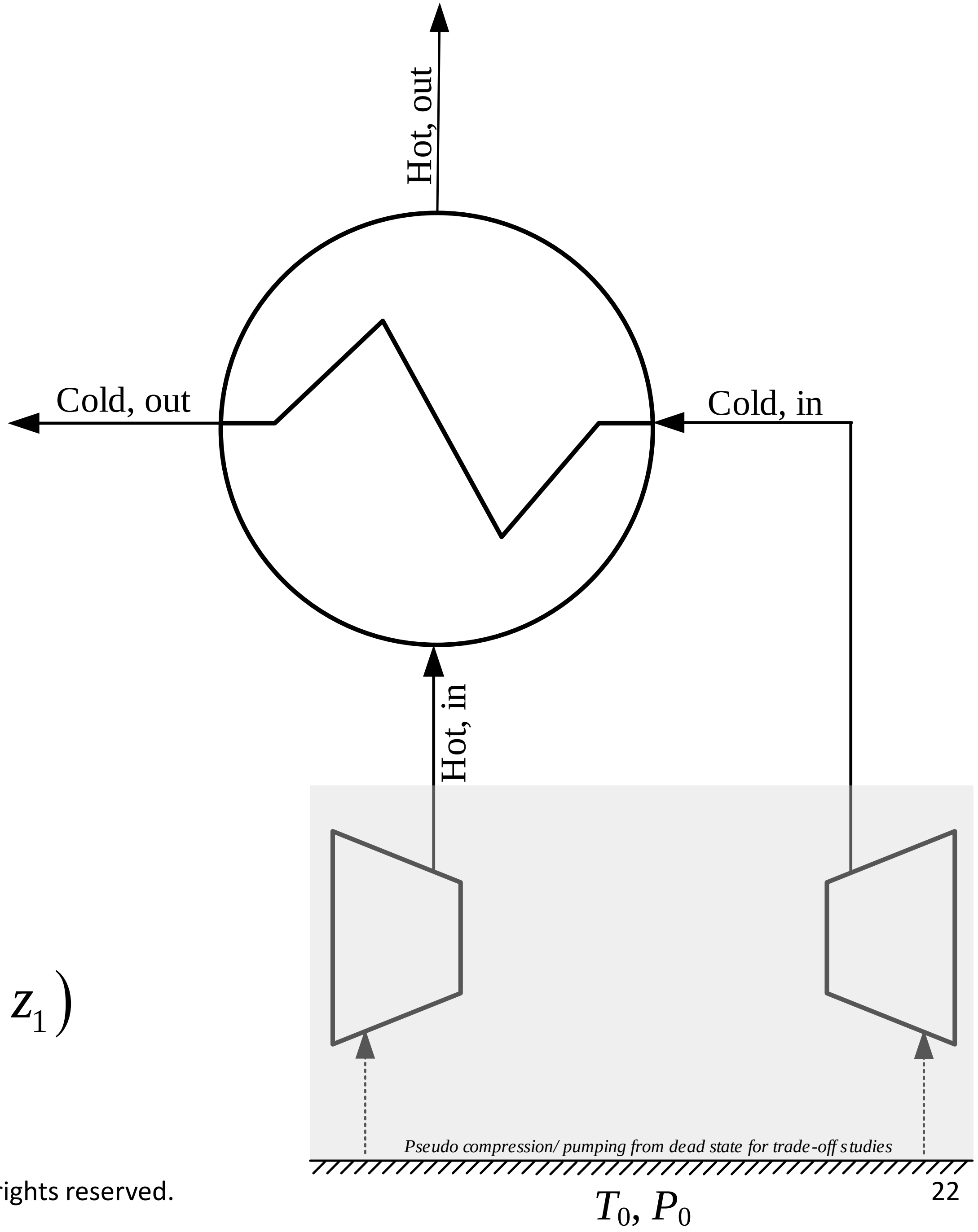
How does performance impact the carbon footprint of a heat exchanger?

