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Predictions of CHF Position and Post-CHF Heat Transfer

Analysis and Computational Predictions in Uniformly and Non-Uniformly Heated Tubes

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Outline

Introduction

General Background

CHF & Post-Dryout Heat Transfer

Results and Comparisons

Implementation of A New Model

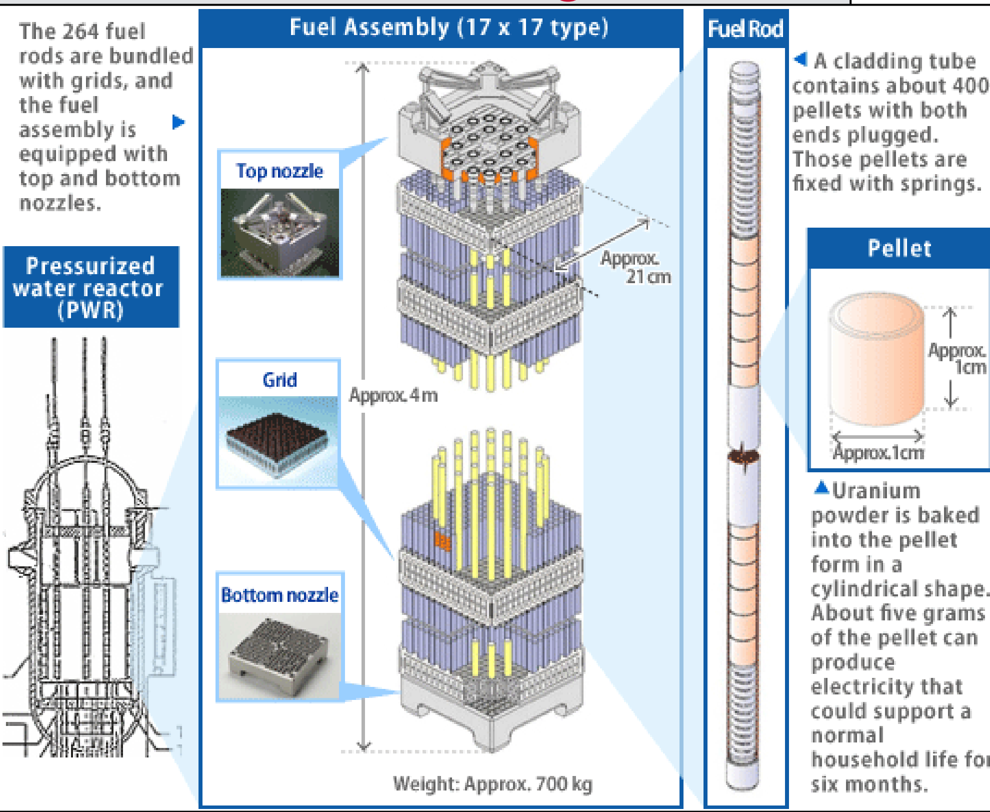
Conclusion

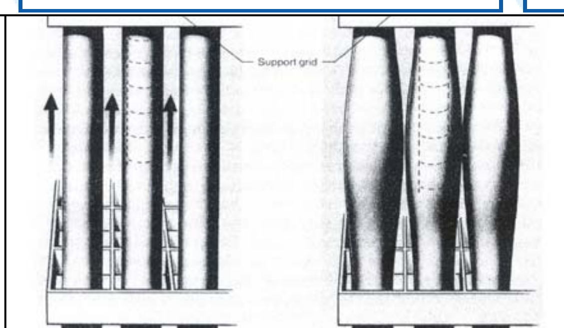
Introduction

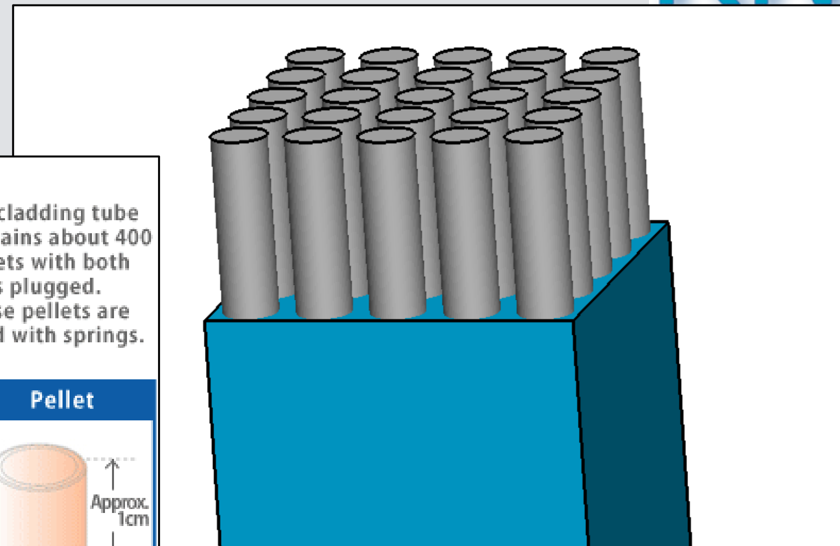
- **Design Basis Accident / Safety**:
  - » Importance of the Critical Heat Flux (CHF)
  - » Importance of the Quench Front propagation
  - » Importance of Post Dryout Heat Transfer and Temperature Distribution (Peak Clad Temperature…)

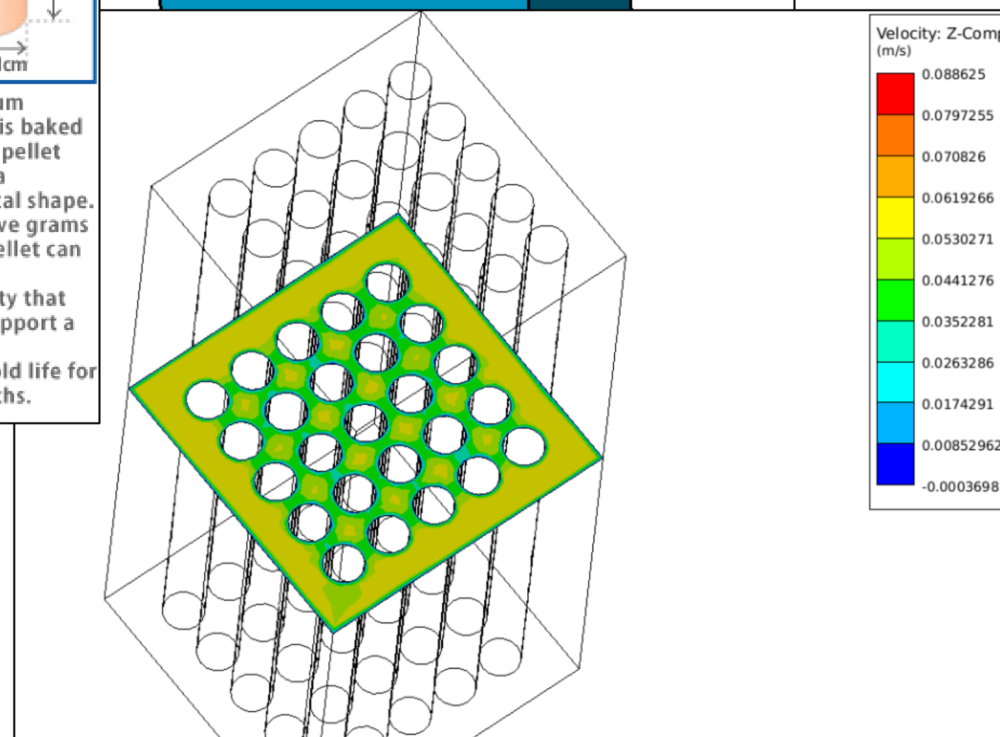
- **Aim**: Modelling of the Reflooding in a deformed geometry (ballooned pins)

