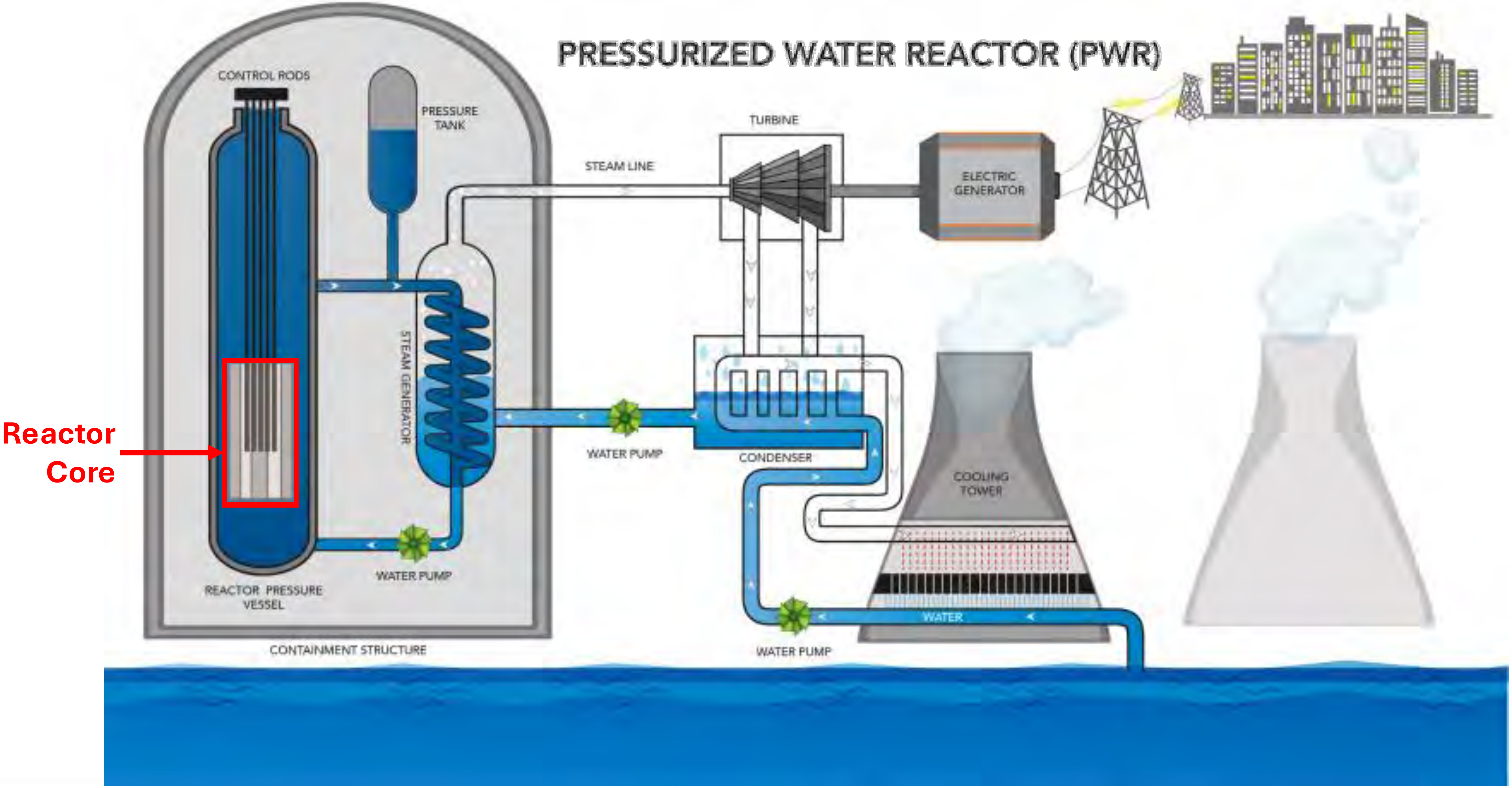
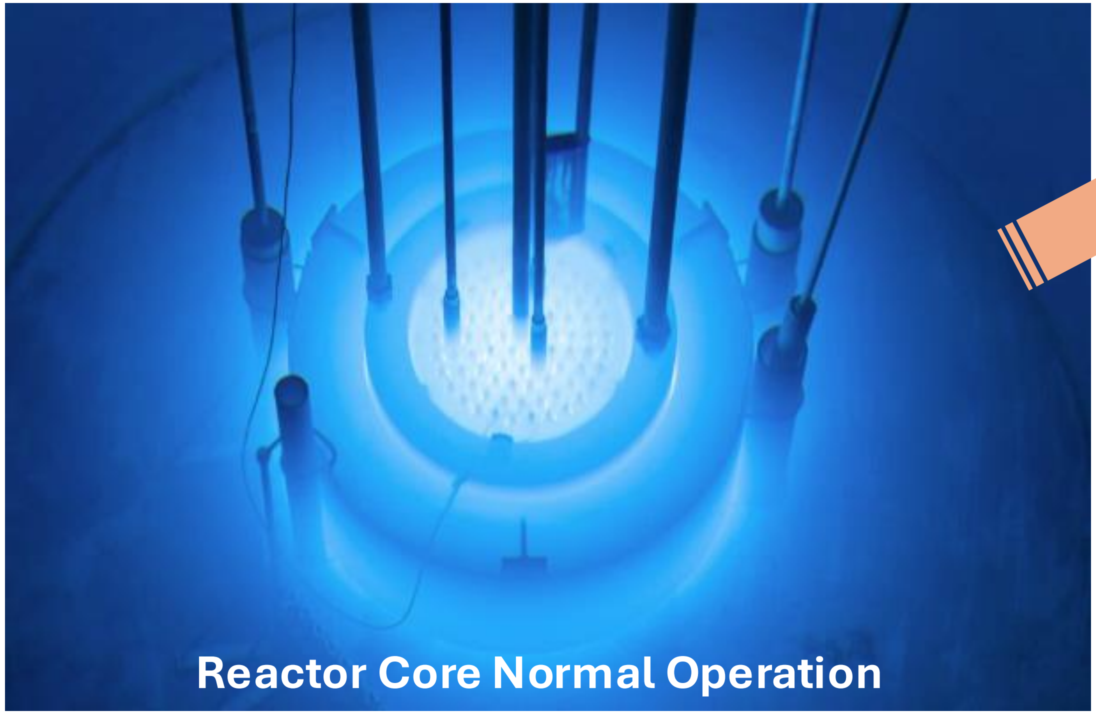
Development of the deep learning-based modeling approaches for nuclear reactor thermal-hydraulics applications