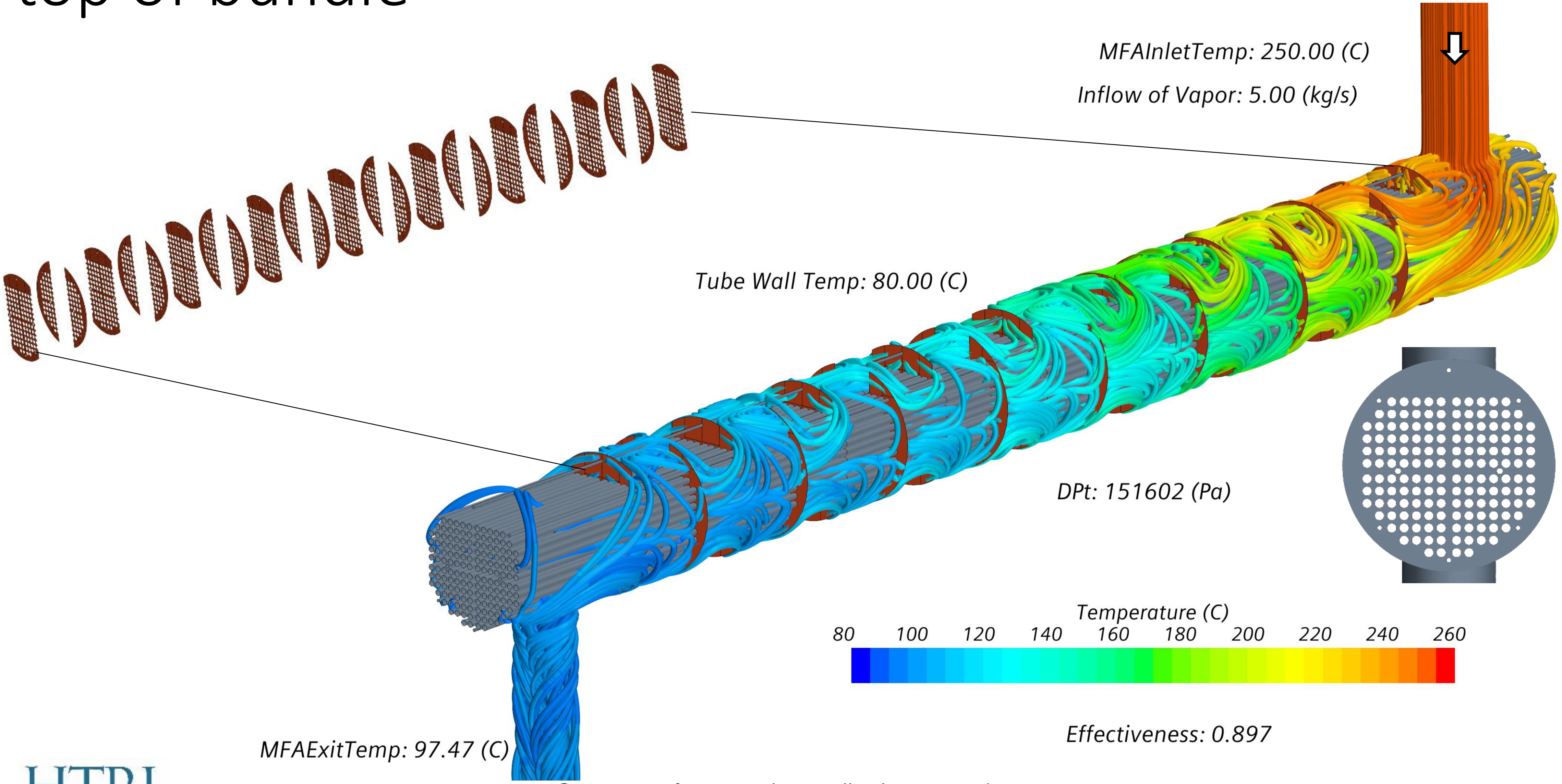
When heat is exchanged, availability reduces

- Hot stream always gives up more availability than acquired by cold stream
- Product of availability destruction and mass of CO_2 per unit energy = carbon footprint

$$\Delta a = (h_2 - h_1) - T_0 (s_2 - s_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$