General Background



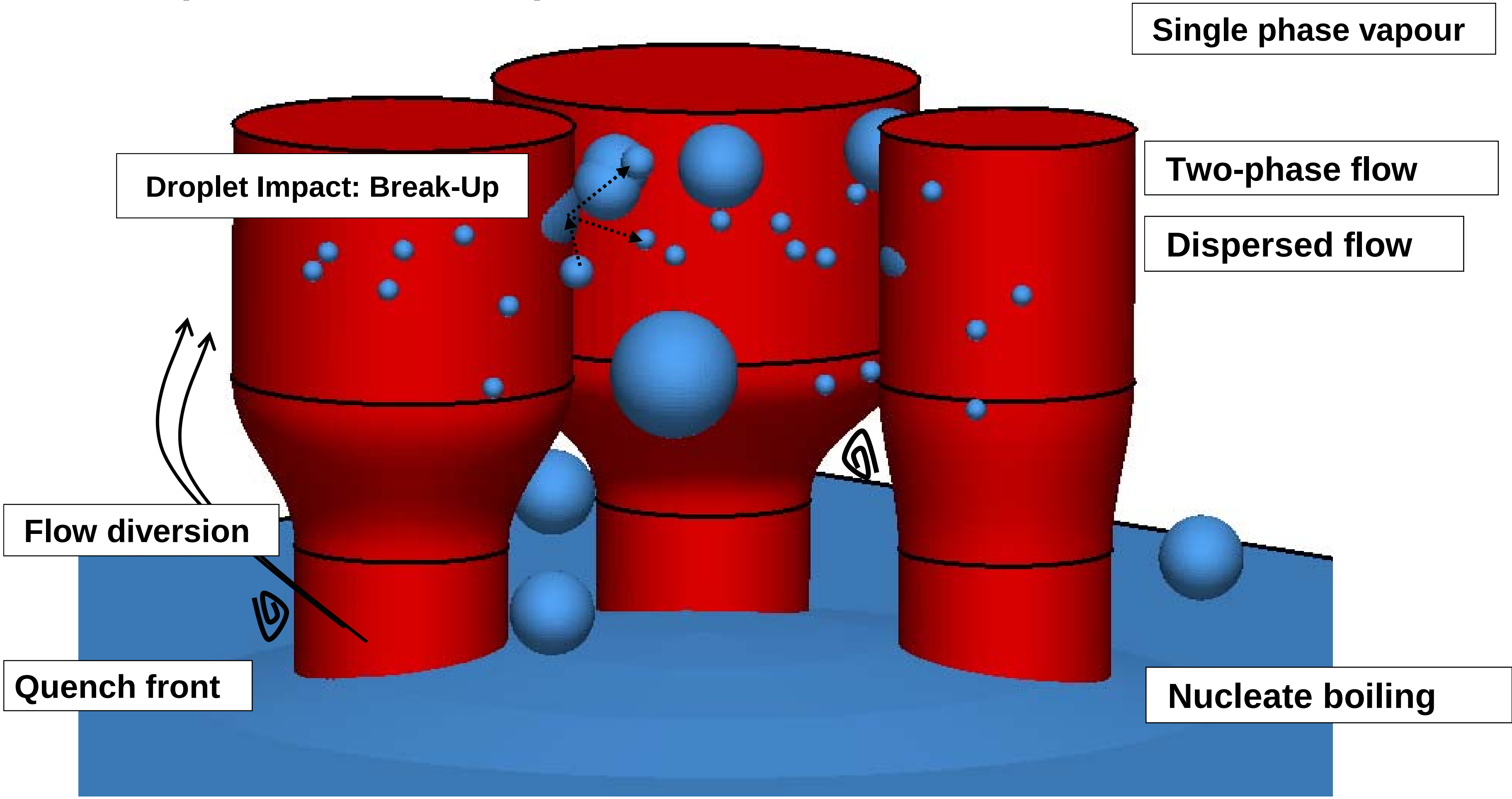






General Background: Few Phenomena

Two-Phase Flow – Droplet Entrainment / Deposition – Turbulence – Cross-flow – Evaporation - Conduction - Convection – Radiation (Rod / Rod; Rod / Droplets; Rod / Steam)



CHF & Post-Dryout Heat Transfer

Present Work:

» **We will try to answer the question whether it is possible to predict the CHF position and temperature profiles for different axial heat flux distributions or not.**

Study of fundamental cases:

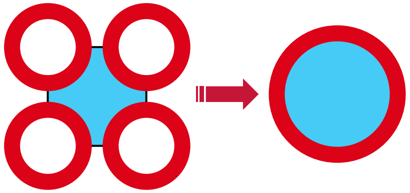
» ***The Bennett Experiments***: 'Heat transfer to steam-water mixtures flowing in uniformly heated tubes in which the critical heat flux has been exceeded', 1967

» ***The Keeys Experiments***: 'Post burnout heat transfer in high pressure steam water mixtures in a tube with a cosine heat flux distribution', 1971

» ***The Becker Experiments***: 'An experimental investigation of post-dryout heat transfer', 1983

Experiments: Heated Tubes

Study of heated tubes NOT rod bundles



Year	Experiment	P (MPa)	G (Kg/m^2s)	D (mm)	L (m)	X	Q (MW/m^2)
1967	Bennett	6.9	393-5235	12.6	5.56	-	0.35-1.84
1972	Keeys	6.9	700-4100	12.7	3.66	0.15-0.95	0.8-1.5
1983	Becker	3-20	500-3000	14.9	7.0	0.03-1.60	0.1-1.25

Uniform Heat Flux Distribution: *Bennett and Becker*

Non-Uniform Heat Flux Distibution: *Keeys*

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Input Description and Geometrical Model

Simulation tests:

- Nodalization study,
- Fine Mesh Technique,
- Comparison between the available CHF correlations,
- Sensitivity to some parameters such as:
  - » Mass Flow Rate,
  - » Pressure
  - » Power,
  - » Power Distributions
- Wall Heat Transfer

Critical Heat Flux

The 3 different correlations implemented into the TRACE Code:

- **AECL-IPPE CHF Table**
  - » “look-up” tables of Groeneveld et al. (1996).
  - » **Implication**: specific local relationship between CHF and local quality for a given mass flux and pressure.

$$\dot{q}''_{CHF} = K \cdot fn\{P, G, x, D_H\}$$

Better results: Relationship between quality and boiling length.

$$x_{CHF} = K_i \frac{A \cdot L_B}{B + L_B}$$

- **AECL-IPPE with Biasi Correlation**
  - » Not based on rod bundle data, assumptions from local CHF correlation into a critical quality correlation.
- **CISE-GE Critical Quality**: a F-Tong like factor is considered to account for the non-uniformity of the heat flux.