Yue Jin
Assistant Professor
Department of Mechanical & Aerospace Engineering
University of Missouri
yj5cy@missouri.edu; +1-573-882-9427

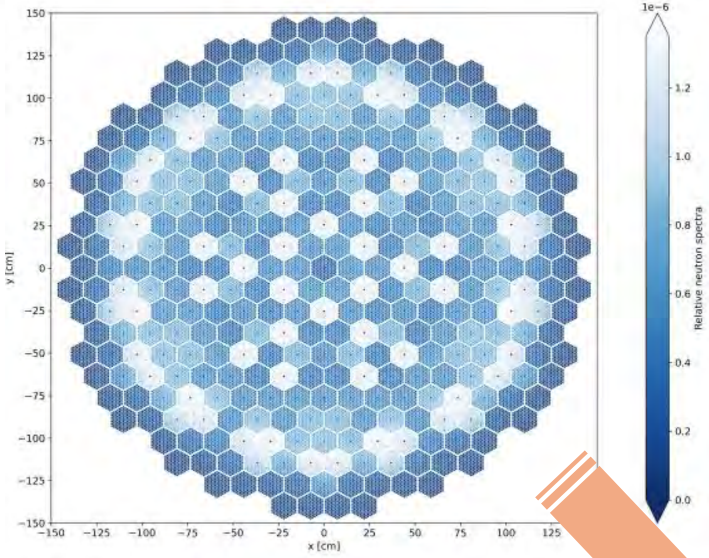
Nuclear Power Plant Operation



Reactor Core Fuel Assembly



Reactor Core Normal Operation



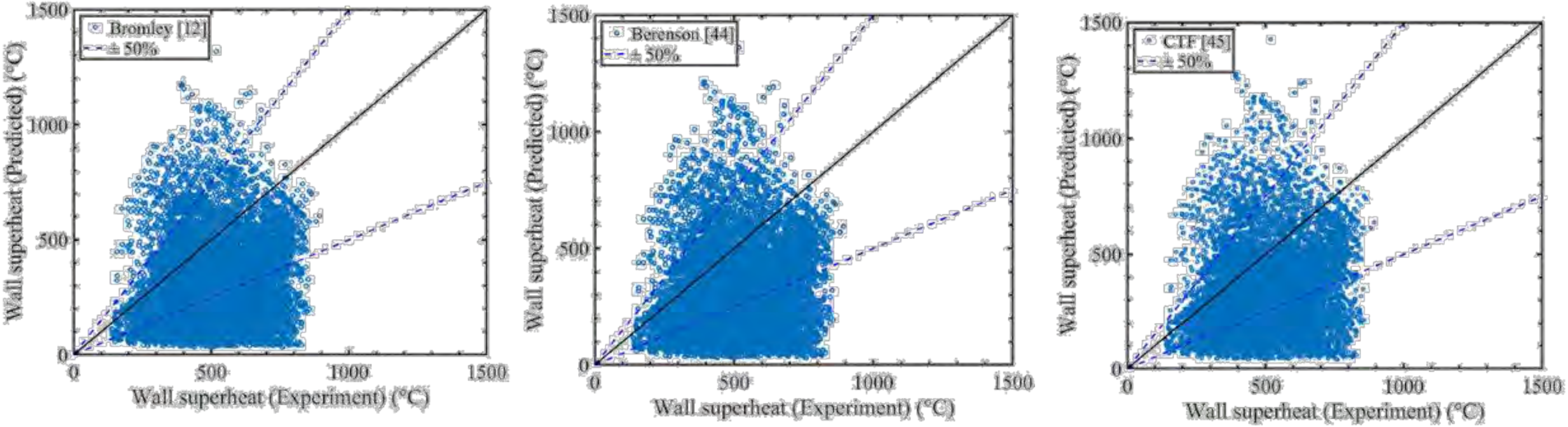
Nuclear Fuel Assembly Layout

Single Fuel Assembly

Single Rod/Pin with Fuel Pellets

*Prevent **Boiling Crisis** and/or **Critical Heat Flux (CHF)** is the **KEY**!*