Example: Gas cooler shows bypass stream across top of bundle



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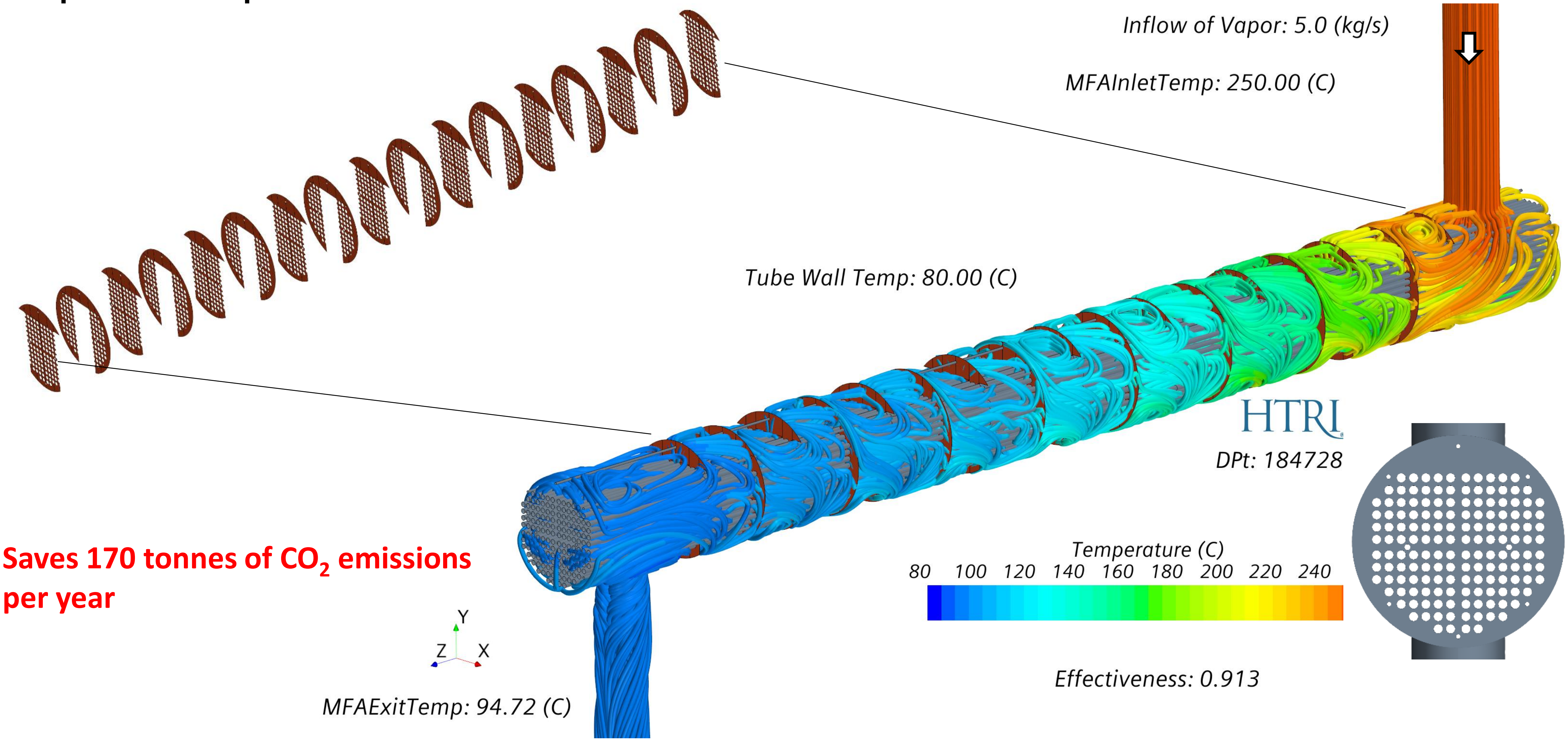
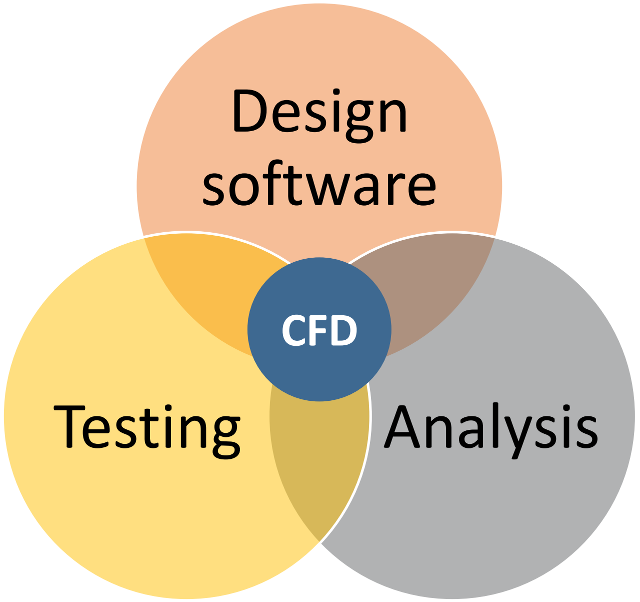
Inverted “U” and “T” baffles block bypass and improve performance



Saves 170 tonnes of CO_2 emissions per year

Summary

- CFD simulation can provide timely, actionable insights into heat exchanger performance issues resulting from
  - maldistribution
  - excess vibration
  - bypass
  - underperforming enhancements
  - fouling
- "Right-sized" approach is key for troubleshooting
- Validation data are always needed



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