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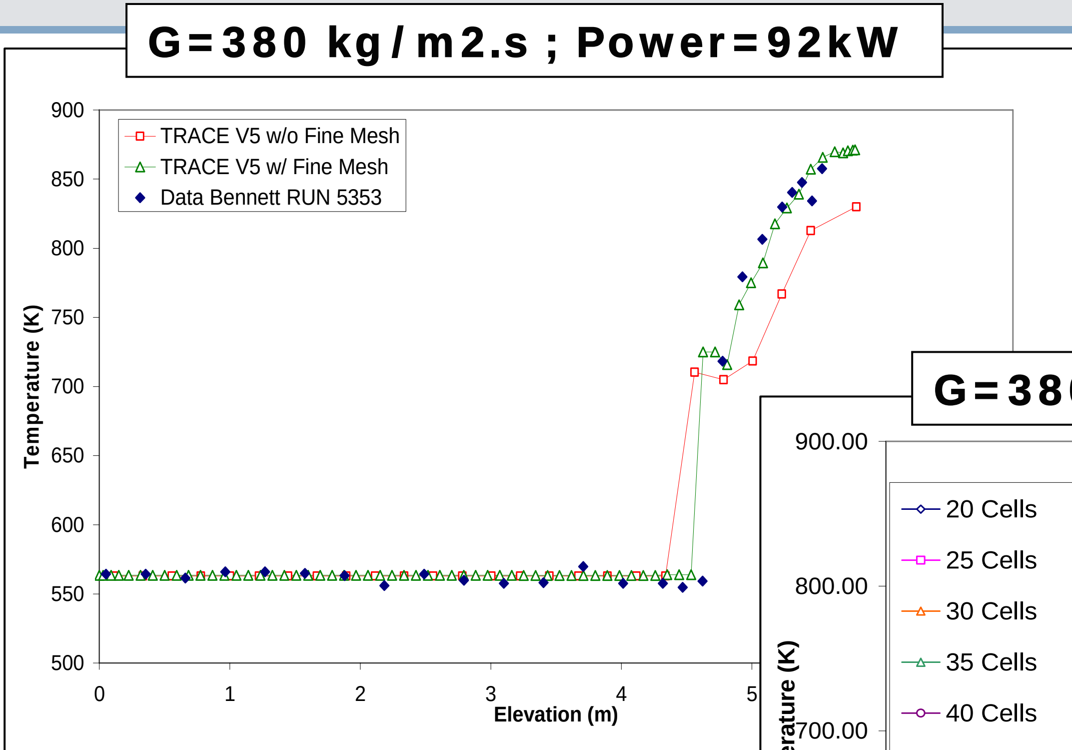
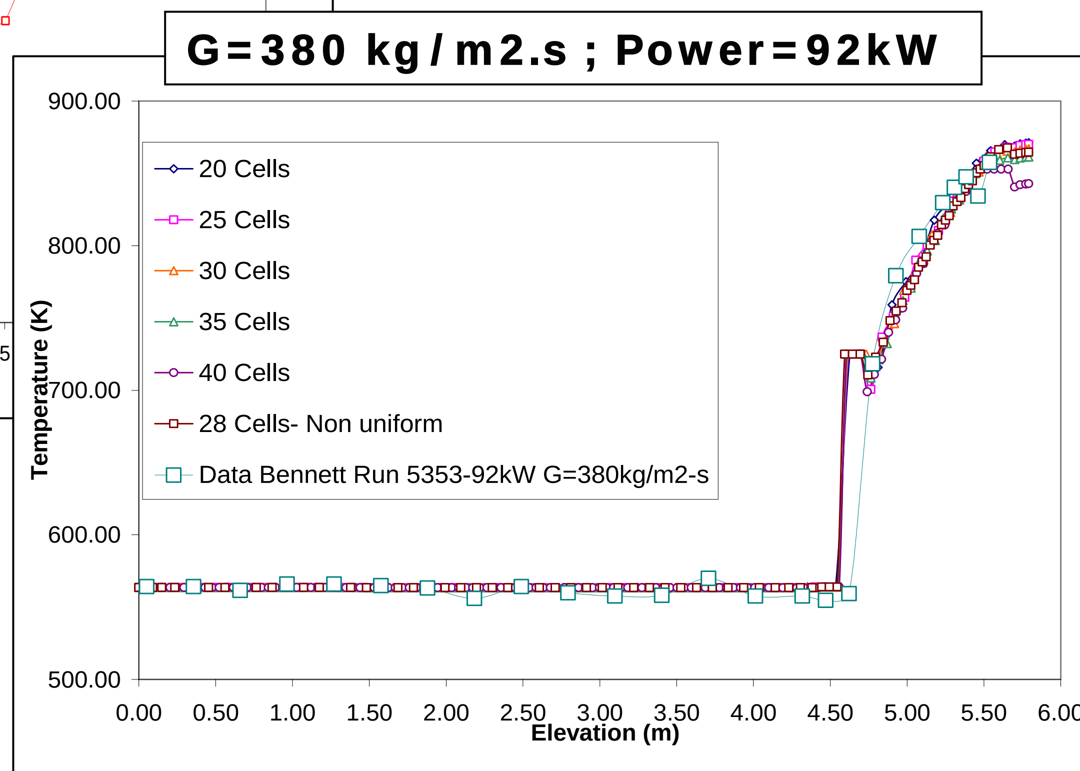
Results and Comparisons : Nodalization & Fine Mesh Technique





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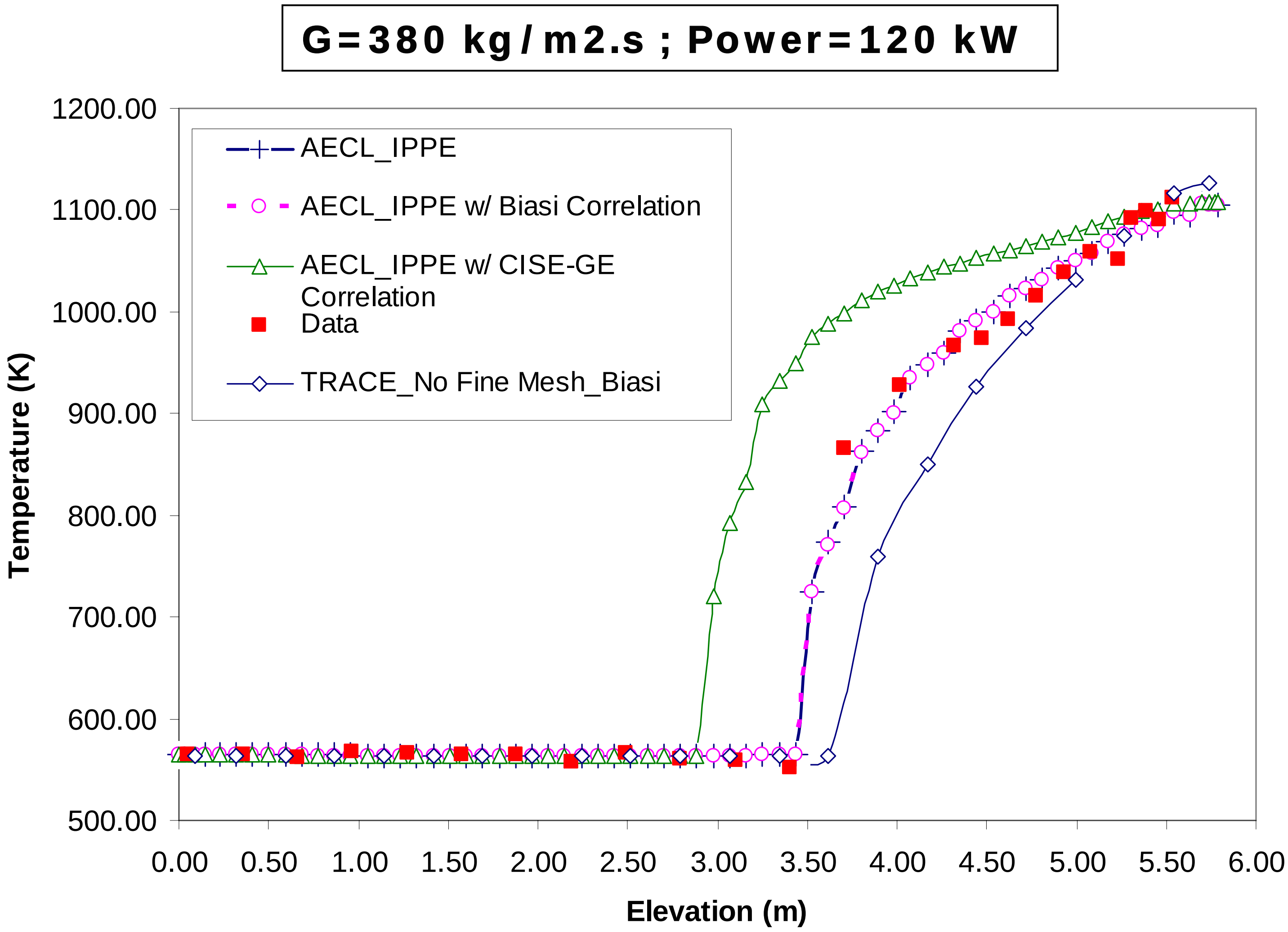
Results and Comparisons: Different Correlations