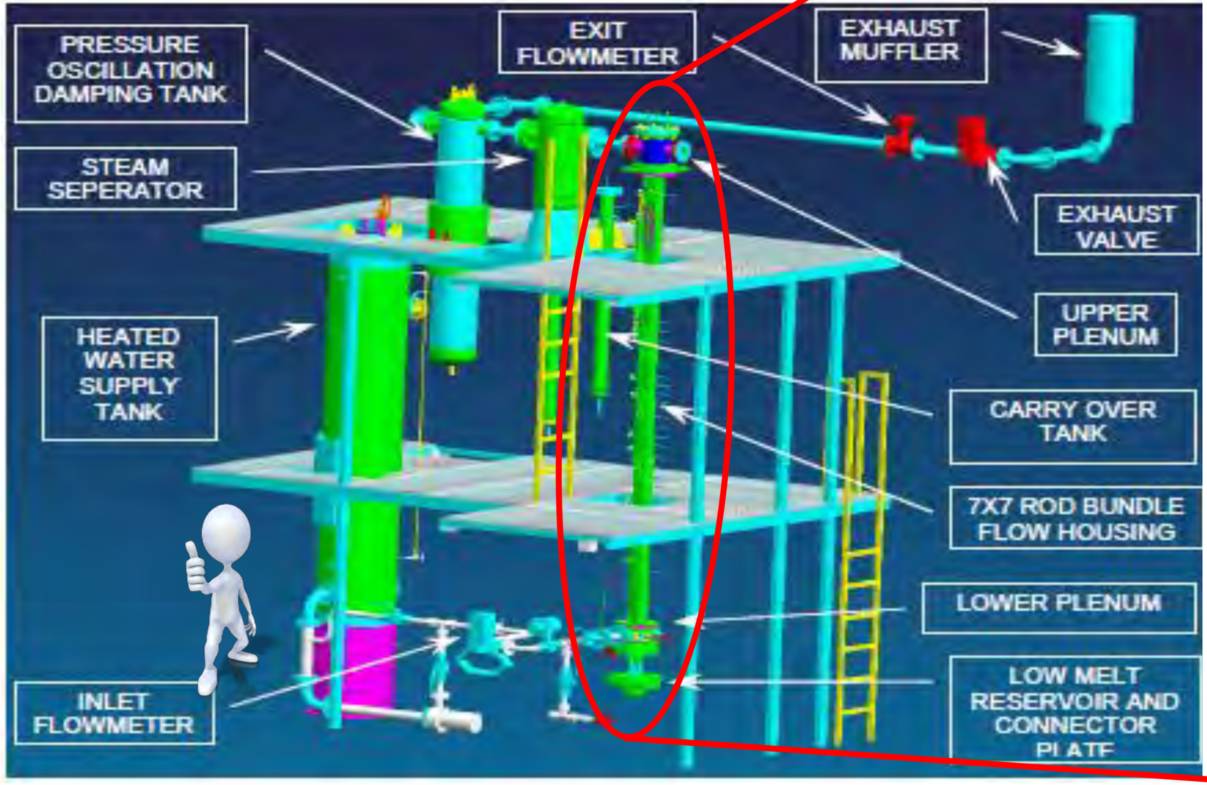
Original CHF Model Predictions

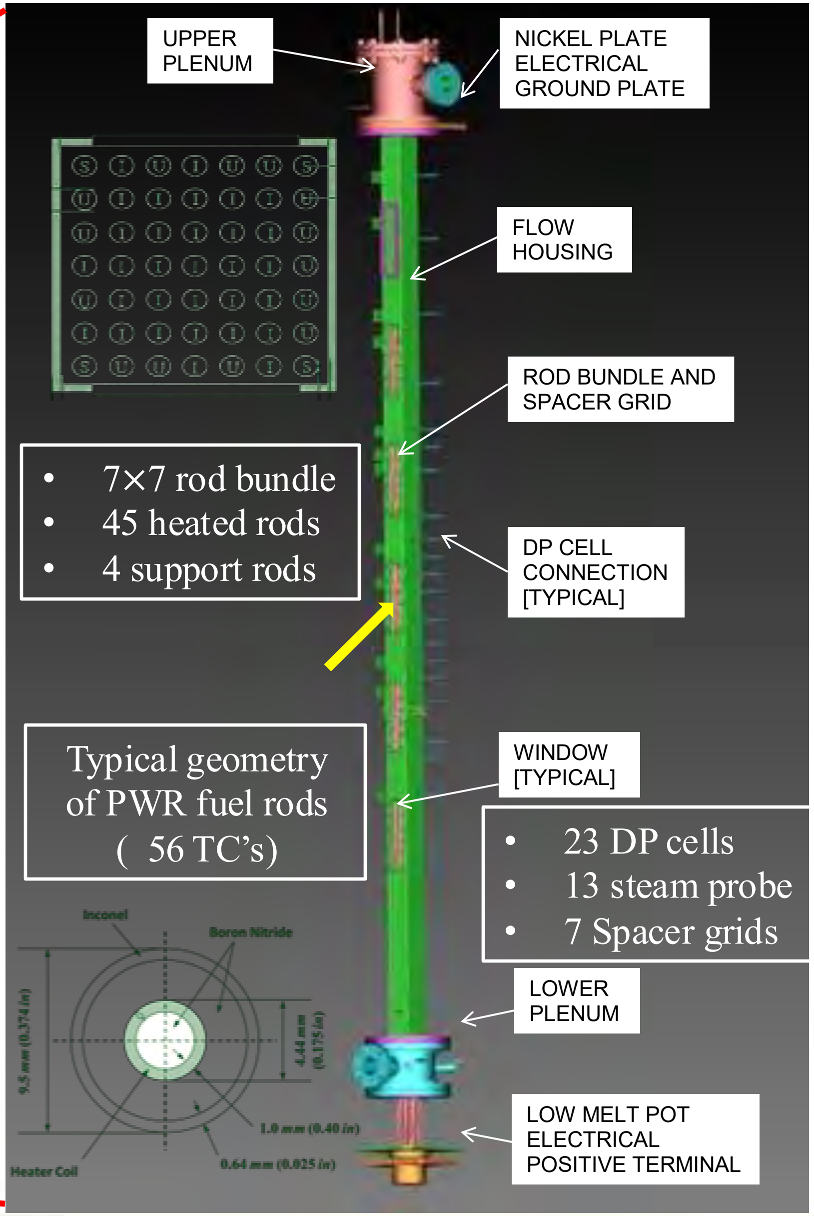


NRC/PSU Rod Bundle Heat Transfer (RBHT) Test Facility

- **System operating pressure**: up to 413.7 *kPa* (60 *Psia*)
- **Inlet water velocity**: -0.2 to 0.2 *m/sec* (-8 to 8 *in/sec*)
- **Peak power**: up to 1.97 *kW/m* (0.6 *kW/ft*)
- **Peak cladding temperature**: up to 1144.3 *K* (1600 ^{o}F)
- **Inlet subcooling**: up to 83 *K* (150 ^{o}F)

