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사단법인 한국원자력학회
KOREAN NUCLEAR SOCIETY

Improvement of CHF Prediction under Non-Uniform Axial Power Profiles through AI-Based Memory-Effect Correction

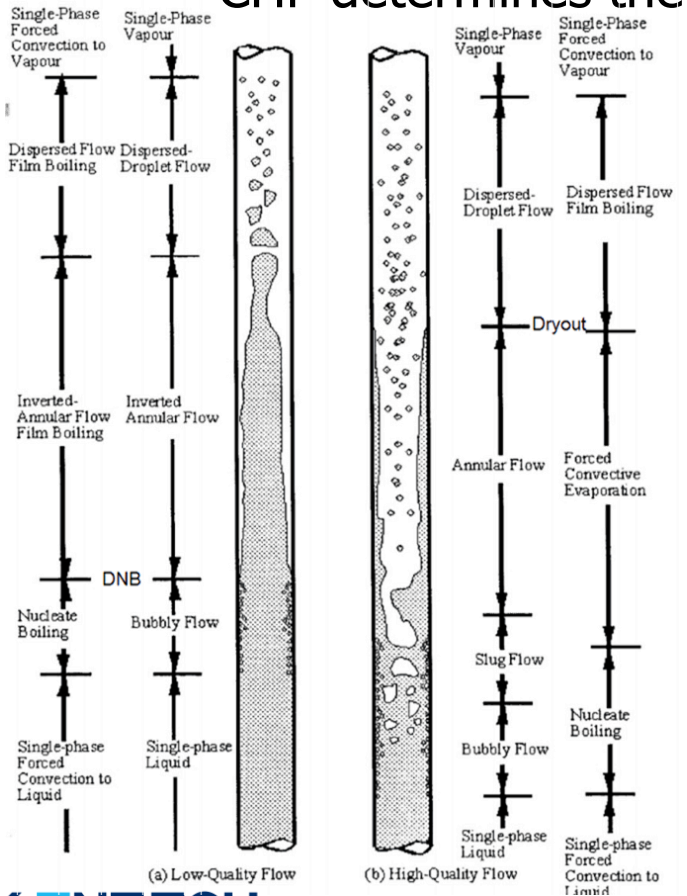
Hyunjun Jang, Kyung Mo Kim*

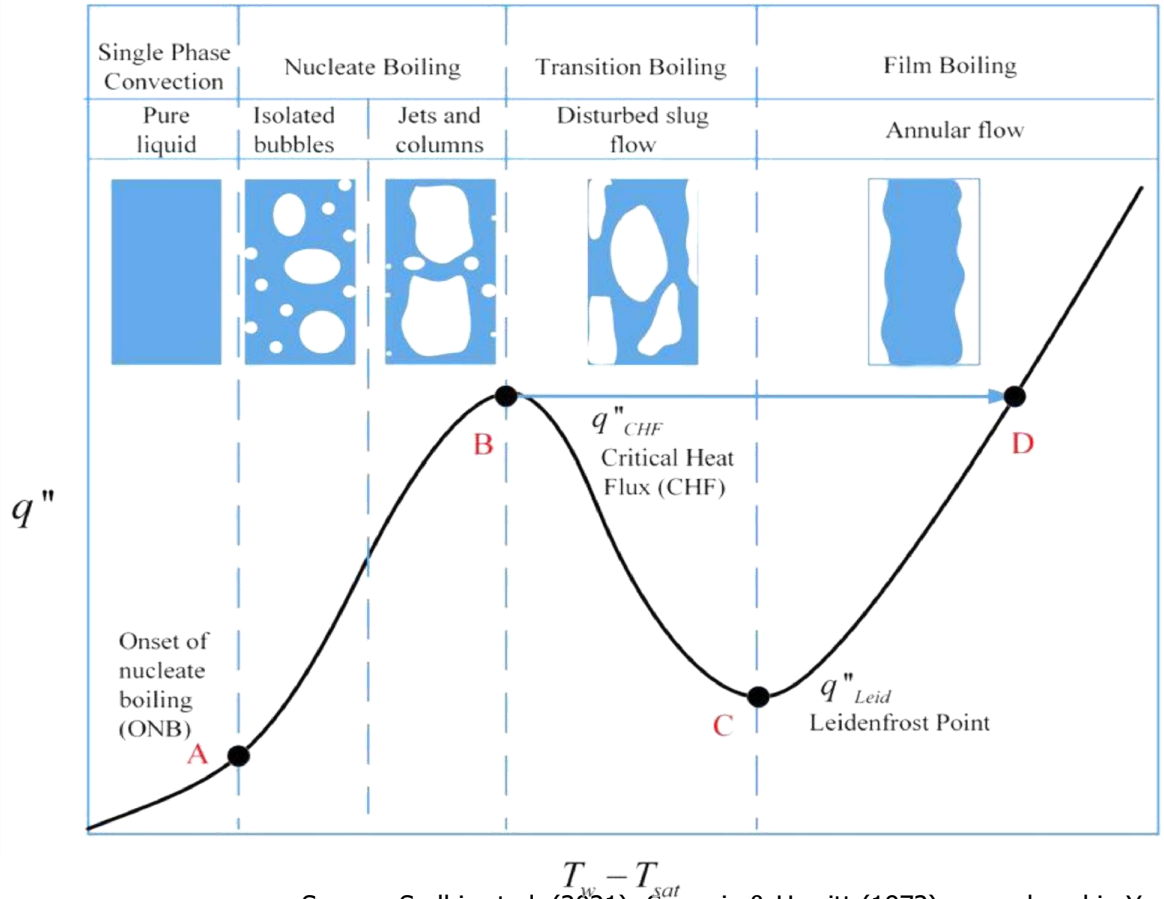
Intelligent Reactor for Innovative Safety (IRIS Lab.)

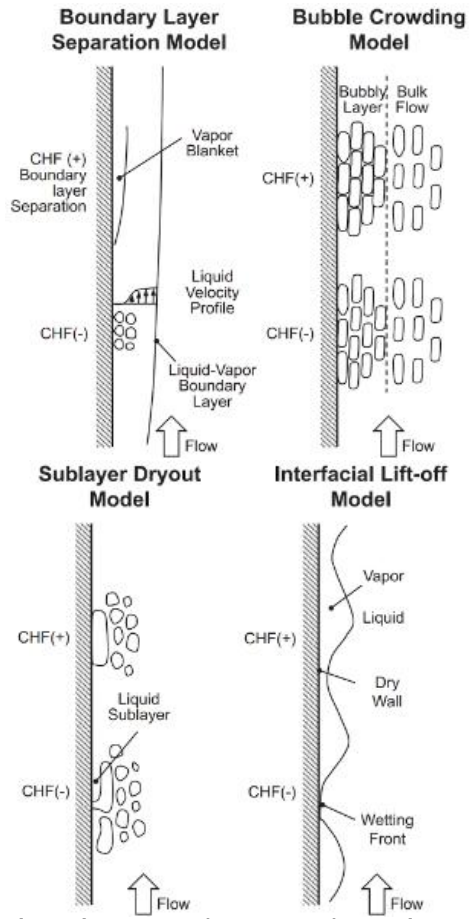
KNS Autumn Meeting. Oct. 30, 2026

Background

- **Critical Heat Flux (CHF):** The heat flux at which boiling crisis occurs
  - At CHF, **heat transfer deteriorates abruptly** (DNB or dryout)
  - CHF determines the thermal safety margin of water-cooled reactors







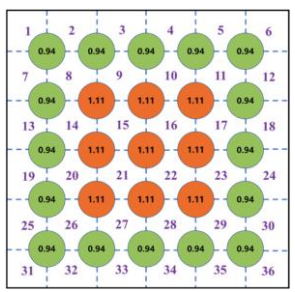
Source: Sudhir et al. (2021), Semeria & Hewitt (1972), reproduced in Yang (2004), C. Konishi & I. Mudawar (2015))

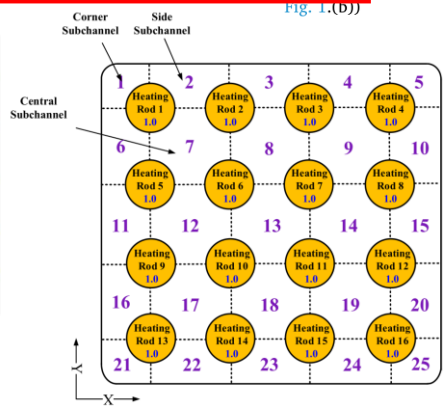
Background

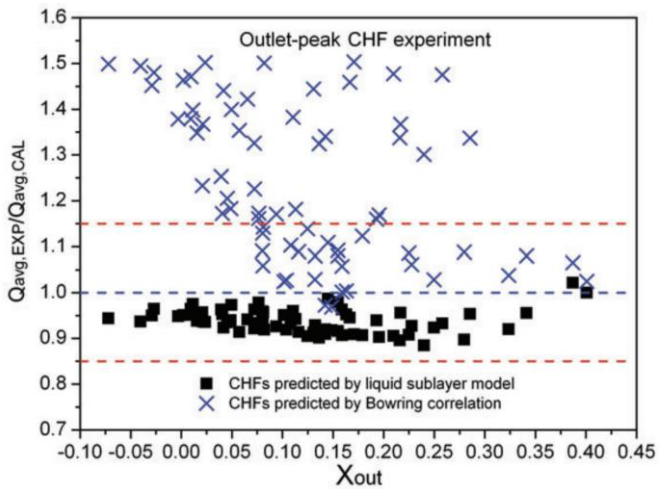
- ❑ **CHF experiments are predominantly performed under uniform heating**
  - Uniform heaters are simpler to fabricate and to control
- ❑ **Reactor cores operate under non-uniform axial power distributions**
  - Under identical geometry and inlet conditions, **CHF differs**

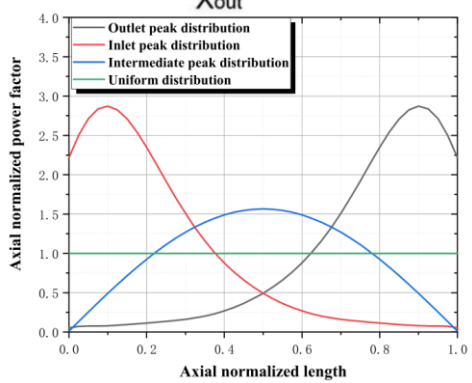
The operating range of typical rod bundles.