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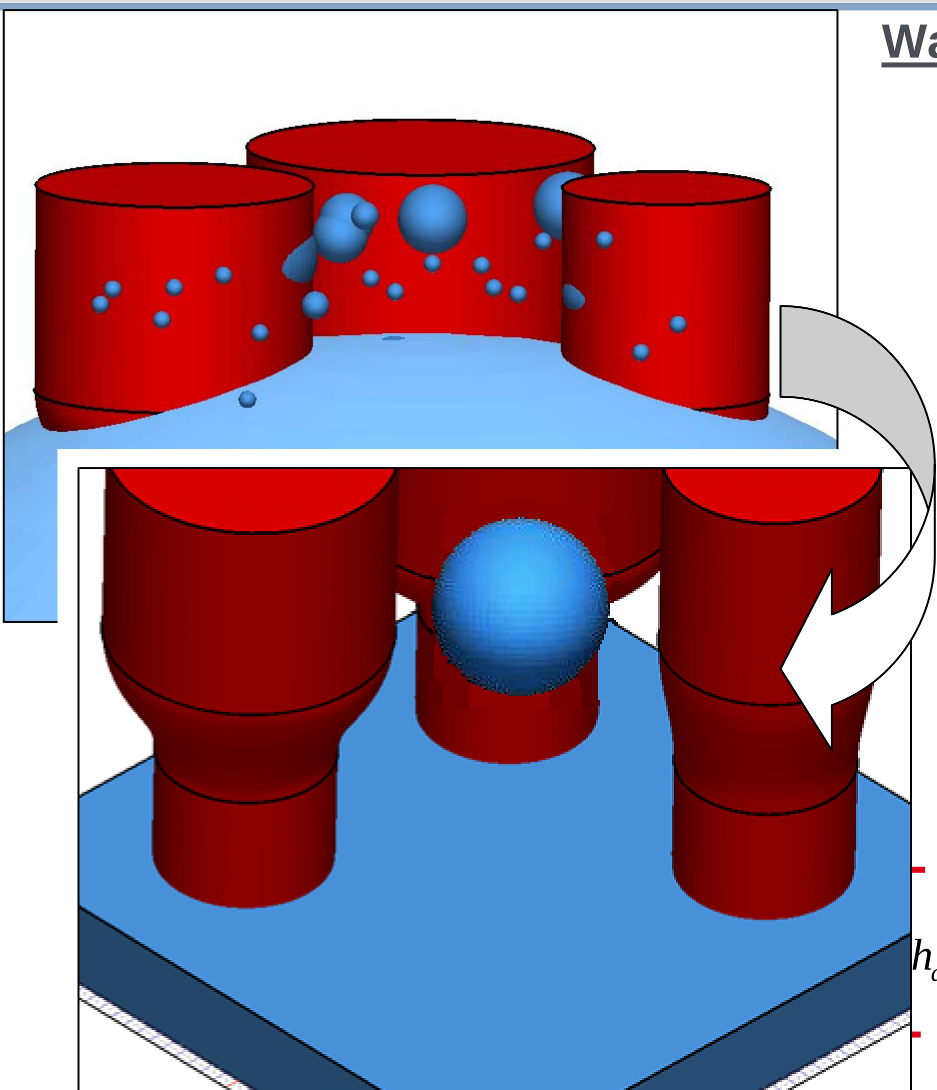
Post-Dryout Heat Transfer



Wall Heat Transfer:

$$q''_{DFFB} = q''_{wg,FC} + q''_{wg,rad} + q''_{wl,rad} + q''_{wd}$$

$$q''_{wg,FC} = \frac{k_g}{D_H} \cdot Nu_{wg,FC} \cdot \Psi_{2\Phi} \cdot (T_w - T_l)$$

$$Nu_{wg,FC} = \begin{cases} Nu_{lam} = 4{,}36 \\ Nu_{turb} = \dfrac{(f/2)(Re - 1000) \cdot Pr}{1 + 12.7 \cdot (f/2)^{1/2} \cdot (Pr^{2/3} - 1)} \end{cases}$$

$$\Psi_{2\Phi} = \left[1 + \frac{(1-\alpha) \cdot g \cdot \Delta\rho \cdot D_H}{2 \cdot f_w \cdot \rho_g \cdot V_g^2} \right]^{1/2}$$

$$h_{dw} = 0.00638 (Re_v - 4000)^{0.6} (1-\alpha)^{2/3} \left[\frac{k_v h_{fg} g \rho_d \rho_v}{(T_w - T_d) \mu_g D_d} \right]^{0.25}$$

NEW

Post-Dryout Heat Transfer

Droplet Drag Coefficient:

$$0 < Re_d < 2 \qquad C_D = 24 / Re_d$$
$$2 \le Re_d < 500 \qquad C_D = 0.4 + 40 / Re_d$$
$$500 \le Re_d \le 10^5 \qquad C_D = 0.44$$

$$C_D = \frac{27}{Re_d^{0.84}}$$

$$C_D = \frac{24}{Re_d} \cdot (1 + 0.1 \cdot Re_d^{0.75})$$

$$C_D^{new} = \frac{C_D}{(1+B)^{0.2}}$$

$$B = \left(\frac{c_{P,g} \cdot (T_g - T_{sat})}{h_{fg}} \right) \cdot \left(1 - \frac{q''_{wd}}{q''_{wg}} + \frac{q''_{rad}}{q''_{conv}} \right) \approx \left(\frac{c_{P,g} \cdot (T_g - T_{sat})}{h_{fg}} \right)$$

$$C_D = \frac{24}{Re_d} \cdot \frac{(1 + 0.15 \cdot Re_d^{0.687})}{(1+B)^{0.2}} \qquad 0 \le Re_d \le 1000$$

NEW

Interfacial Heat Transfer:

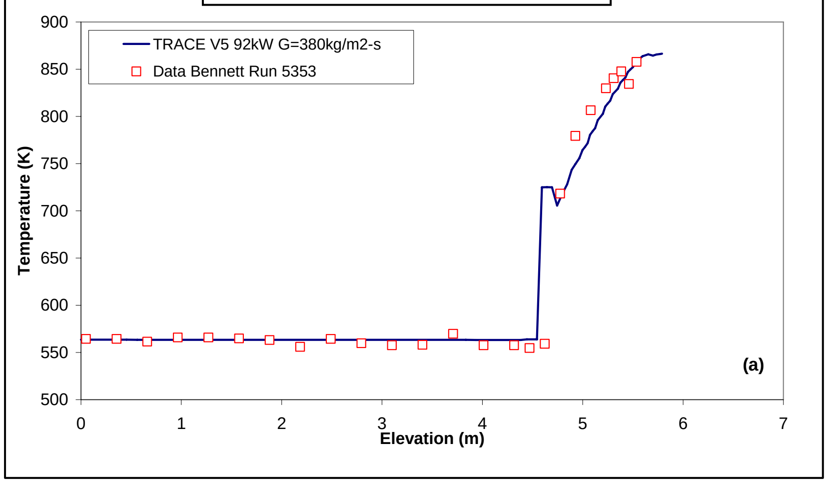
$$Nu_d = 2 + 0.60\,\mathrm{Re}^{1/2}\,\mathrm{Pr}_v^{1/3}$$

$$Nu_d = \frac{1.56 + 0.616 Re_d^{1/2} Pr_g^{1/3}}{(1+B)^{\beta}} \qquad 0.07 < \beta < 2.79$$