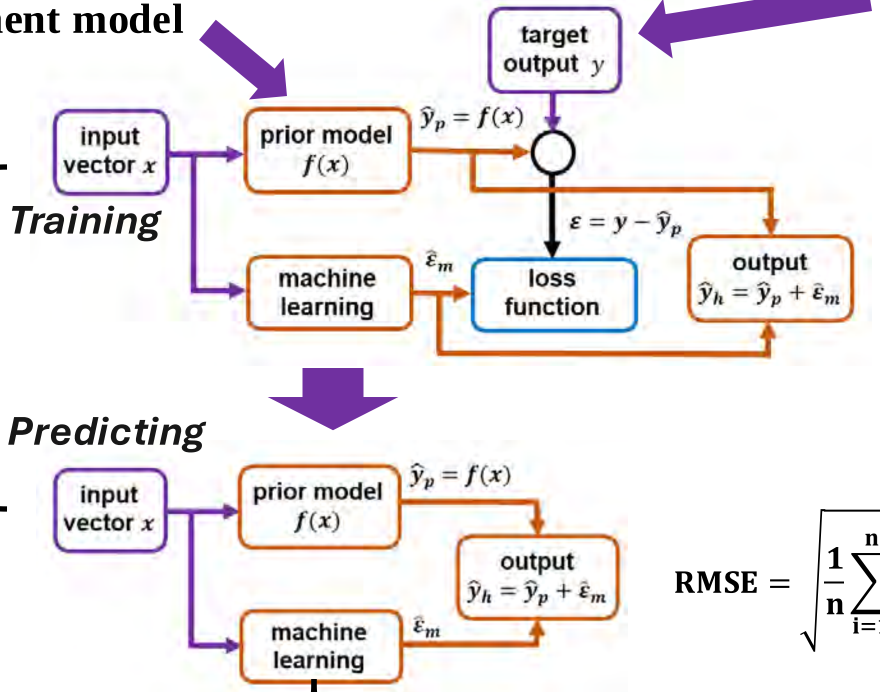
Working fluid: Water or Steam





Physics Informed ML Structures

Standalone I&M Model and pool entrainment model



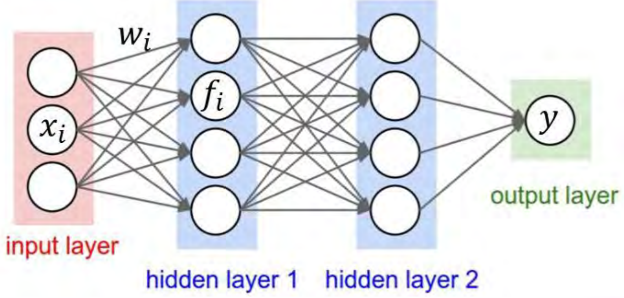
ML input space, *x*,
- Pressure
- Inlet mass flow rate
- Rod temperature
- Fluid density
- Viscosity

Exp #	Inlet Velocity m/s (in/s)	Pressure kPa (psia)	Initial PCT K (ºF)	Subcooling K (ºF)	Peak Power kW/m (kW/ft)
7063	0.0254 (1)	275.8 (40)	1033 (1400)	10 (18)	1.31 (0.4)
7090	0.0254 (1)			10 (18)	1.31 (0.4)
7095	0.0254 (1)			80 (150)	1.31 (0.4)
7112	0.0254 (1)			50 (90)	0.97 (0.3)
7151	0.0191 (0.75)			53 (96)	1.31 (0.4)
7157	0.0254 (1)			11 (20)	1.31 (0.4)
7166	0.0254 (1)			80 (150)	1.31 (0.4)
7168	0.0254 (1)			51 (91)	0.97 (0.3)
7174	0.0191 (0.75)			53 (96)	1.31 (0.4)
8009	0.0254 (1)			22.2 (40)	1.31 (0.4)
8011	0.0254 (1)			53.3 (96)	1.31 (0.4)
8018	0.0254 (1)			53.3 (96)	1.31 (0.4)
8021	0.0254 (1)	137.9 (20)		22.2 (40)	1.31 (0.4)
8023	0.0254 (1)	413.7 (60)		22.2 (40)	1.31 (0.4)
8040	0.058 (2)	275.8 (40)		53.3 (96)	1.31 (0.4)
8041	0.0254 (1)	206.8 (30)		22.2 (40)	1.31 (0.4)

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{y_{pred,i} - y_{exp,i}}{y_{exp,i}}\right)^2}$$

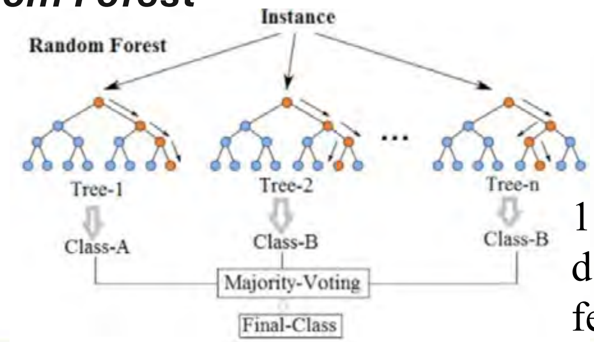
Total 10,047 data points
- 80% training and 20% validation
- Optimal ML architectures obtained through a comprehensive grid search study
- Early stop to prevent over training
- 10-fold cross-validation to address model over-fitting

Neuron Network



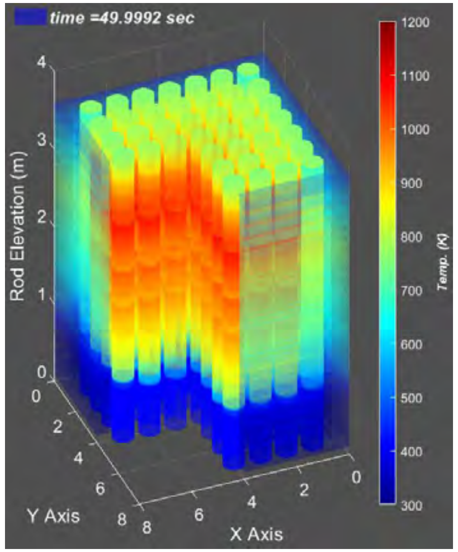
ANN architecture: 32/64/32/1 with "ADAM" optimizer, epoch of 90, and batch size of 350.