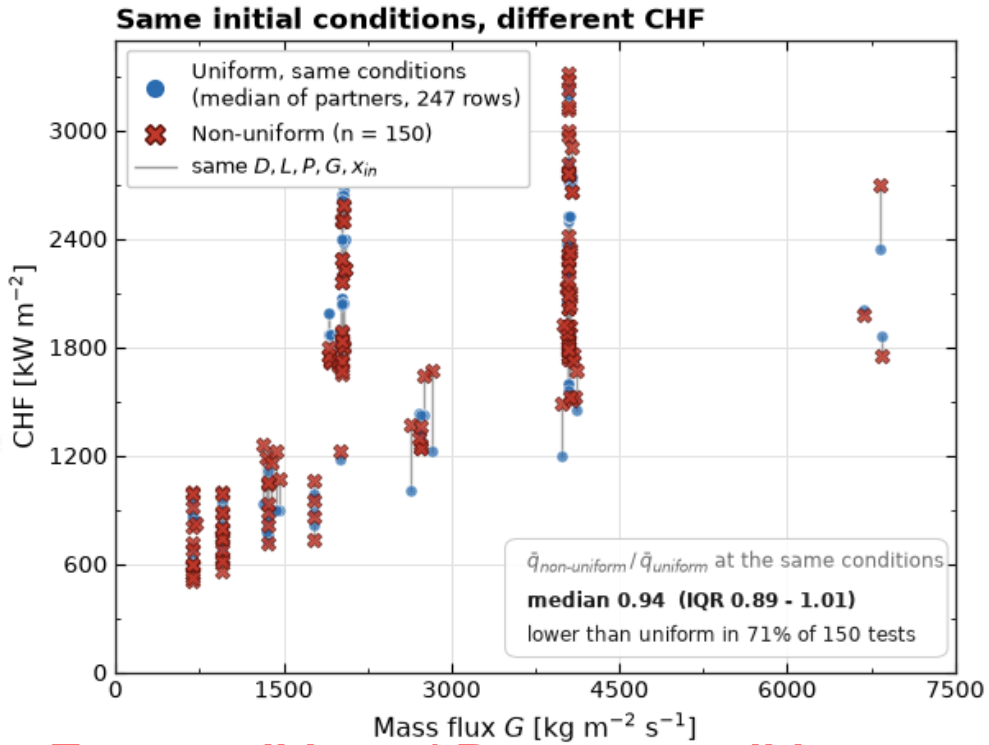
Operating parameters	No.1 rod bundle	No.2 rod bundle	No.3 rod bundle	No.4 rod bundle	No.5 rod bundle
Number of data	25	25	43	32	35
Pressure/MPa	6.89	6.89	12.4 ~ 16.0	10.3 ~ 16.6	10.3 ~ 16.7
Inlet temperature/℃	128.3 ~ 273.1	180.0 ~ 279.7	261.1 ~ 334.4	211.8 ~ 318.1	255.9 ~ 319.6
Inlet mass flux/ kg/m^{2}s	328.2 ~ 1696.4	329.5 ~ 1715.3	1323.5 ~ 4089.7	2004.2 ~ 4160.2	1935.0 ~ 4755.5
Critical power/ MW	1.09 ~ 3.16	0.75 ~ 2.44	1.53 ~ 3.53	2.36 ~ 4.15	2.85 ~ 5.19
Radial power distribution	uniform (Fig. 10. (a))	non-uniform (Fig. 10. (b))	uniform (Fig. 11. (a))	non-uniform (Fig. 11. (b))	non-uniform (Fig. 11. (b))
Axial power distribution	uniform	uniform	uniform	uniform	non-uniform (Fig. 1.(b))











Test conditions ≠ Reactor conditions

Source: Zhao et al. (2015), Zhu et al. (2024)

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Background

❑ Correction factors: prediction of non-uniform CHF from uniform data

- Numerous correlations and correction factors (Tong, Smolin, Groeneveld, Hwang)
- However, errors against non-uniform measurements **exceed 50 %** in some cases

$$F = \frac{C\int_{z_{ONB}}^{z_C} q''e^{-C(z_C-z)}\,dz}{q''_{loc}\{1-e^{-C(z_C-z_{ONB})}\}}$$

Tong's F factor (1966)

$$F = \frac{C\int_{0}^{z_C} q''e^{-C(z_C-z)}\,dz}{q''_{loc}}$$

Smolin's F factor (1978)

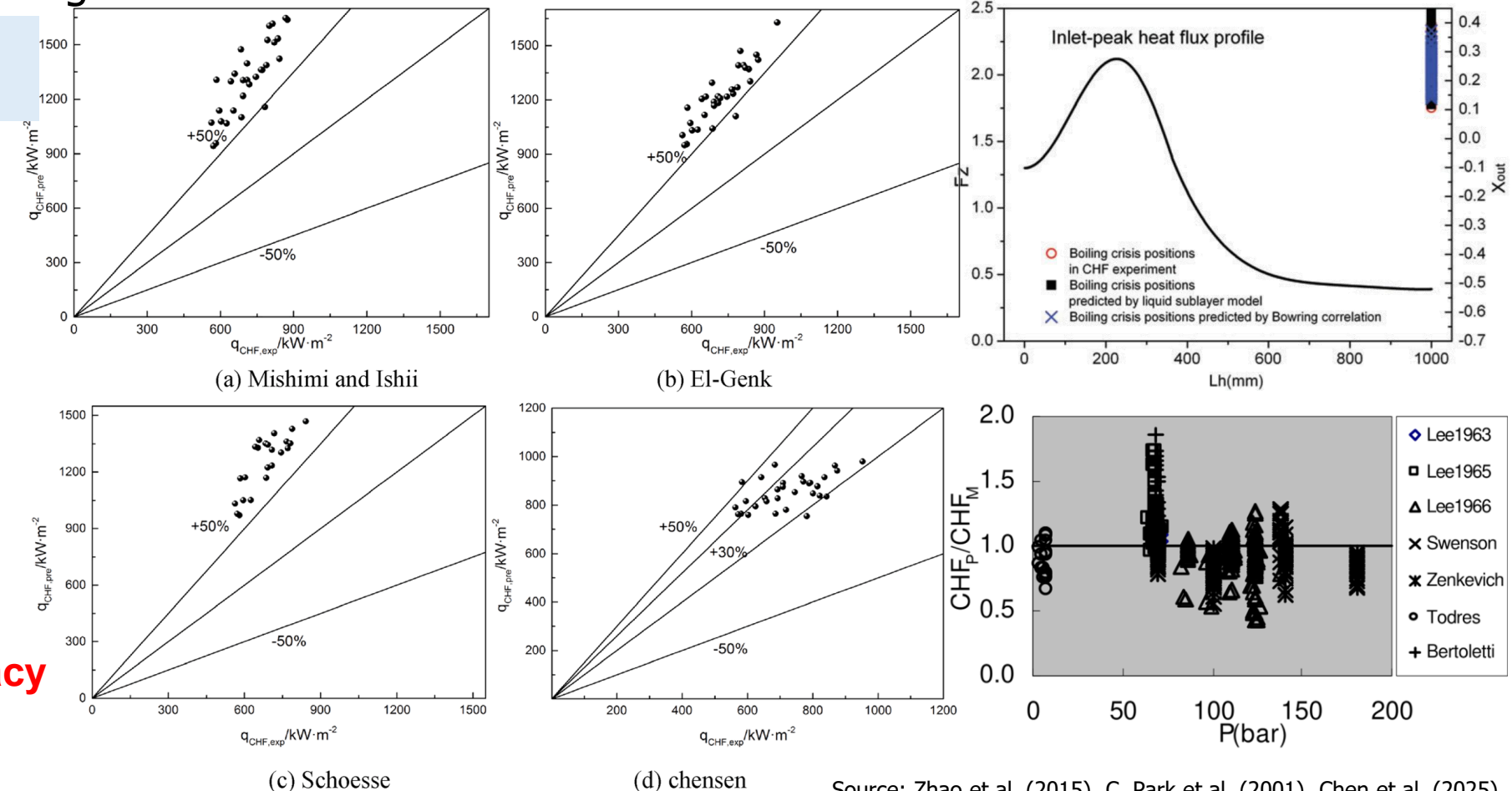
$$F = \frac{\int_{z_b}^{z_C} q''(z)\,dz}{q''_{loc}(z_C-z_b)}$$

Groeneveld's F factor (1986)

$$F = \frac{K_1 C\int_{z_{OSV}}^{z_C} q''e^{-C(z_C-z)}\,dz}{q''_{loc}\{1-e^{-C(z_C-z_{OSV})}\}}$$

Hwang's F factor (2001)

Limited prediction accuracy

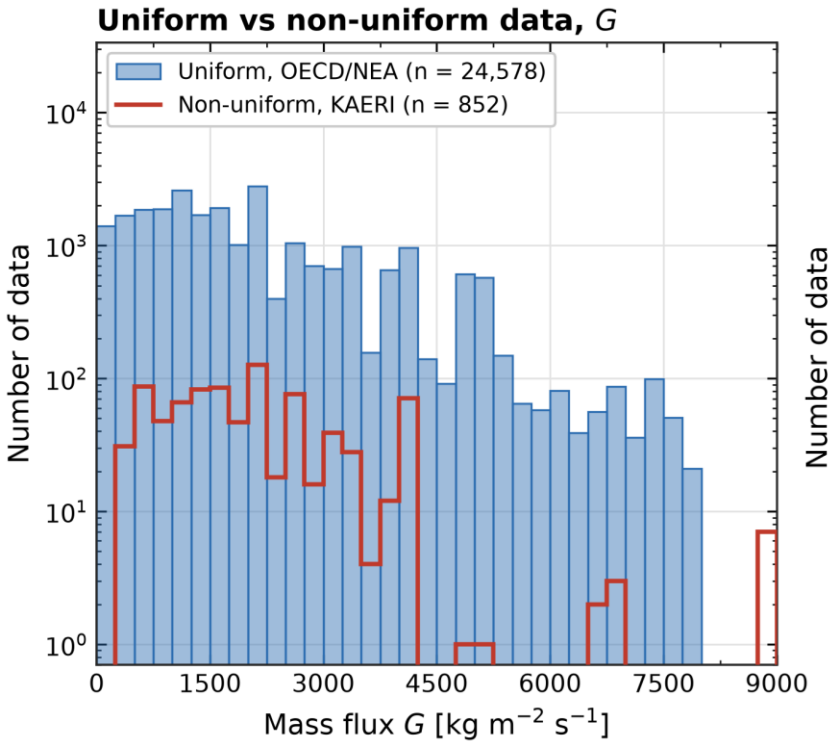


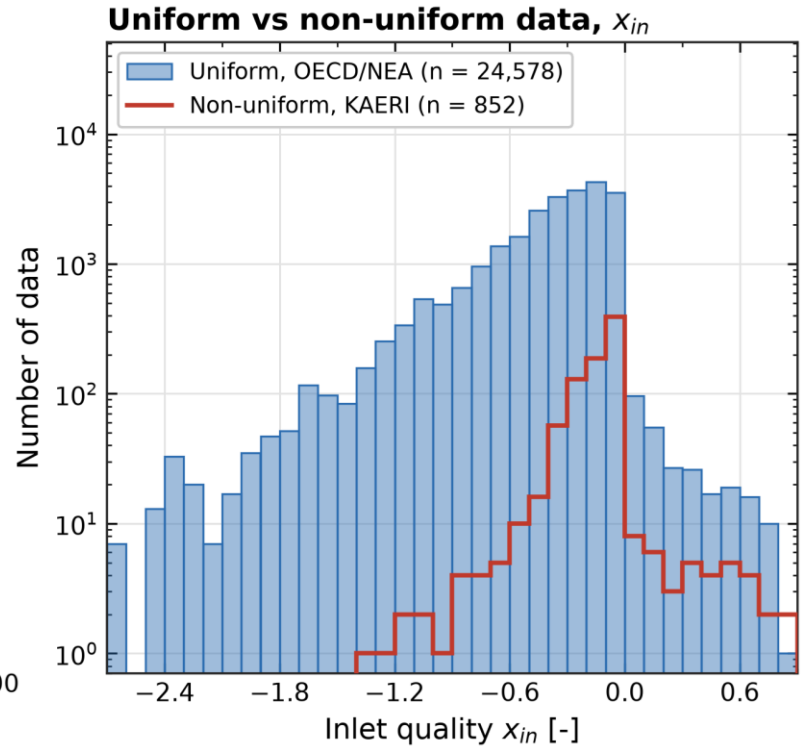
Source: Zhao et al. (2015), C. Park et al. (2001), Chen et al. (2025)