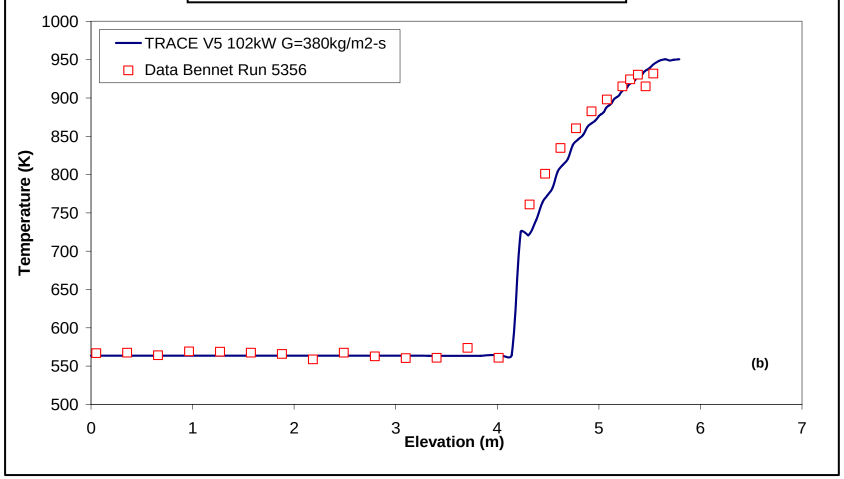
NEW

Results and Comparisons : CHF Predictions (Bennett tests, G= 380kg/m2.s)

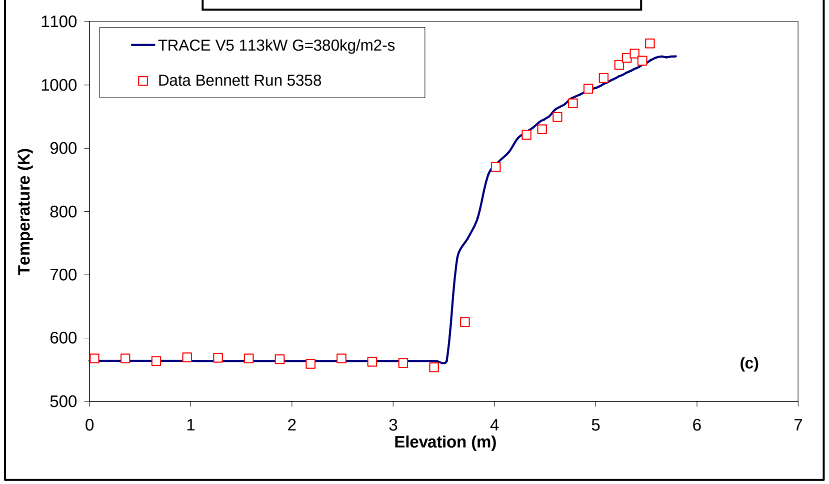
Power=92kW



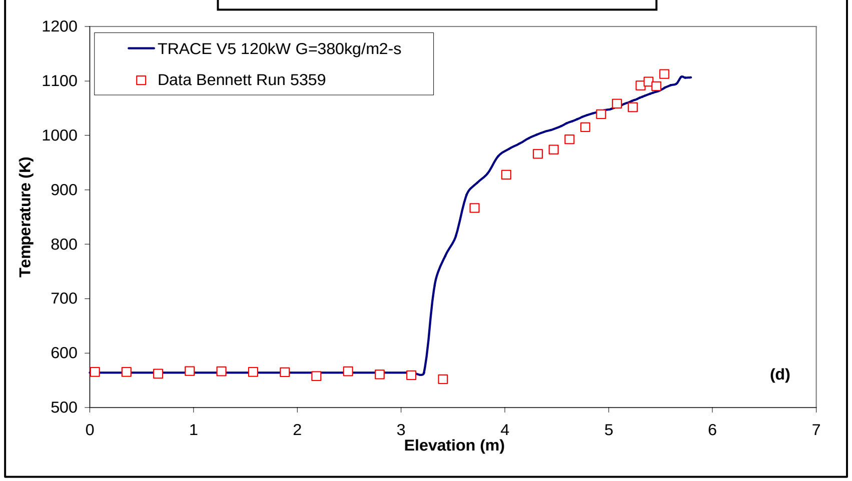
Power=102kW



Power=113kW



Power=120kW



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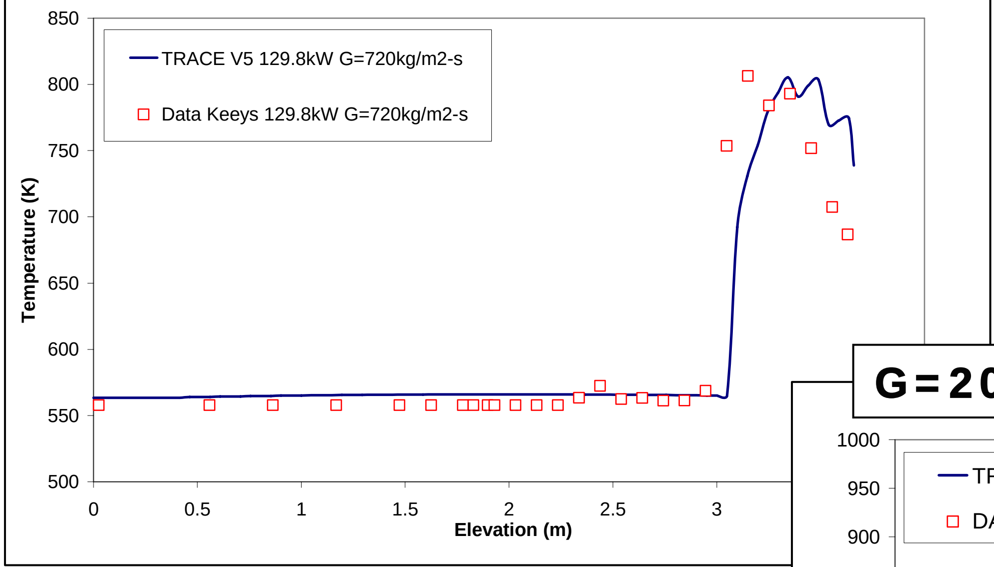
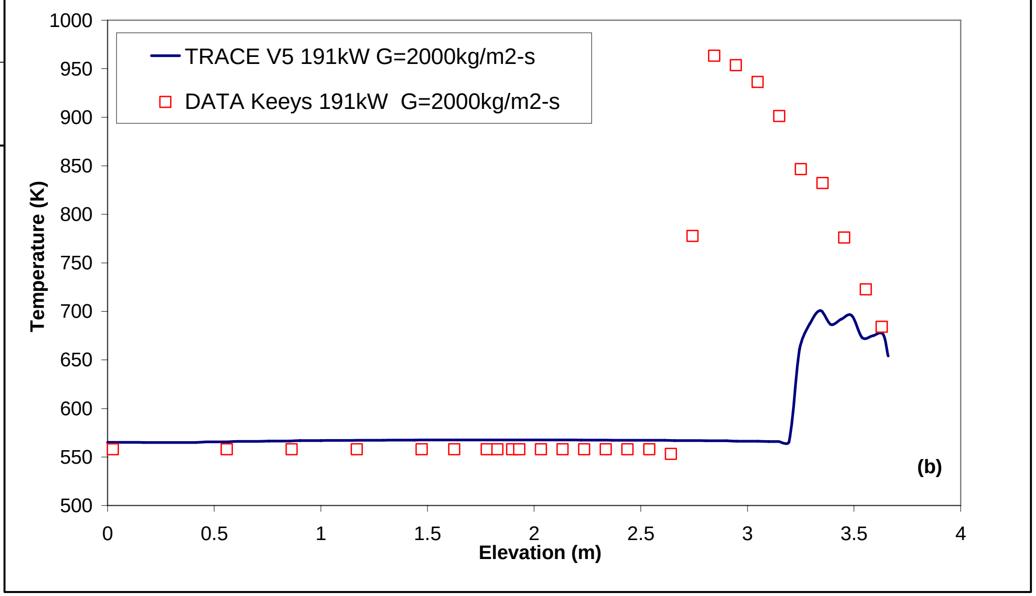
Results and Comparisons : CHF Predictions (Keeys tests)