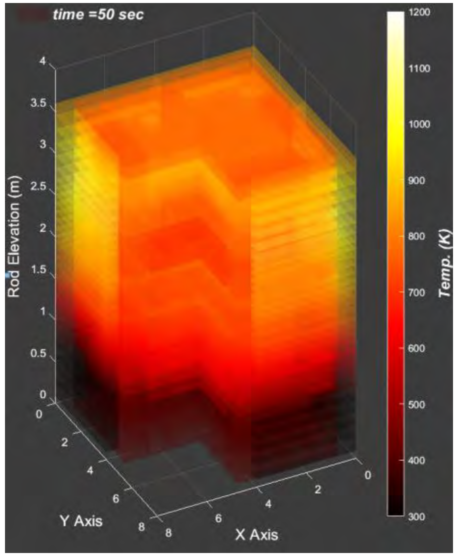
Random Forest

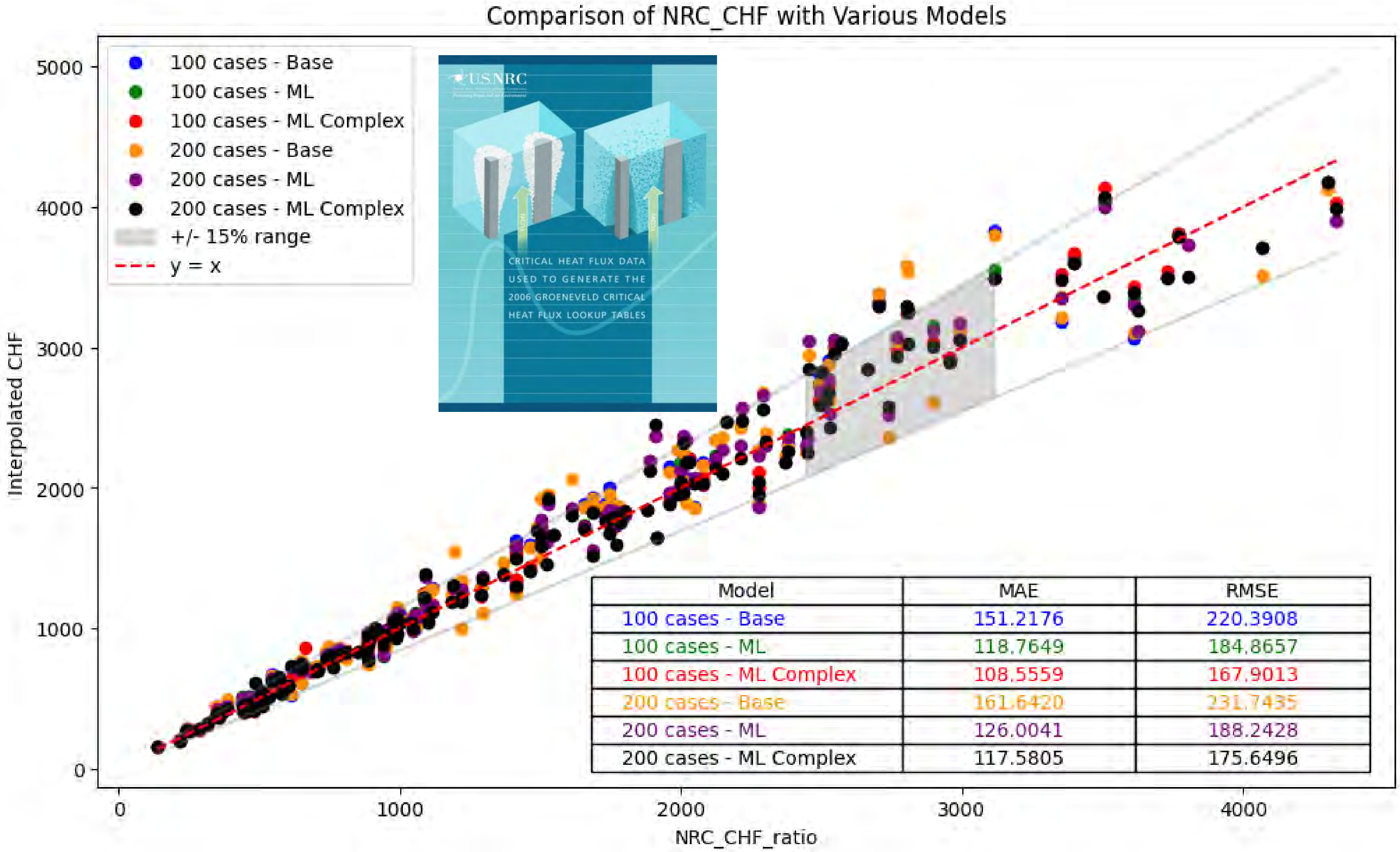


160 estimators with max depth of 35 and max feature of 0.6

ML CHF Model Predictions – Preliminary

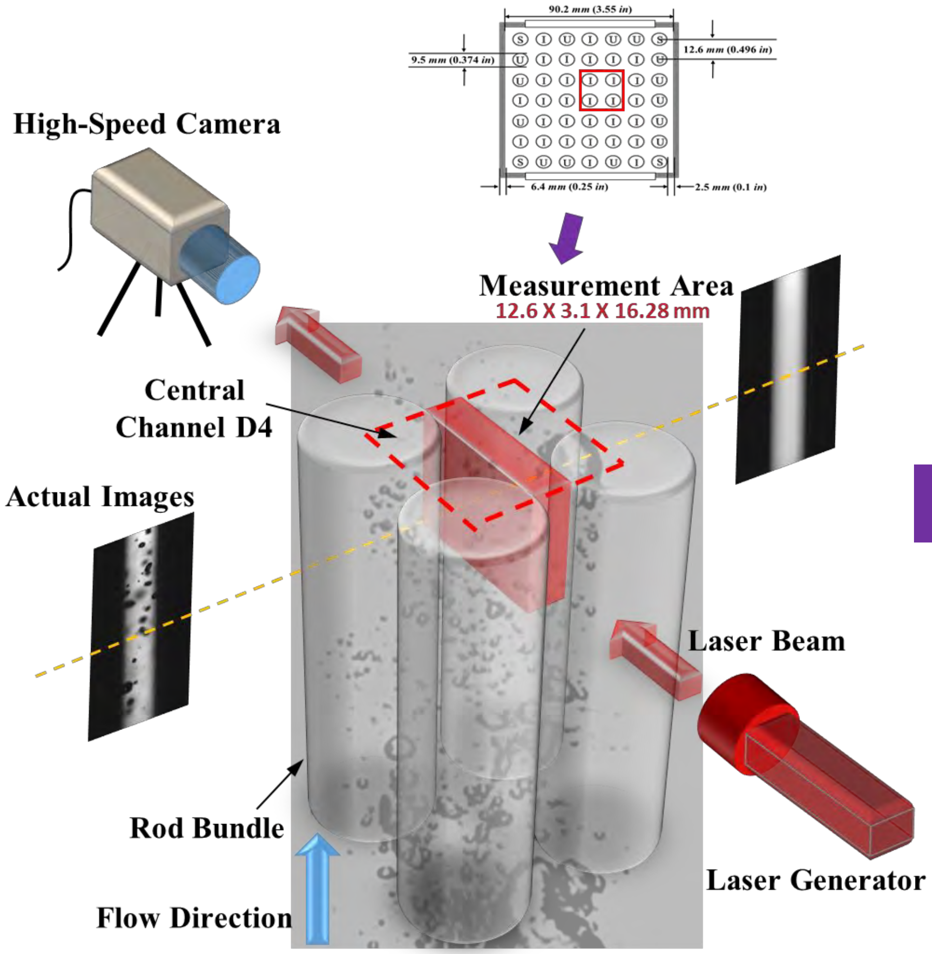


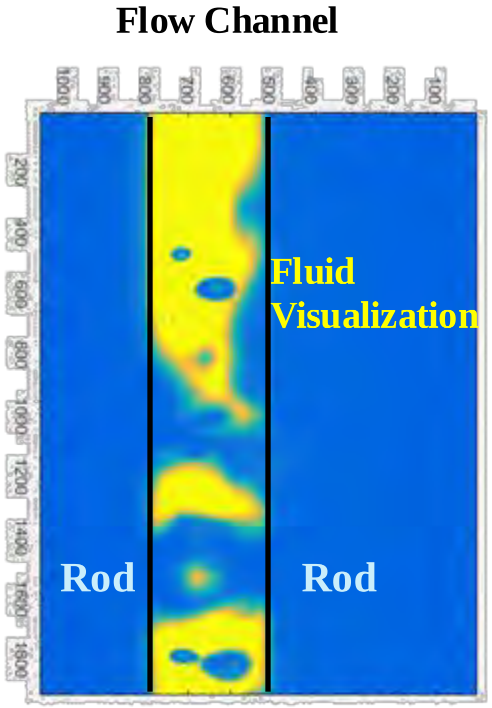