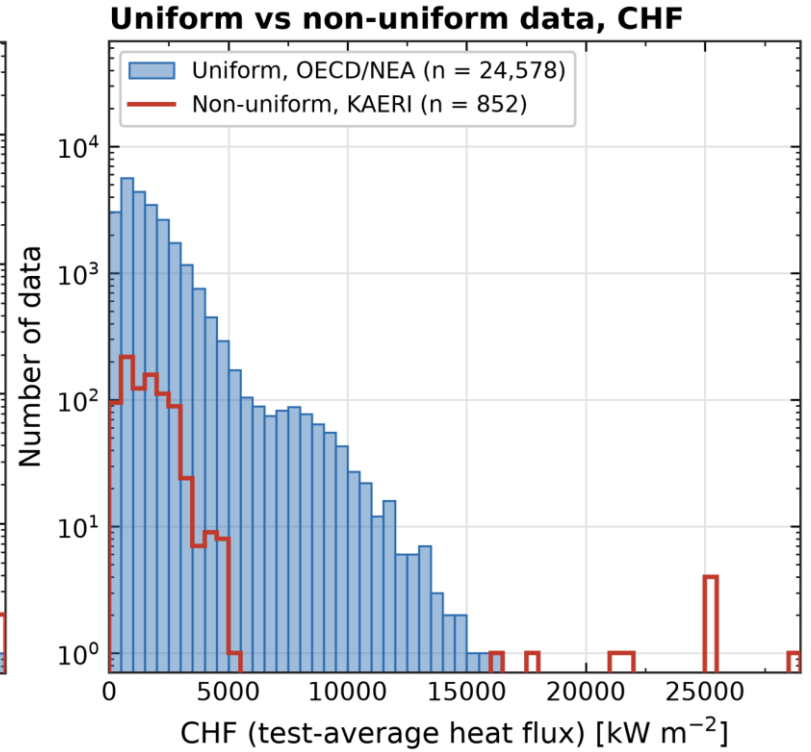
Background

❑ Non-uniform data do not span the uniform parameter space

- Only 852 non-uniform tests are available (≈ **3 %** of 24,578 uniform tests)
- The distributions of G, inlet quality, and CHF differ markedly
- Additional non-uniform experiments are costly to perform







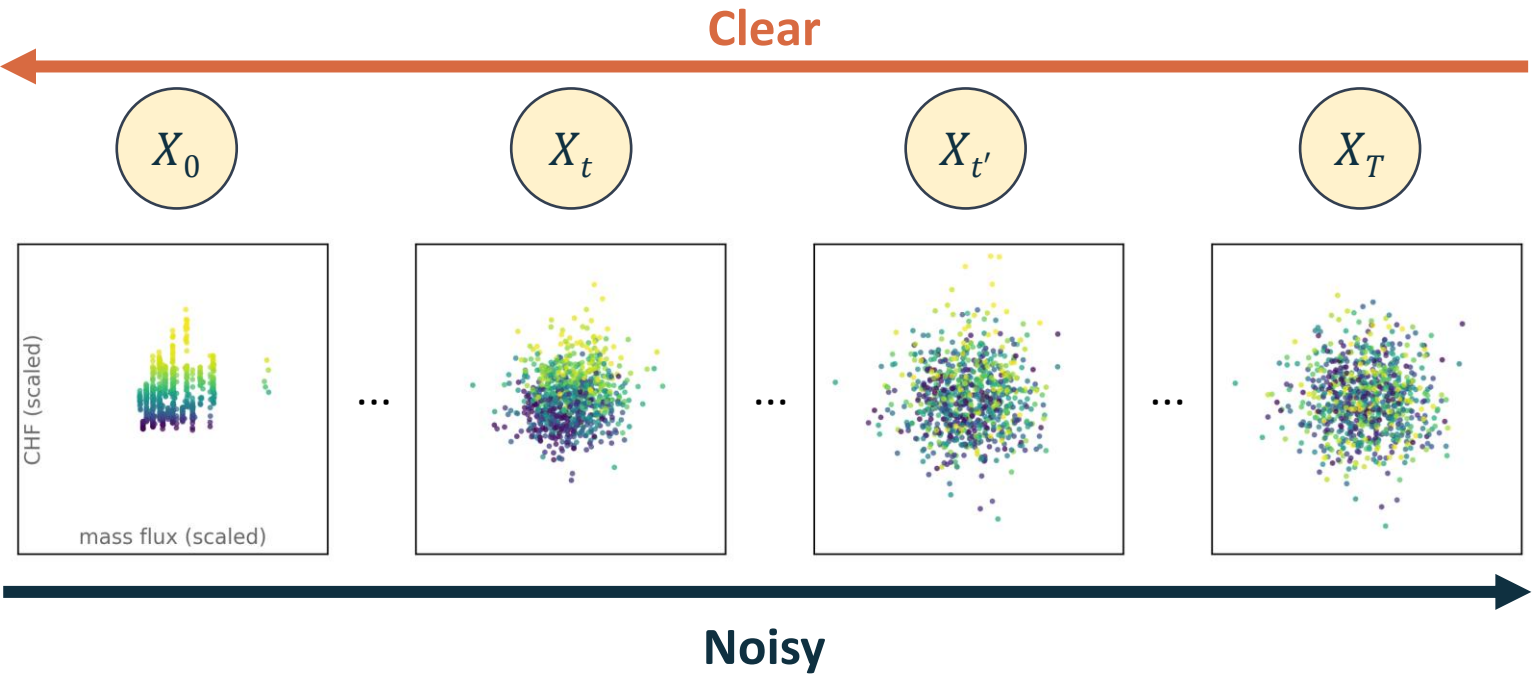
Data prediction + generation model required

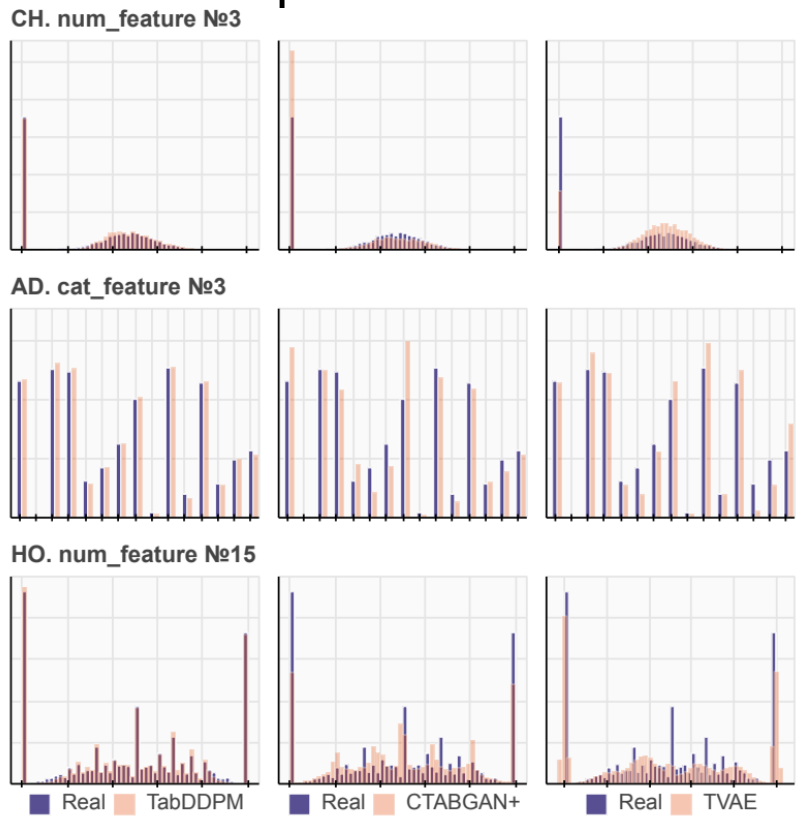
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Source: Groeneveld (2019), Park (2000) via Bourisaw et al. (2025)

Background

- **Two processes over T = 1,000 small steps**
  - **Forward (fixed, no learning):** Gaussian noise is gradually added to a data sample until it becomes pure noise
  - **Reverse (learned):** a neural network learns to undo one noise step at a time





Solution for data scarcity

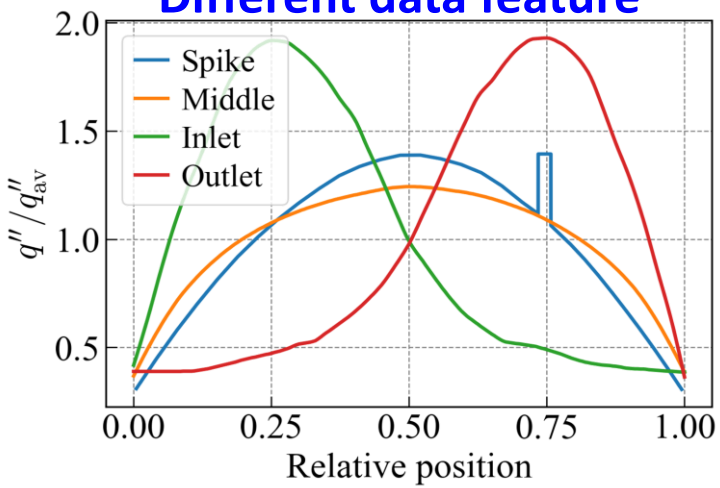
Source: Kotelnikov et al. (2023).