G=720 kg/m2.s ; Power=129.8kW



G=2000 kg/m2.s ; Power=191kW



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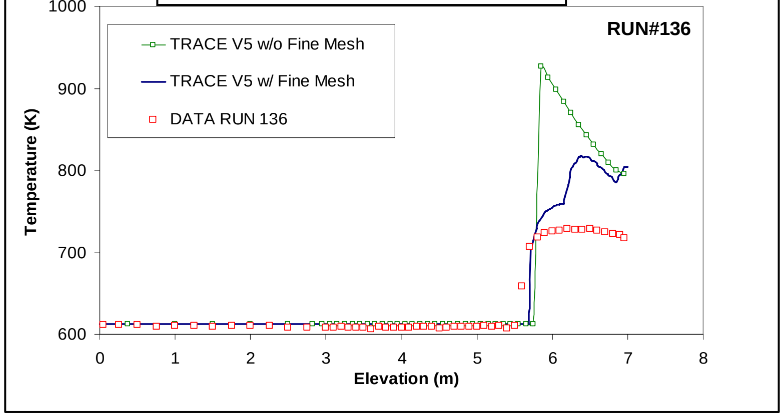
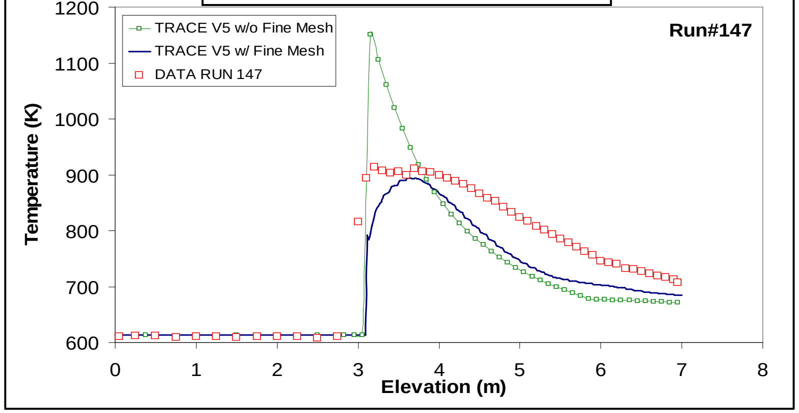
Results and Comparisons : CHF Predictions - Effect of Mass Flow Rate (Becker Tests)