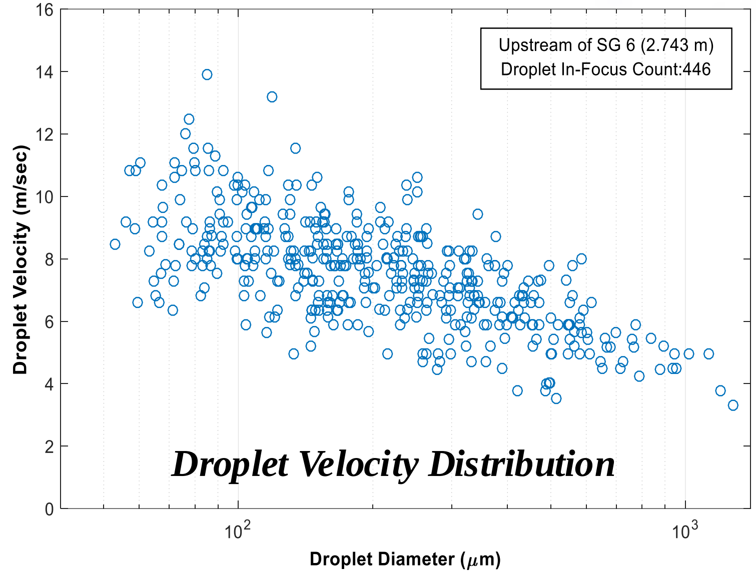


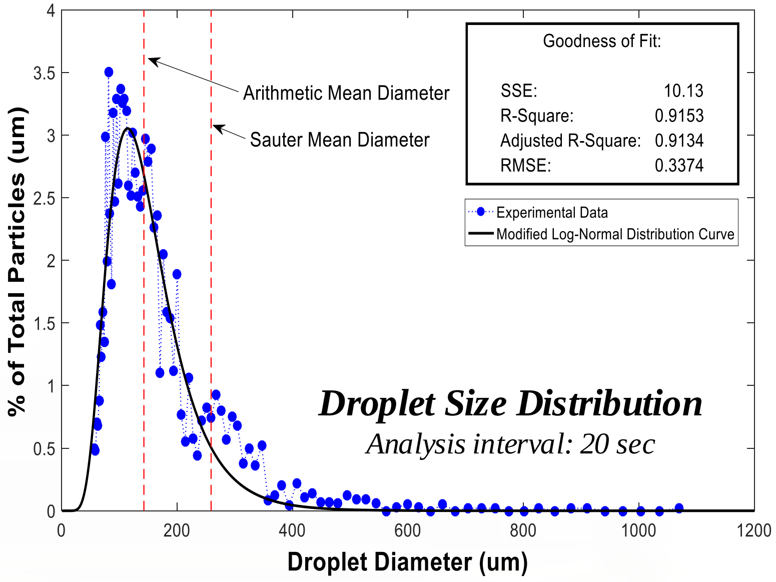
Model	MAE	RMSE
100 cases - Base	151.2176	220.3908
100 cases - ML	118.7649	184.8657
100 cases - ML Complex	108.5559	167.9013
200 cases - Base	161.6420	231.7435
200 cases - ML	126.0041	188.2428
200 cases - ML Complex	117.5805	175.6496