Background

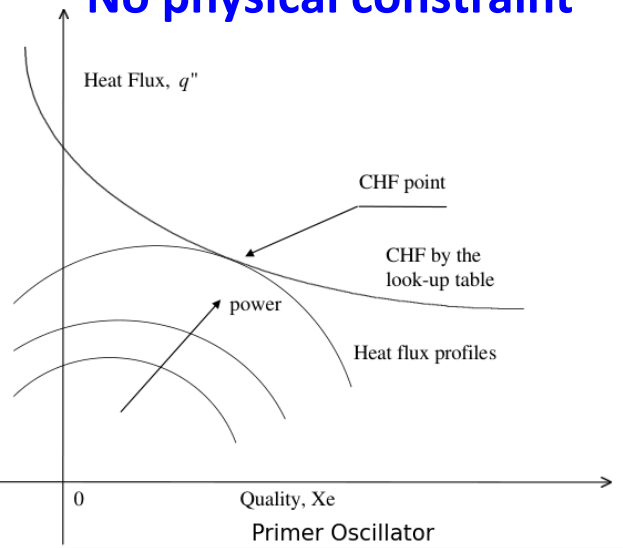
❑ Purely data-driven ML models exhibit three limitations

- NN accuracy degrades for non-uniform CHF

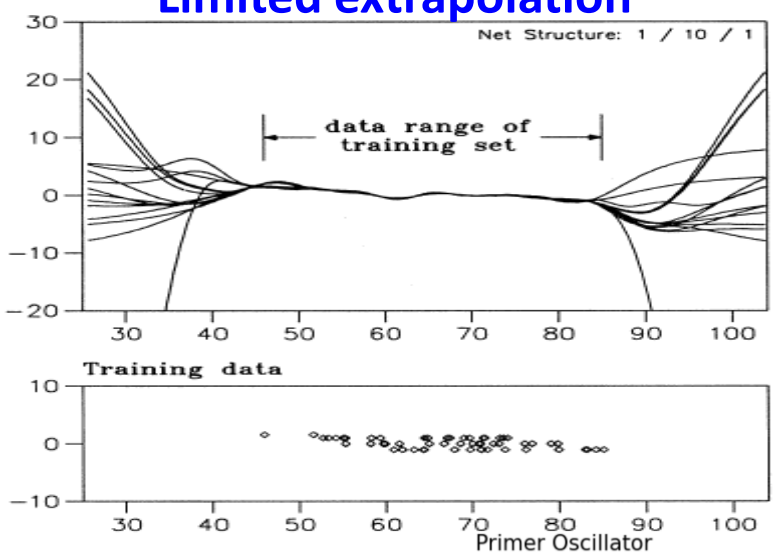
Different data feature

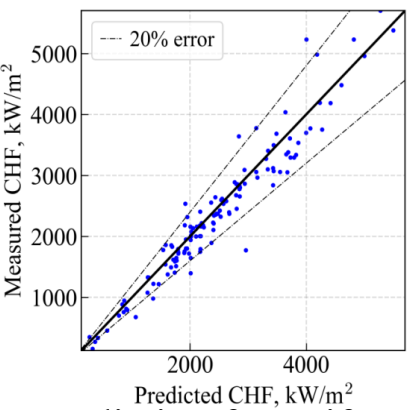


No physical constraint

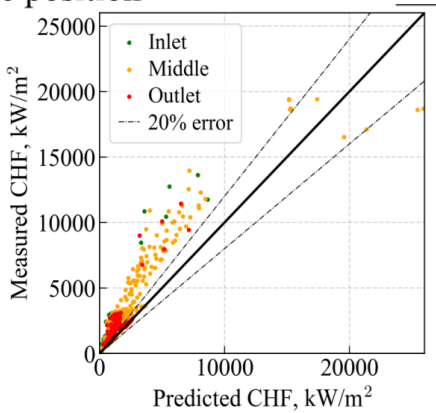


Limited extrapolation

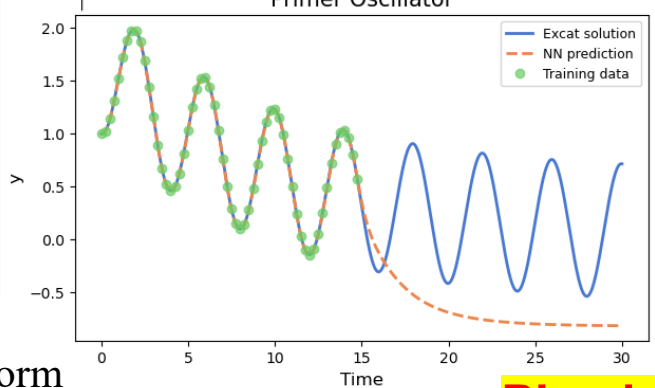




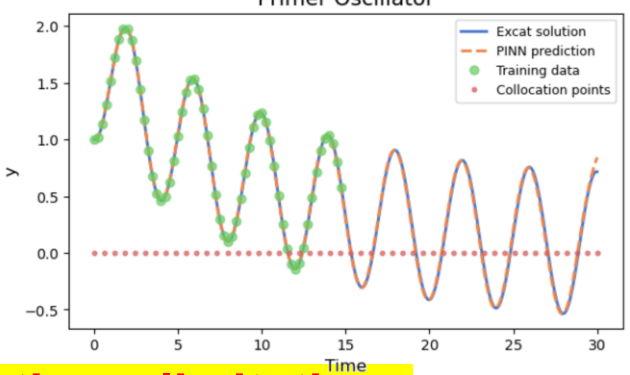
Prediction for uniform



Prediction for non-uniform



Add physics constraints



Physics resolves these limitations

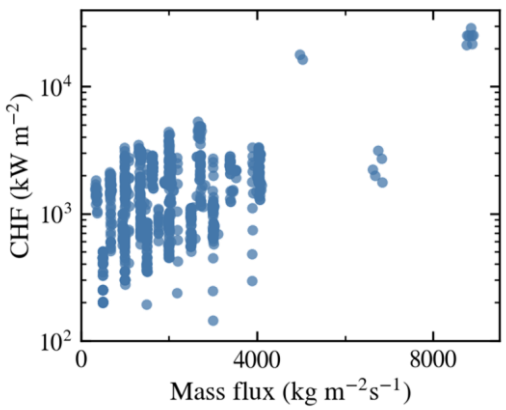
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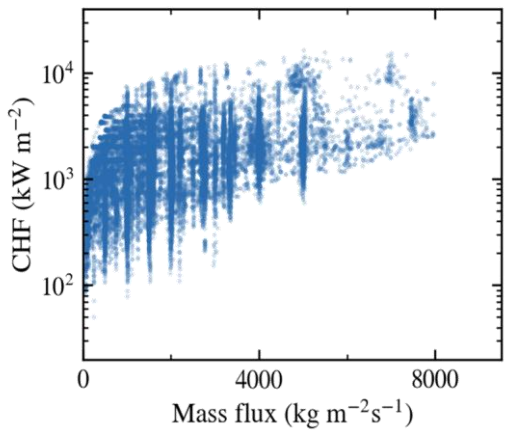
Source: Bourisaw et al. (2025), Lohninger (1999), C. Park et al. (2001), Lu et al. (2024), Ben (2022)

Research Goal

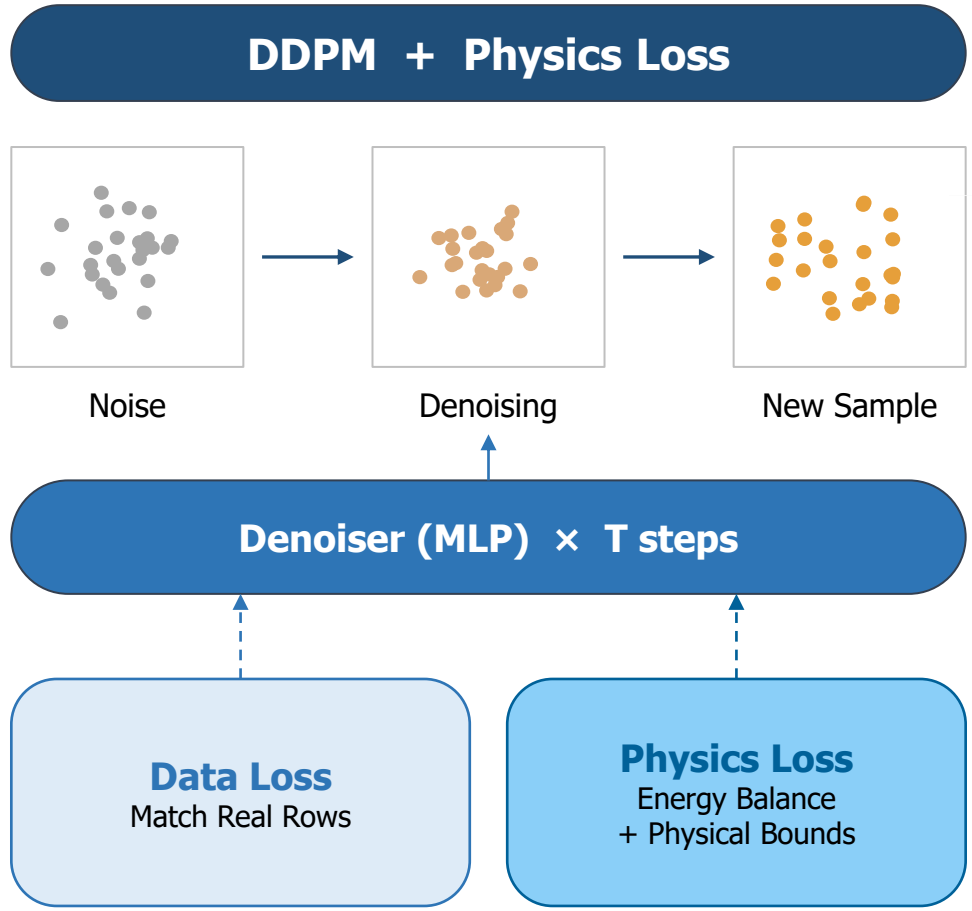
❑ **Objective:** one physics-informed model for uniform and non-uniform CHF

- PIDM: a denoising diffusion probabilistic model (DDPM) with a physics loss

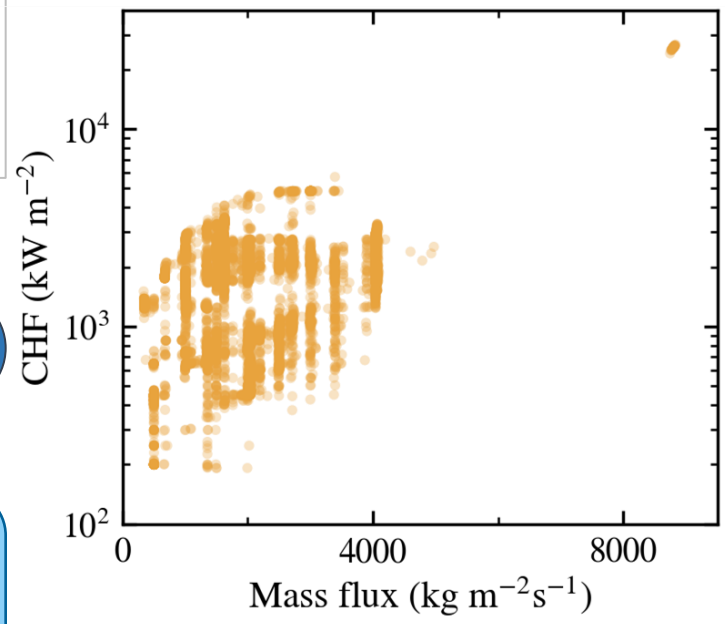




Measured data



Physics-informed model



PIDM output

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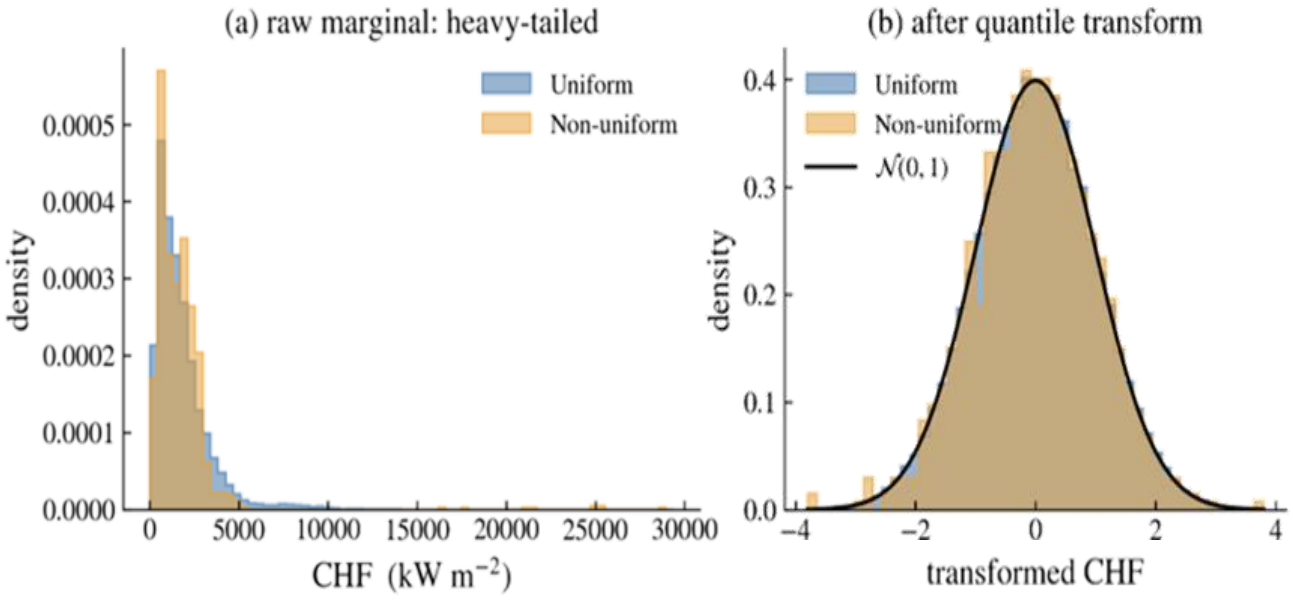
Input Data Feature