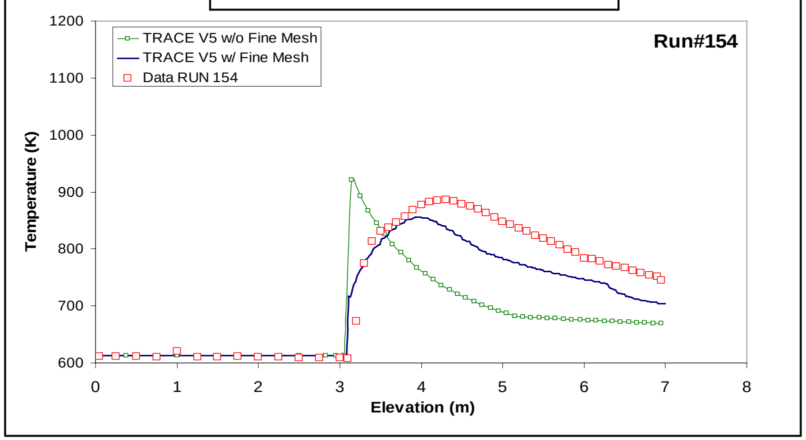
G=1977 kg/m2-s



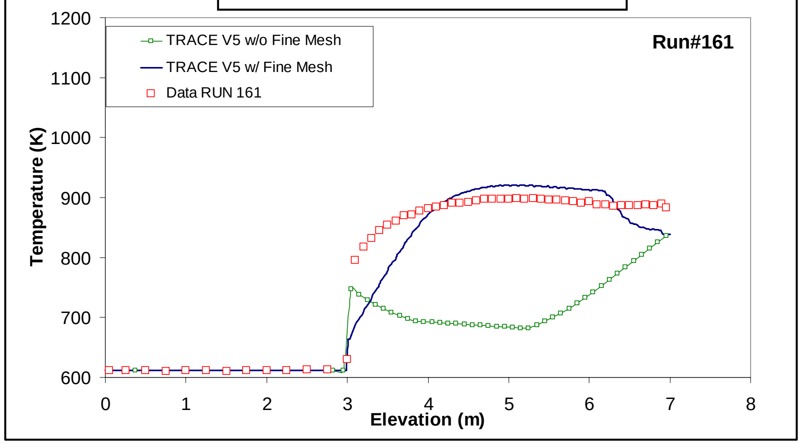
G=1494 kg/m2-s



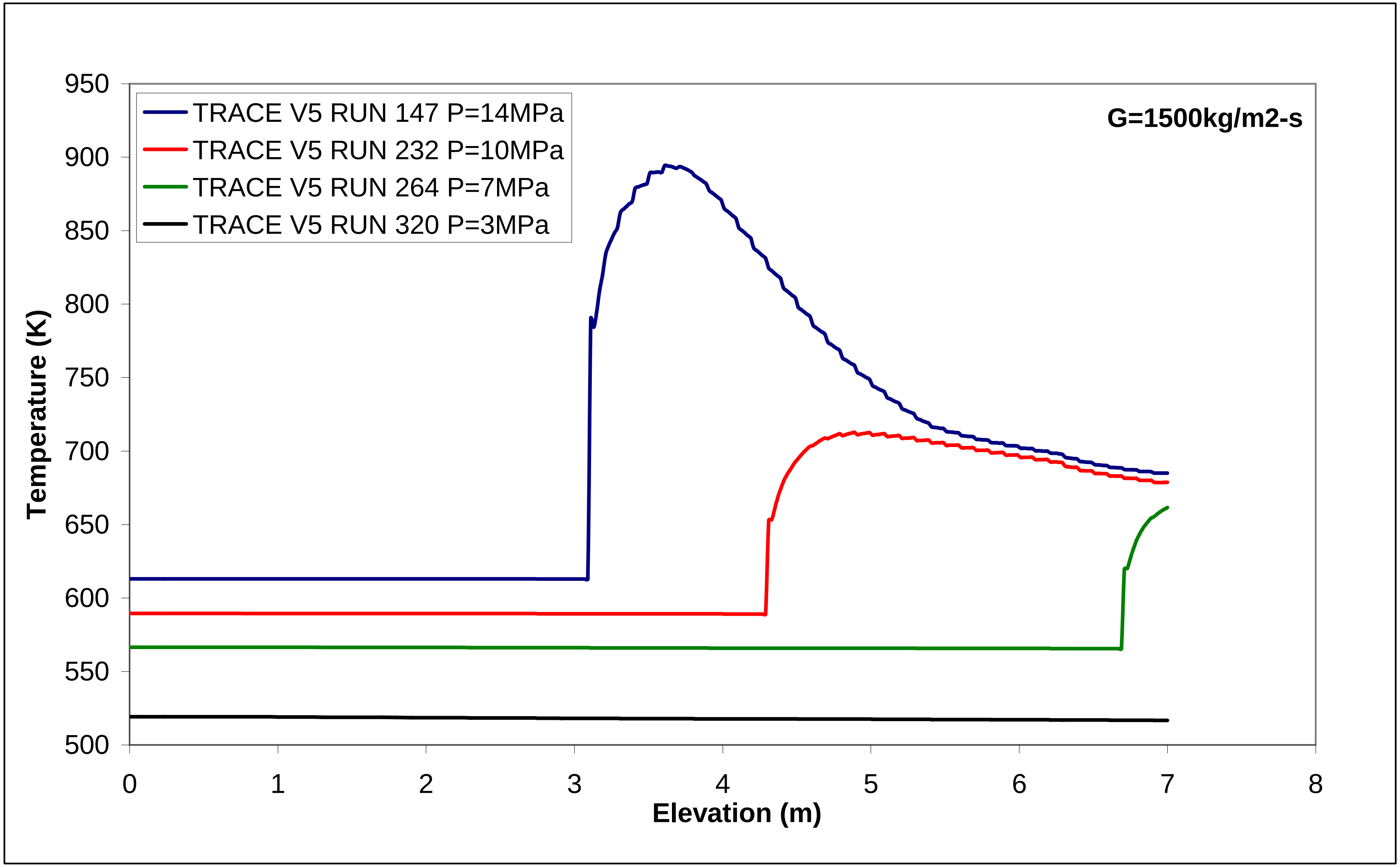
G=1006 kg/m2-s



G=503 kg/m2-s

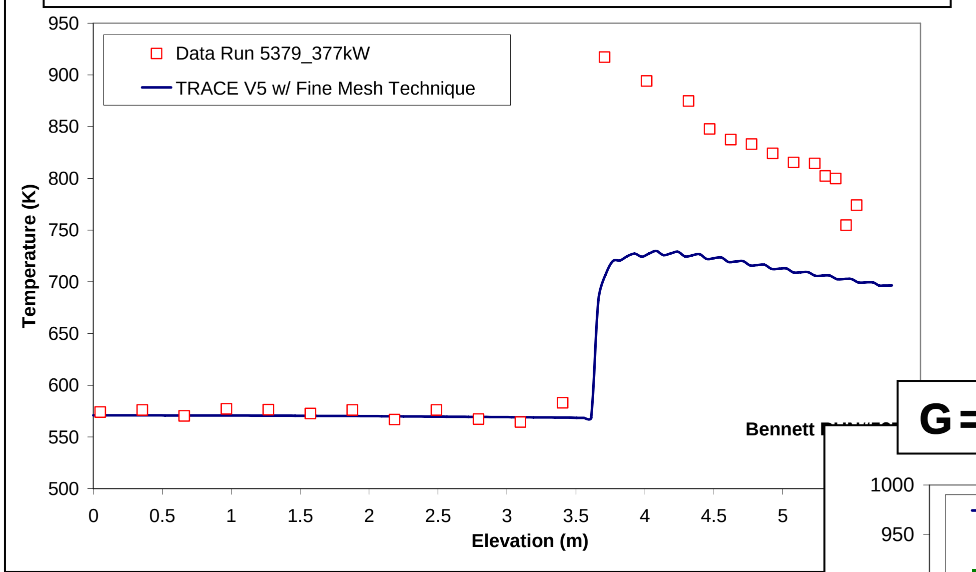


Results and Comparisons : CHF Predictions - Effect of Pressure (Becker Tests)

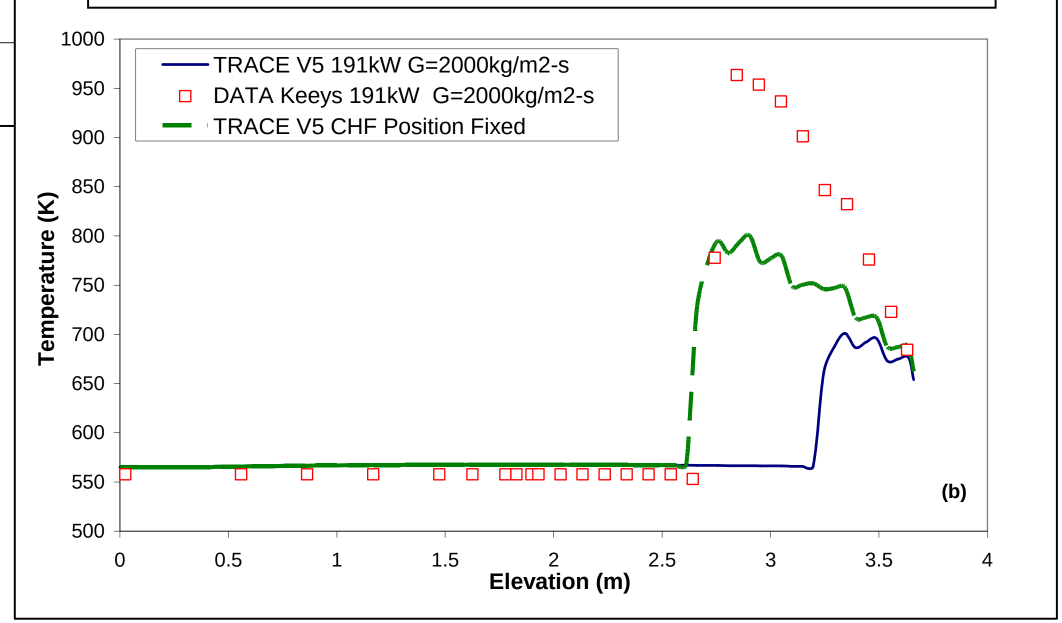


Results and Comparisons : CHF Position Imposed

G=3800 kg/m2.s ; Power=377kW



G=2000 kg/m2.s ; Power=191kW



Results

Parameters	Sensitivity
Nodalization	—
Fine Mesh Technique	+++
Correlations	++
Power	+++
Mass Flow Rate	+++

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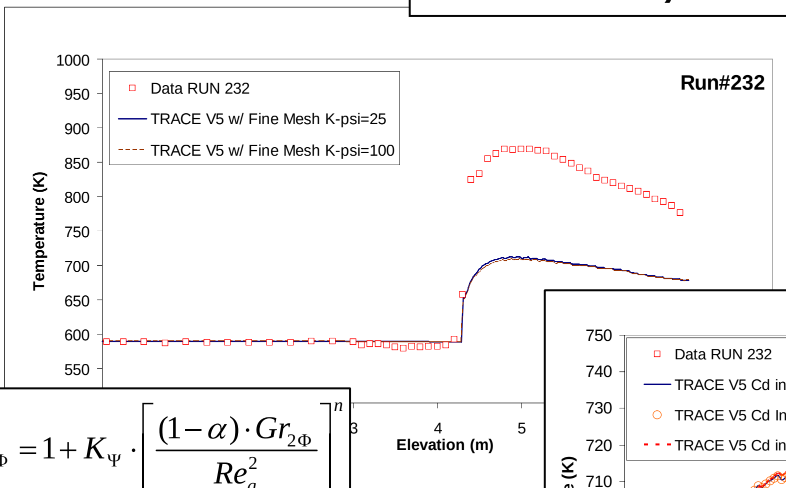
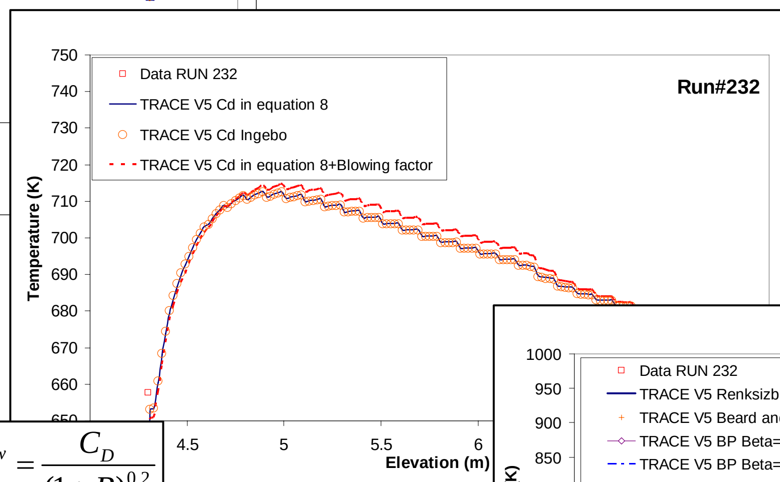
Post-CHF Parameters (studied for a particular Becker Test)