Laser Imaging System

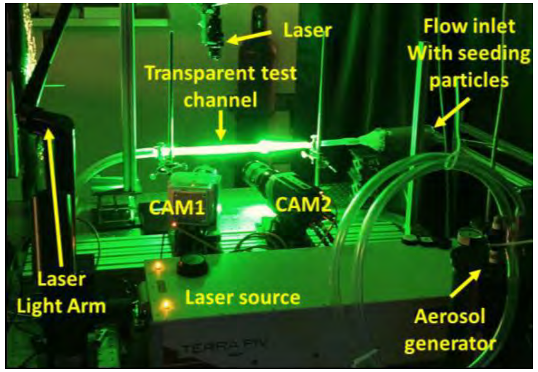






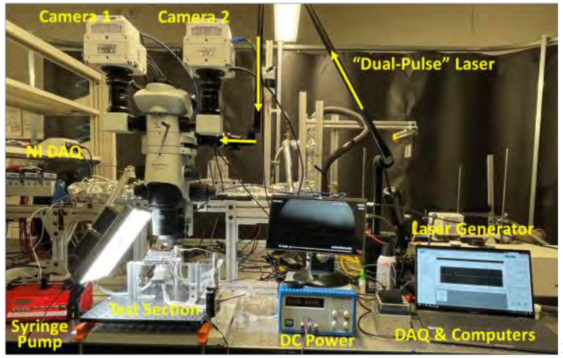


ML CHF Model Predictions – Preliminary

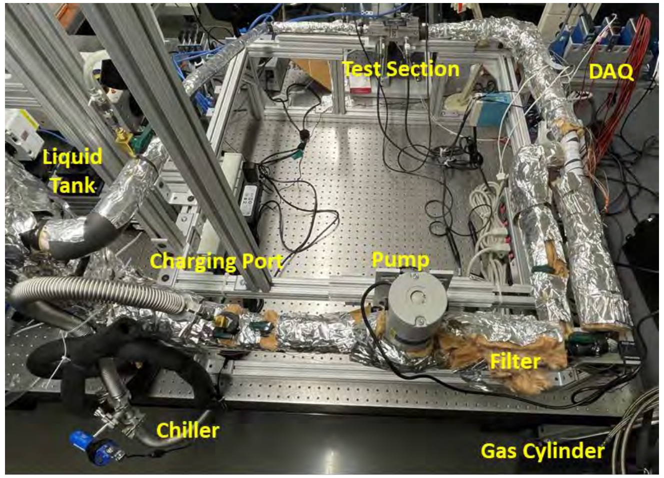


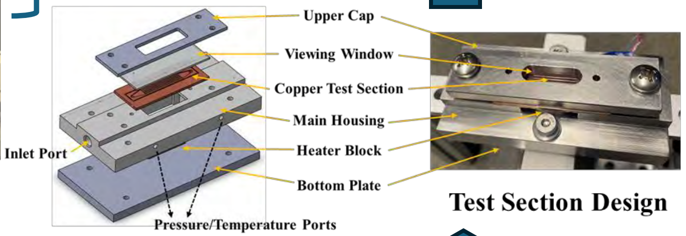
Macro-Scale Stereo-PIV

Micro-Scale Stereo-PIV

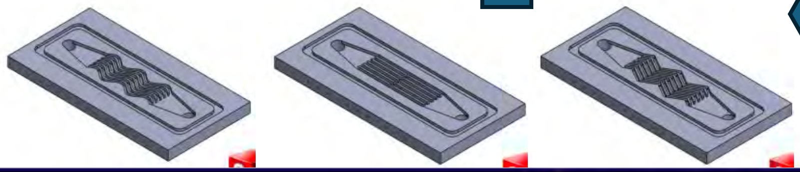


Flow and Heat Transfer Loop

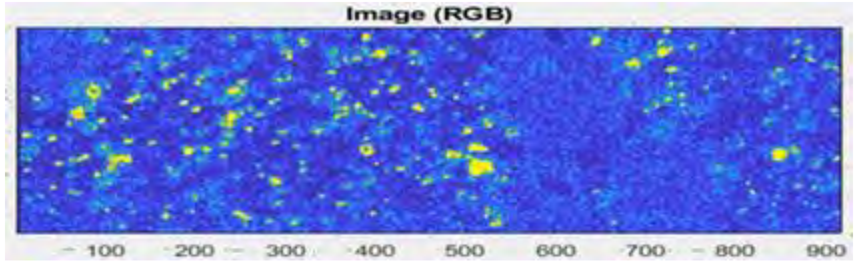


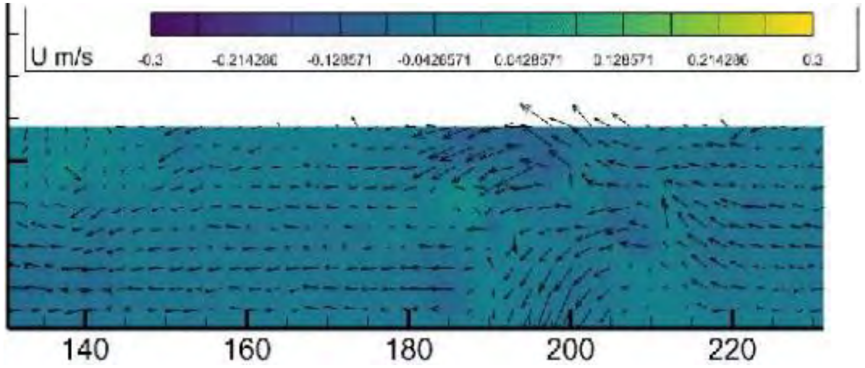


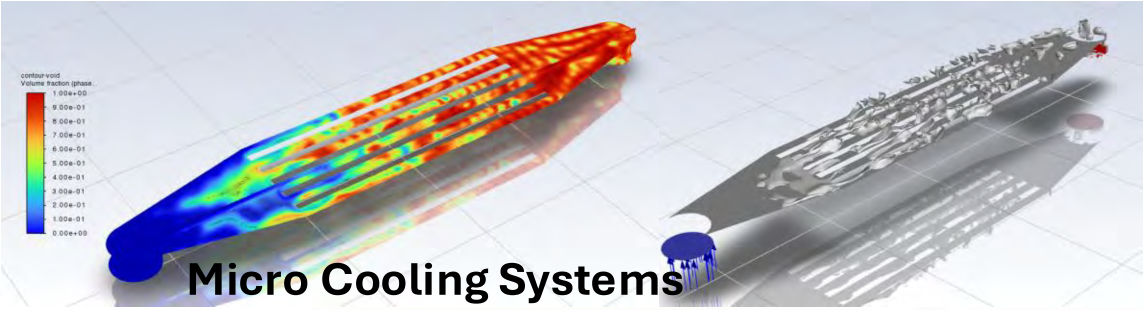
Test Section Design



Velocity Profile in Microchannel

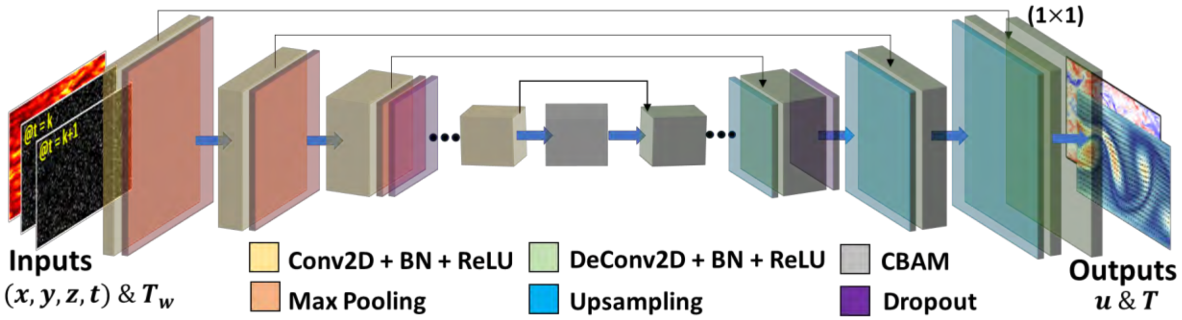






Micro Cooling Systems

Computer Vision Aided Image Processing Techniques

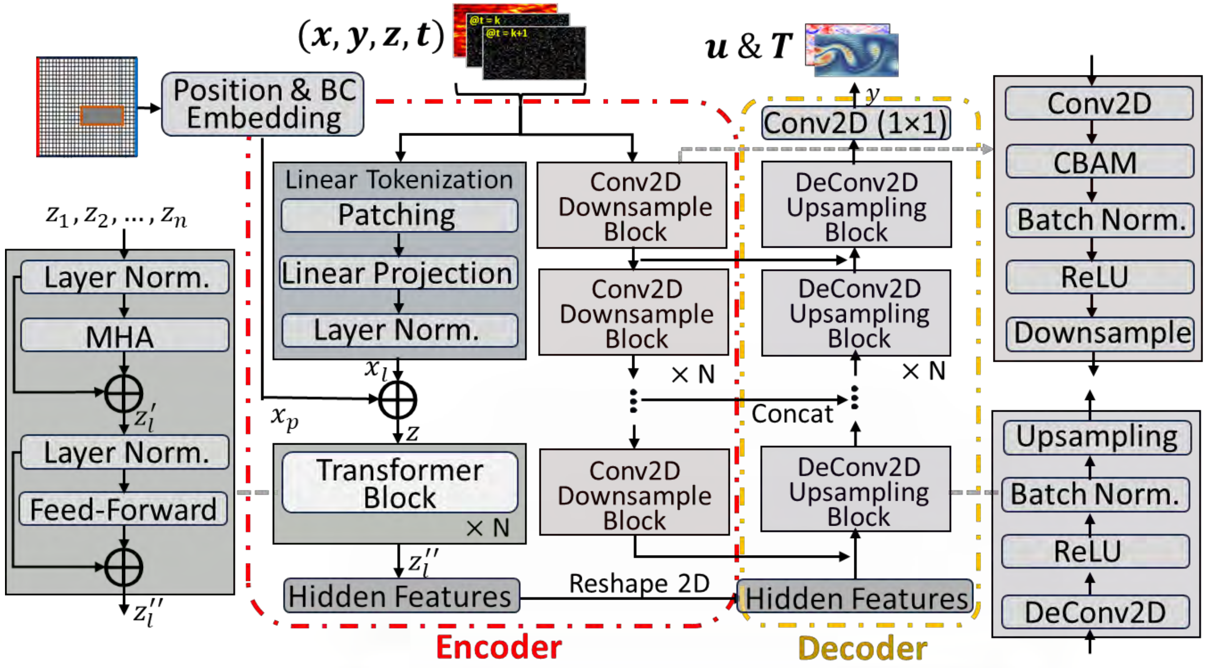


Fully Convolutional Neural Network (FCN) - Convolutional Block Attention Module (CBAM)

- Downsampling block consists of a convolution layer (Cov2D), batch normalization (BN), activation function, and max pooling layer
- Upsampling block restores the feature domain through deconvolution layers (DeCov2D)

Vision Transformer (ViT) based Model

- Encoder: linear tokenization block combined with both the position and known boundary conditions Transformer blocks with a multi-head self-attention (MHA) followed by a feed-forward neural network also with residual connections.
- Decoder: identical number of upsampling blocks



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yj5cy@missouri.edu
Department of Mechanical and Aerospace Engineering
University of Missouri