❑ Input Data: Two types of CHF

- **Uniform**: OECD/NEA CHF database, 24,578 tube tests
- **Non-uniform**: KAERI compilation, 852 tests with measured CHF location

❑ Preprocessing

- Heavy-tailed variables mapped to a standard normal distribution for stable training

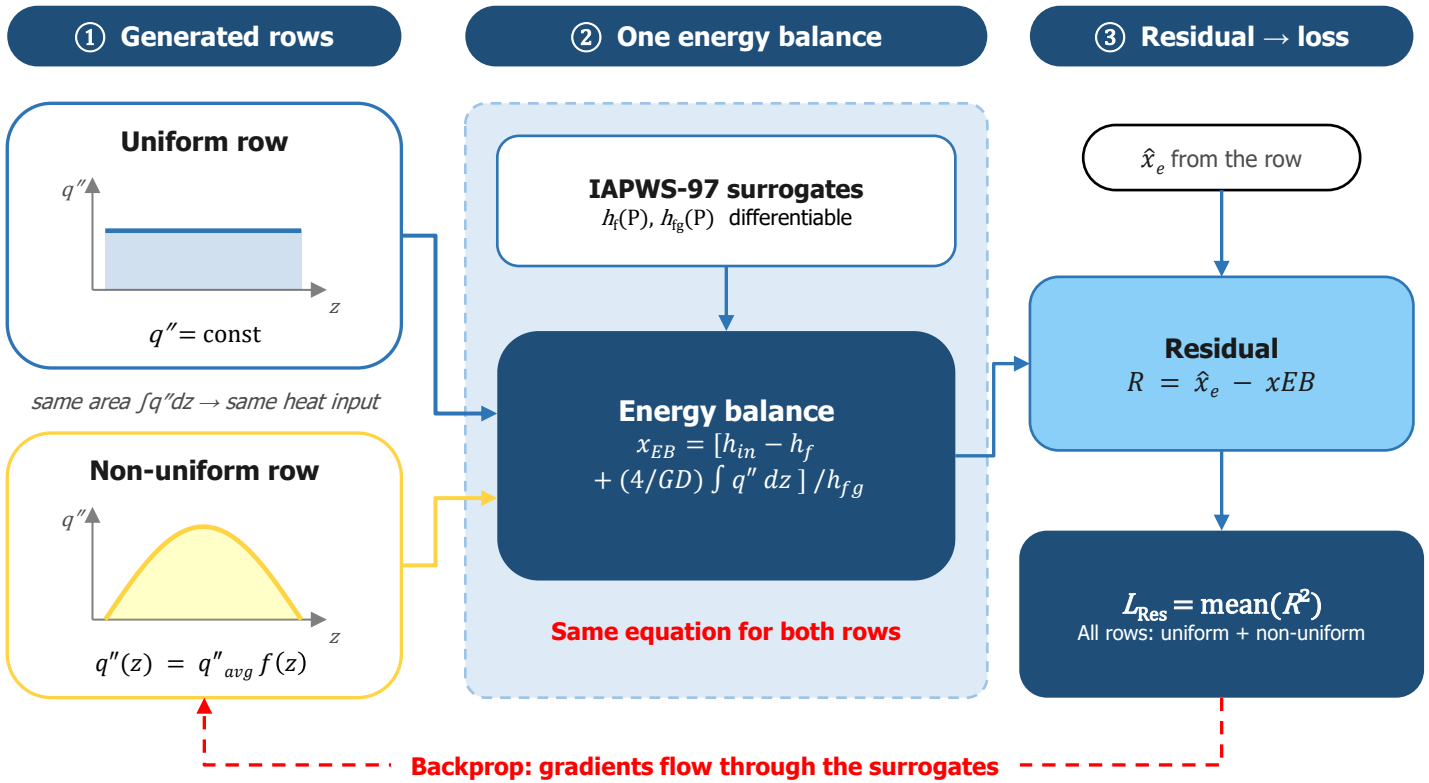


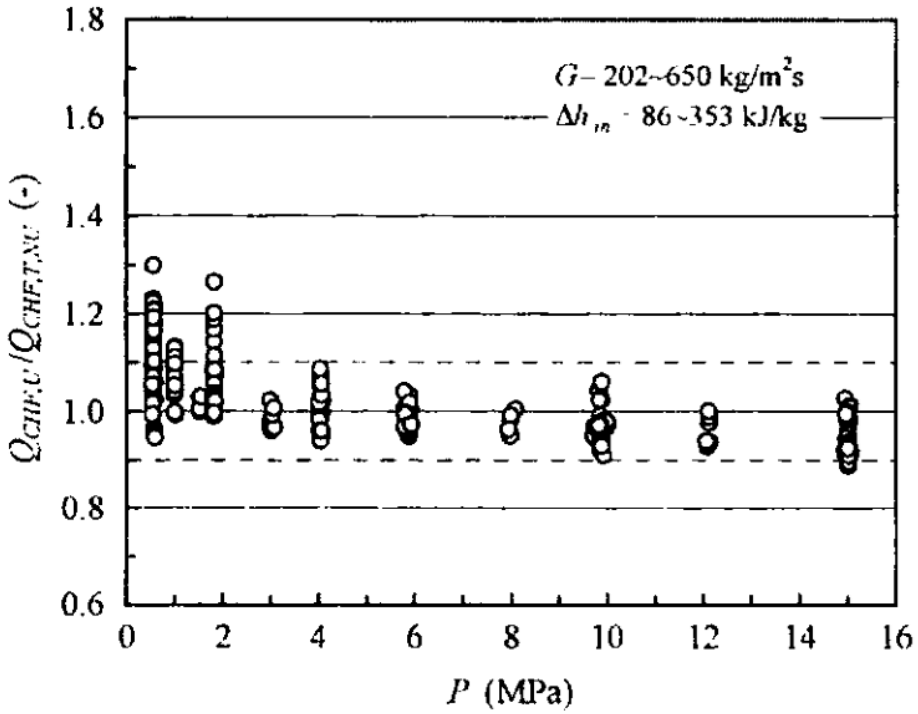
Parameter [unit]	Uniform CHF	Non-uniform CHF
Tube inner diameter, D	2 – 16	5 – 28
Heated length, L	0.05 – 20.0	0.06 – 7.0
System pressure, P	0.1 – 20.0	0.4 – 18.0
Mass flux, G	8 – 7,964	328 – 8,916
Quality at CHF, x_e	−0.50 – 1.00	−0.71 – 1.09
Inlet temperature, T_{in}	6 – 362	11 – 340
Critical heat flux, q''_{CHF}	50 – 16,339	143 – 28,800
Axial heat-flux shape	Flat (q″ = const)	Inlet / middle / outlet

Single Energy Balance for Both Datasets

❑ The energy balance links power and quality for any heat-flux shape

- $x(z) = x_{in} + \frac{4}{(G\,D\,h_{fg})}\int_0^z q''\,dz$, uniform heating: q'' = const
- A single physics loss imposes the same constraint on both sample types





Uniform / non-uniform total critical power ≈ 1 (±10 %) above 2 MPa [Chun et al. 2003]

Local CHF differs, but total heat input at CHF agrees → One energy balance for both

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Source: Chun et al. (2003)

PIDM Loss Function

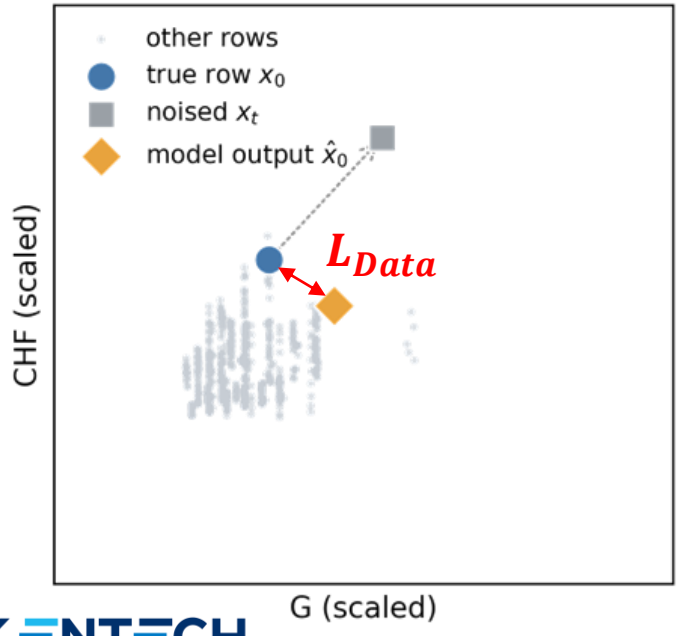
❑ **Problem:** a purely statistical model may generate samples that are **statistically plausible** but thermodynamically inconsistent

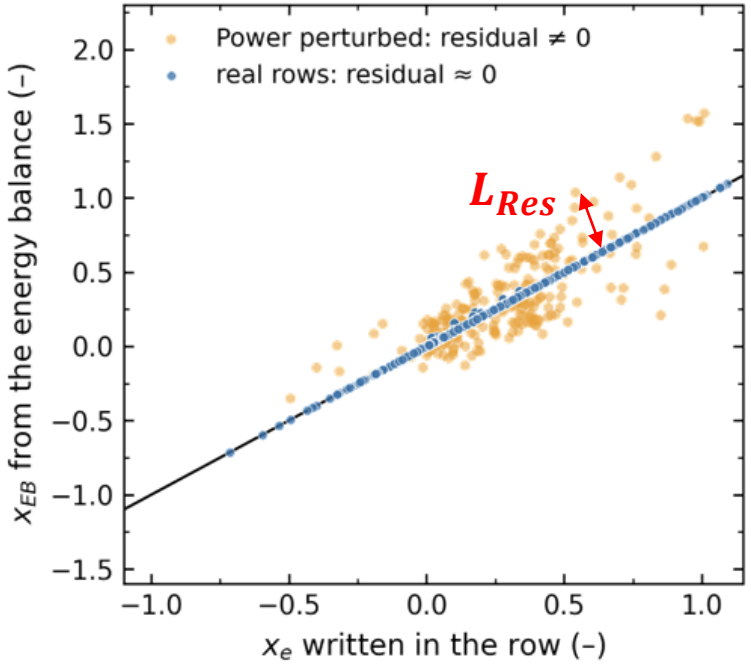
$$L_{Total} = L_{Data} + \lambda_R \cdot L_{Res} + \lambda_B \cdot L_{Bnd}$$