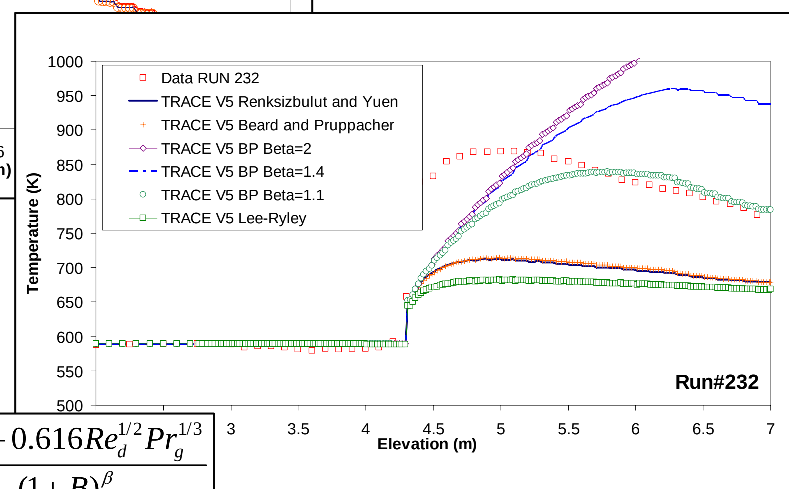
P=10MPa; G=1500kg/m2-s; Power=248kW



$$\Psi_{2\Phi} = 1 + K_{\Psi} \cdot \left[\frac{(1-\alpha)\cdot Gr_{2\Phi}}{Re_g^2}\right]^n$$



$$C_D^{new} = \frac{C_D}{(1+B)^{0.2}}$$



$$Nu_d = \frac{1.56 + 0.616 Re_d^{1/2} Pr_g^{1/3}}{(1+B)^{\beta}}$$

A selected set of constitutive laws for heated single tubes

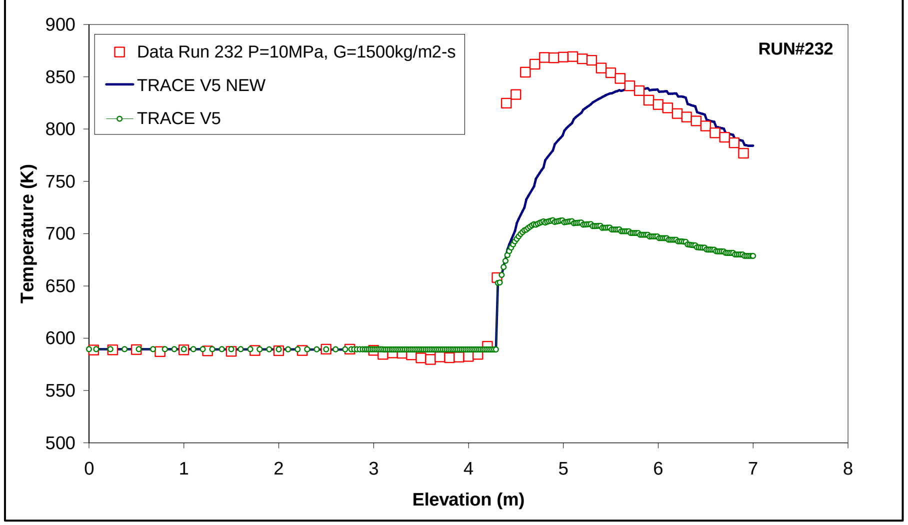
Implementation of a new model:

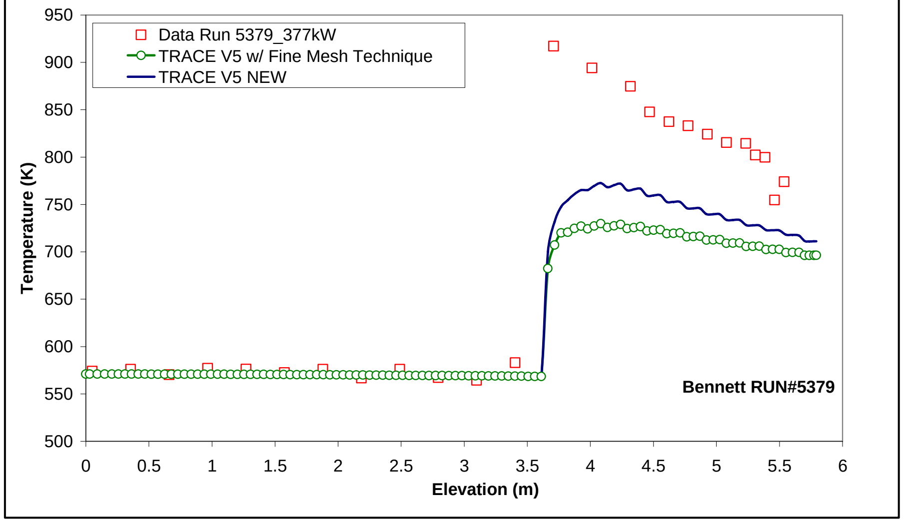
•***Interfacial droplet drag***: modified version of the Schiller-Naumann correlation accounting for the mass efflux.

•***Interfacial heat transfer***: Blowing factor applied to the Beard and Pruppacher correlation

•***Wall heat transfer***: Two-phase enhancement factor explicitly calculated for round tubes.

P=10MPa; G=1500kg/m2-s; Power=248kW





Discussion

Quench Front Propagation:

» CHF Correlations:

- ‘look-up’ tables of Groeneveld,
- Local conditions hypothesis,
- Boiling length/quality relationship.

Discrepancies in the Post-CHF region (DFFB)

» Precursory cooling effects

» Droplet field model?

- Droplet size
- Multi-group discretization of droplets diameters

» Interfacial Area Transport Equation

» Near Wall Turbulence and Macroscopic Turbulence Model.

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Conclusion

- **Ability to predict the point of CHF reasonably well**
  - » Look-Up Tables + Biasi Correlation: Low Mass & Heat Fluxes (Bennett)
- **PCT not well predicted for the case of a non-uniform heat flux**
  - » Interfacial terms,
  - » Droplet size (one representative droplet, Sauter Mean Diameter) and number density
- **Two-Phase Enhancement Factor**: No major influence for these calculations
- **Droplet Drag Coefficient**: No important role in the calculations performed here.
- **Interfacial Heat Transfer**: strongly dependent on the blowing factor

- **I am very grateful to Dr. Jones (British Energy) and Dr. Lillington (SERCO) for their constant assistance.**
- **I would like to acknowledge the EPSRC for the funding under grant EP/C549465/1**

Thank you for your attention !!