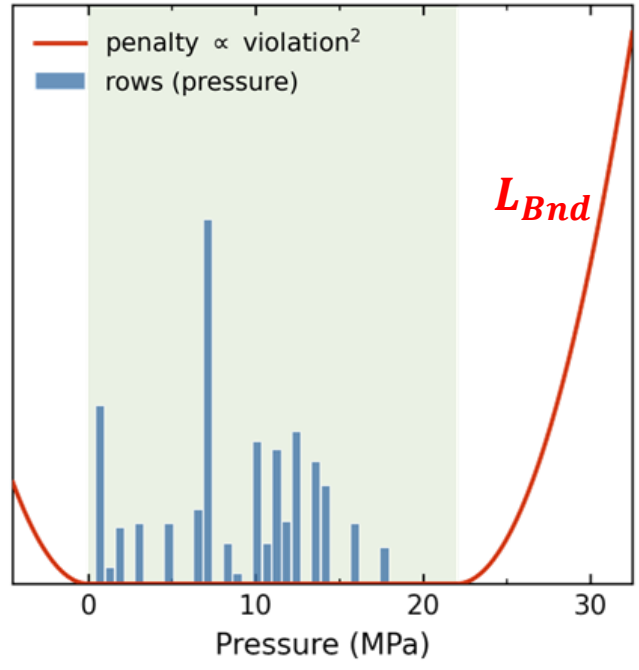
- $\mathbf{L_{Data}}$ — Reconstruction of the measured data
- $\mathbf{L_{Res}}$ — Consistency with the energy balance
- $\mathbf{L_{Bnd}}$ — Confinement to the physical domain

L_{Res}: Residual loss

L_{Bnd}: Boundary loss

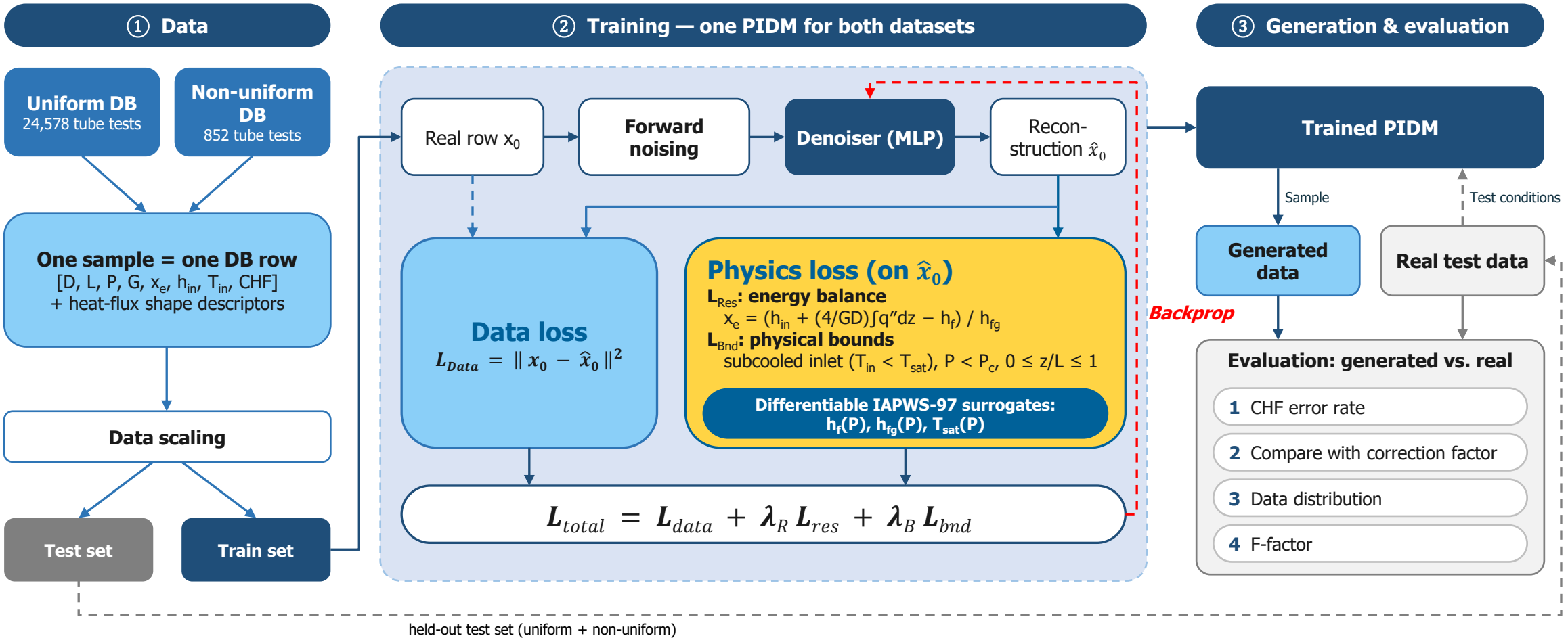






Overall Architecture

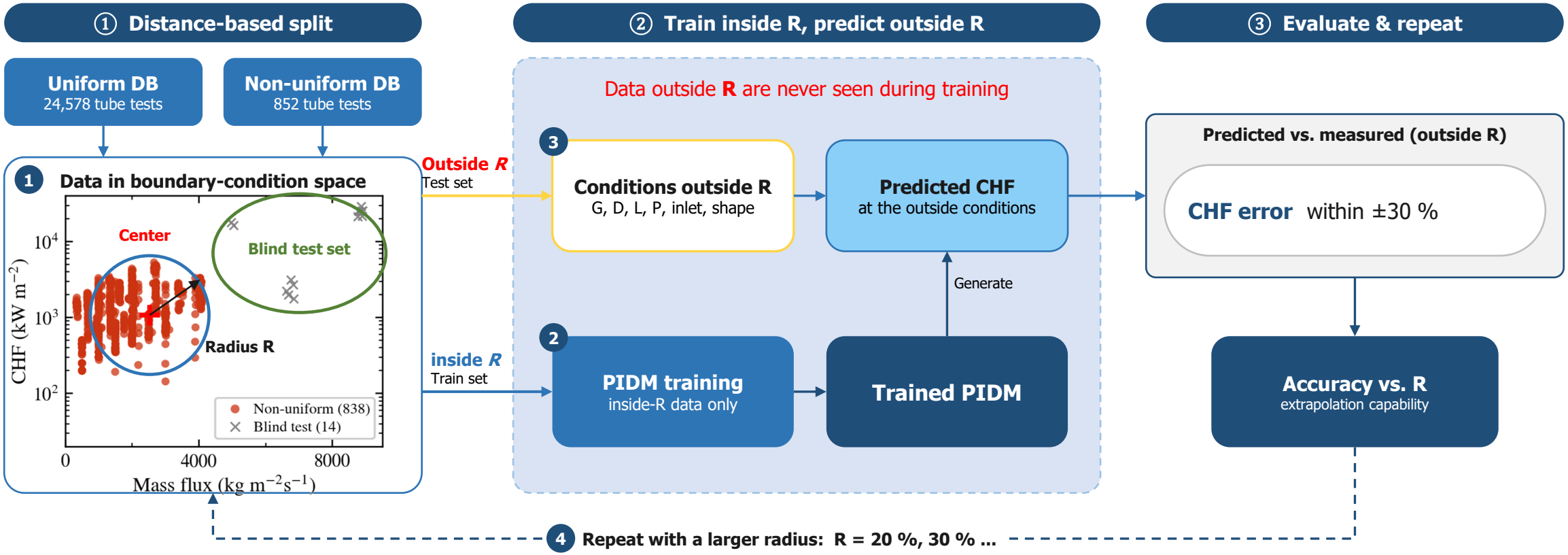
❑ PIDM architecture



Extrapolation Test

❑ Goal: Evaluate PIDM on boundary conditions excluded from training

- A random train/test split assesses interpolation within the data cloud only



Accuracy outside R measures PIDM's ability to extrapolate beyond its training data

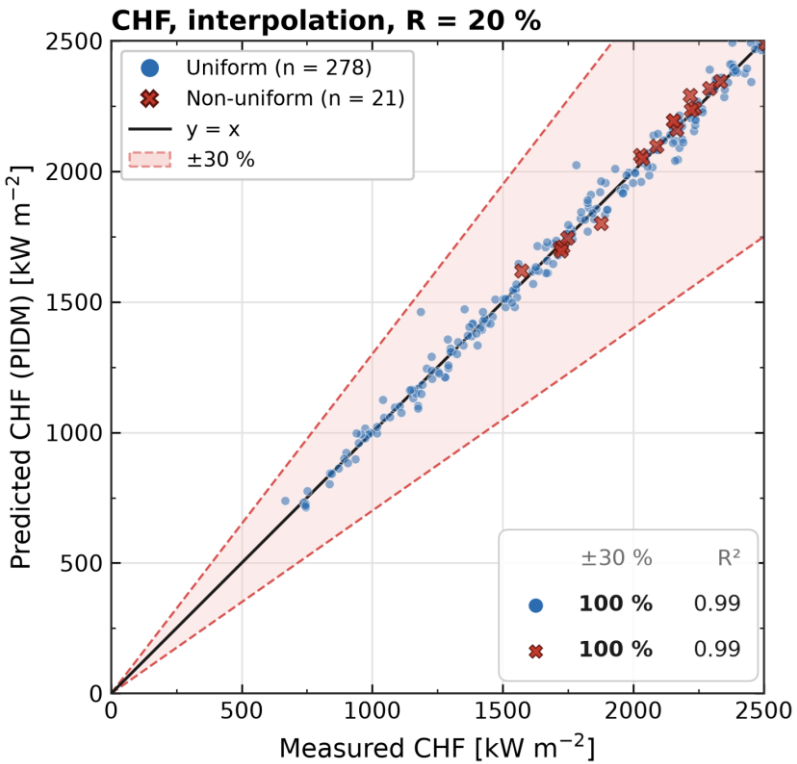
Results: R = 20 %

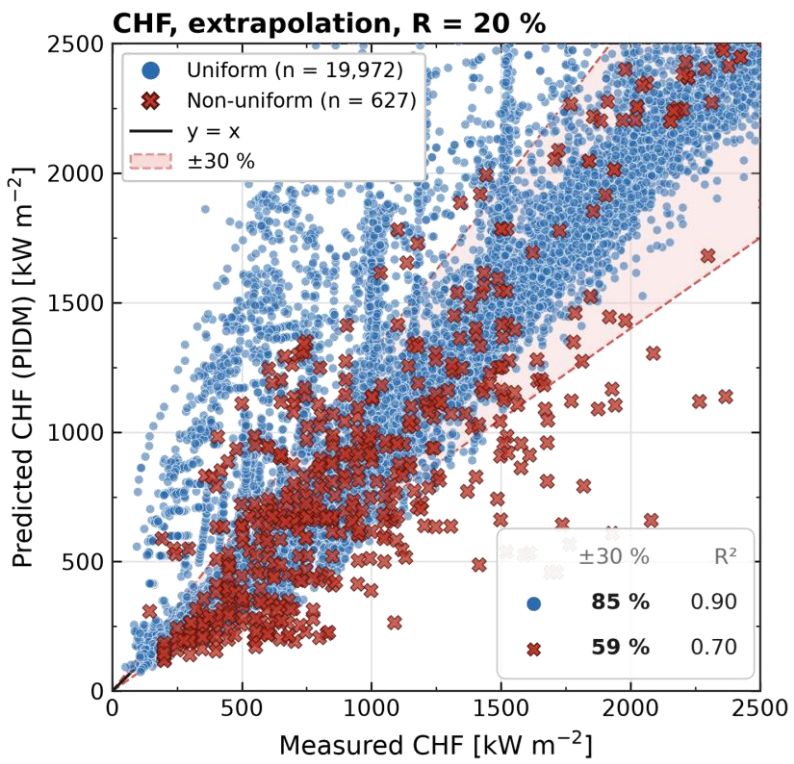
❑ **R = 20 %: smallest training region**

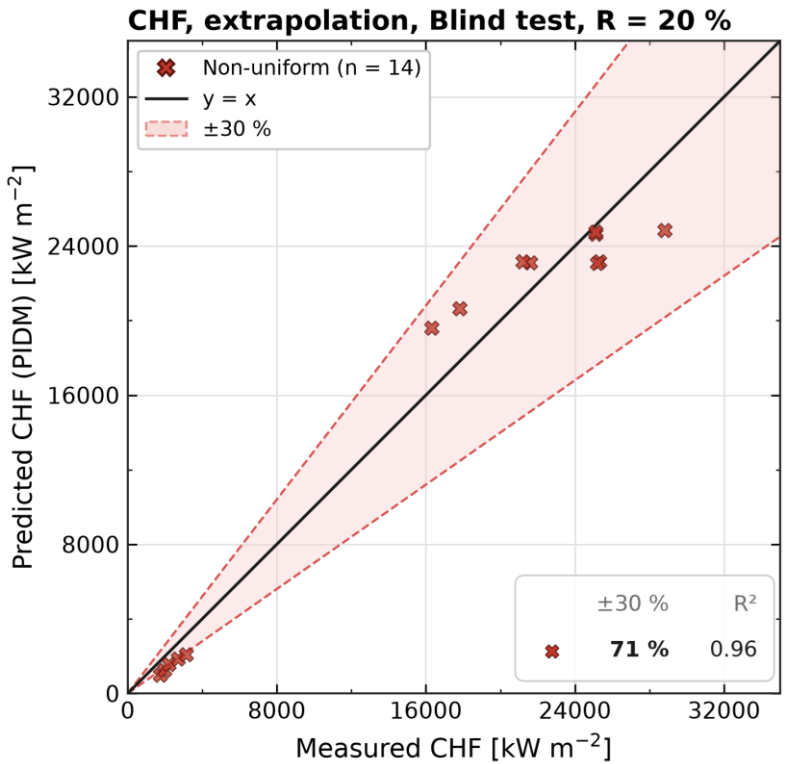
- Interpolation: 100 % (uniform) and 100 % (non-uniform) within ±30 %
- Extrapolation: 85 % and 59 % within ±30 %
- Blind test set: 71 %

Uniform

Non-uniform







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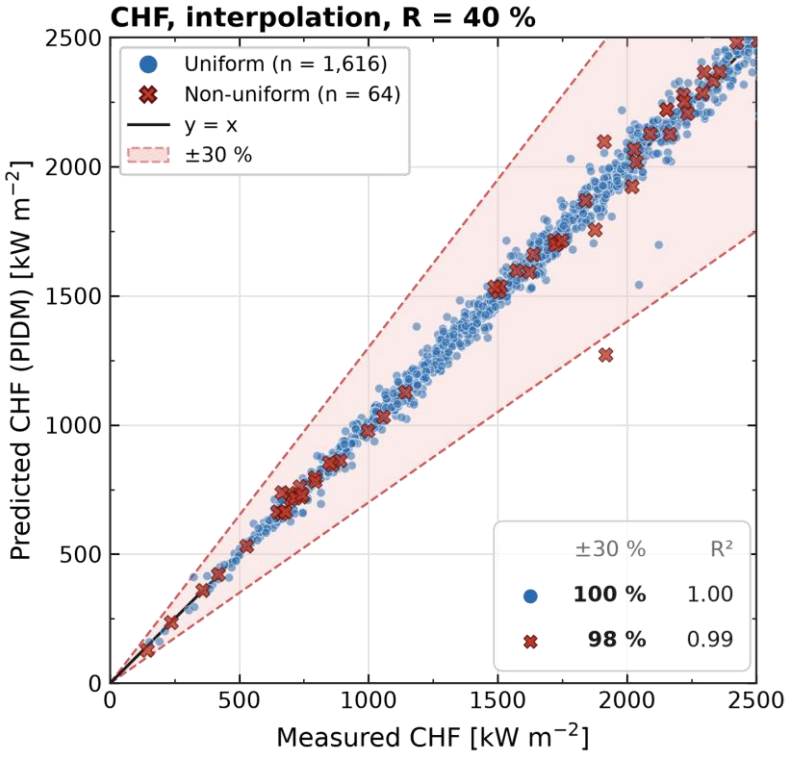
Non-uniform extrapolation is limited at small R (59 %)

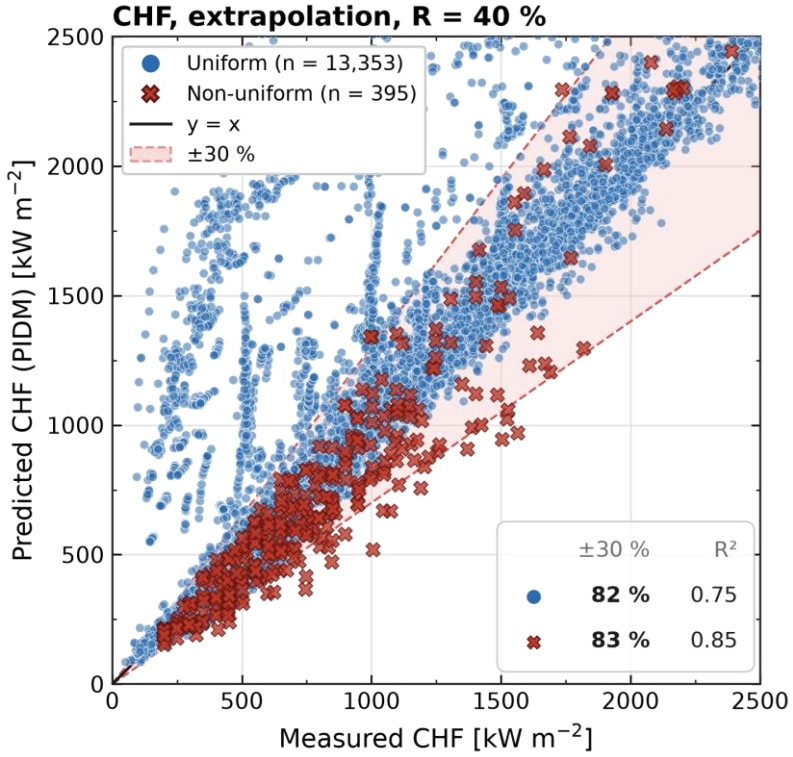
Results: R = 40 %

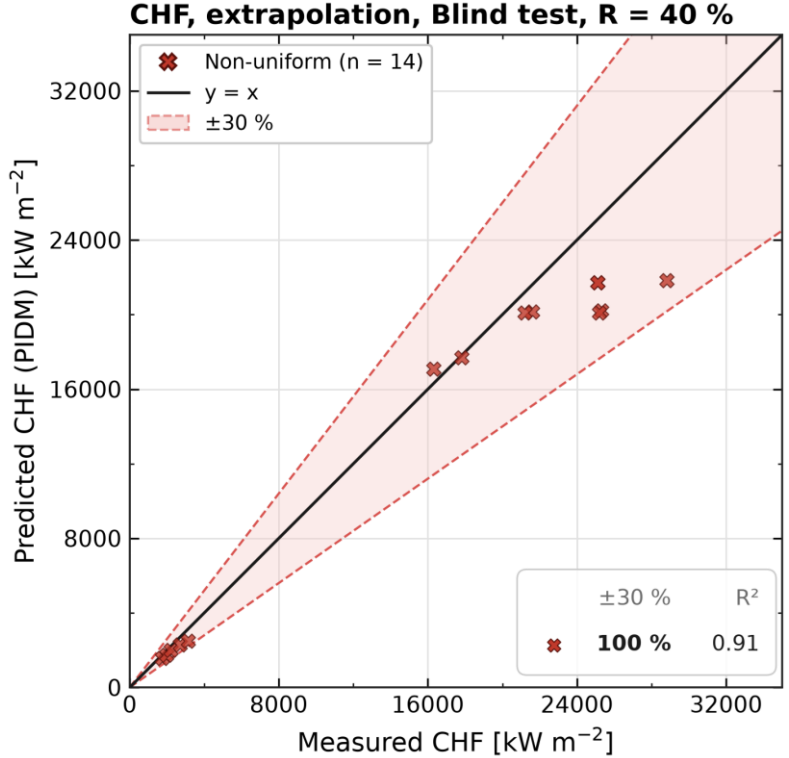
❑ R = 40 %: non-uniform extrapolation improves

- Interpolation: 100 % (uniform) and 98 % (non-uniform) within ±30 %
- Extrapolation: 82 % (uniform) and 83 % (non-uniform)
- Blind test set: 100 %; high CHF slightly under-predicted but within ±30 %

Uniform
Non-uniform







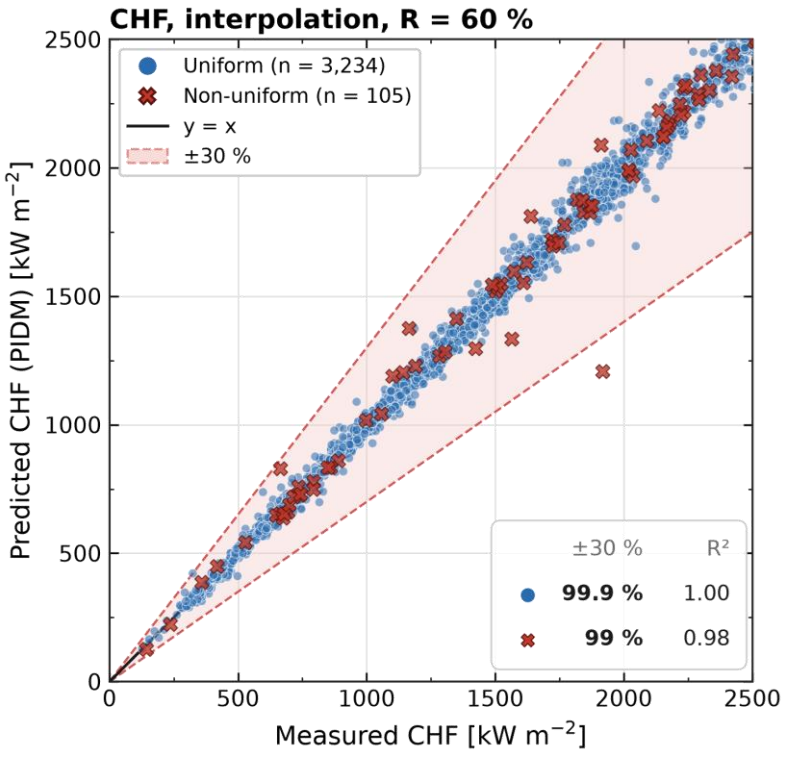
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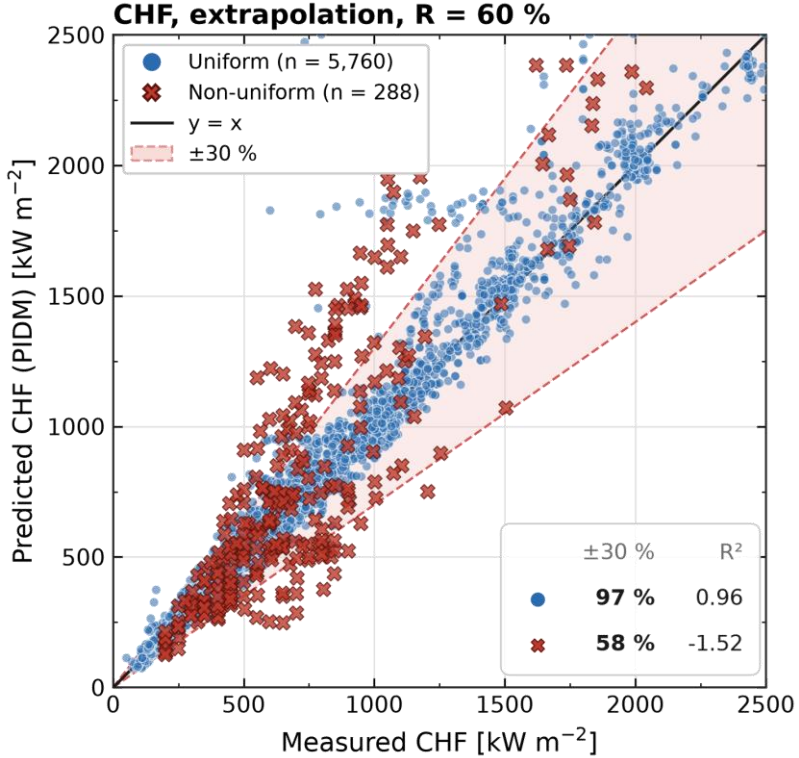
Non-uniform extrapolation recovered

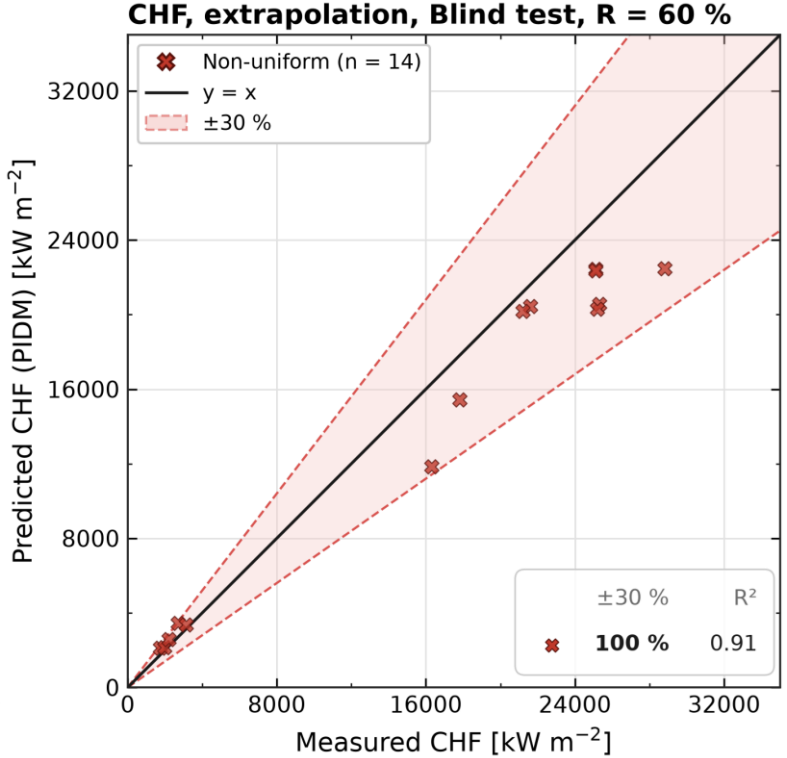
Results: R = 60 %

- **R = 60 %: uniform extrapolation reaches 97 %, non-uniform drops to 58 %**
  - Interpolation: 100 % (uniform) and 99 % (non-uniform) within ±30 %
  - Extrapolation: 97 % (uniform) and 58 % (non-uniform)
  - Blind test set: 100 % within ±30 % (n = 14)

Uniform
Non-uniform







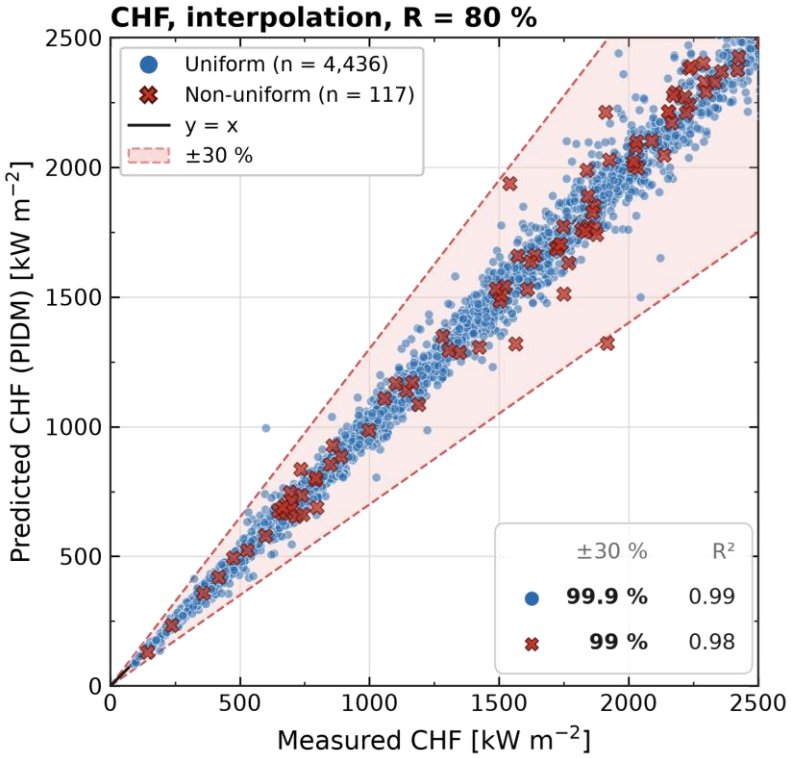
Low non-uniform CHF is over-predicted

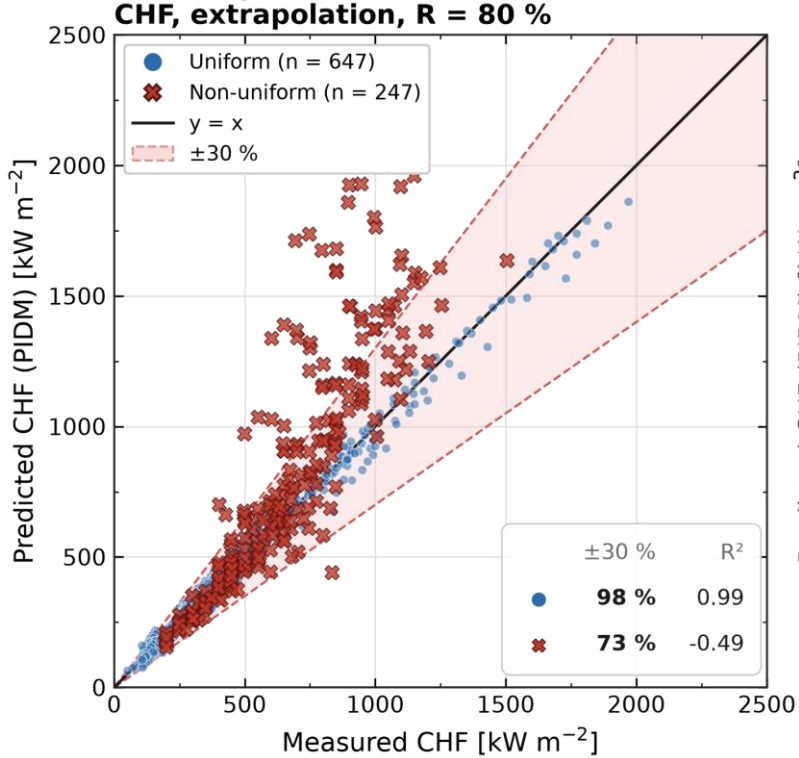
Results: R = 80 %

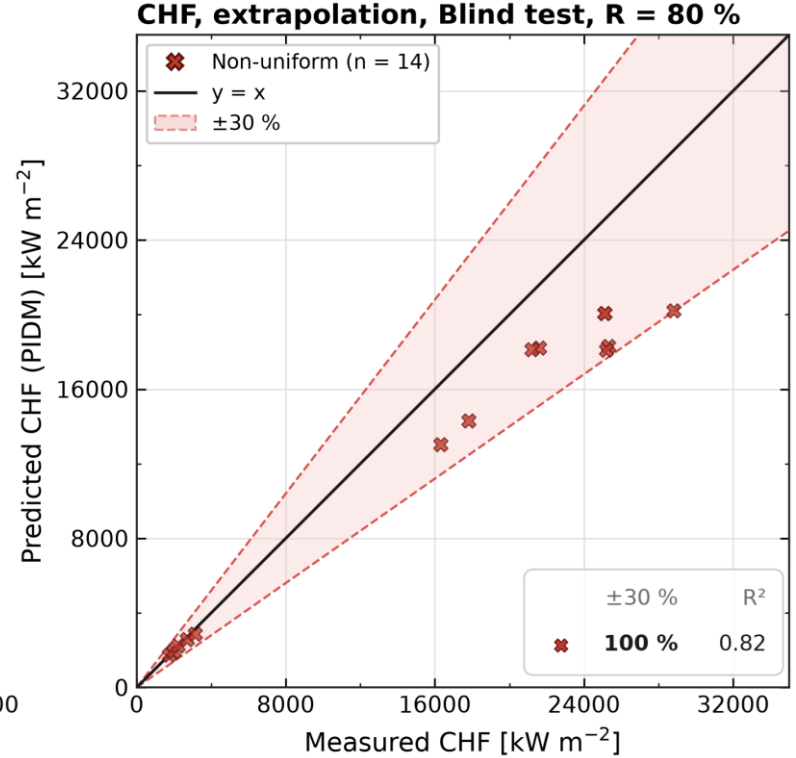
❑ R = 80 %: non-uniform extrapolation remains limited

- Interpolation: 100 % (uniform) and 99 % (non-uniform) within ±30 %
- Extrapolation: 98 % and 73 %, low non-uniform CHF is over-predicted
- Blind test set: 100 % (n = 14); high CHF is under-predicted

● Uniform
✖ Non-uniform







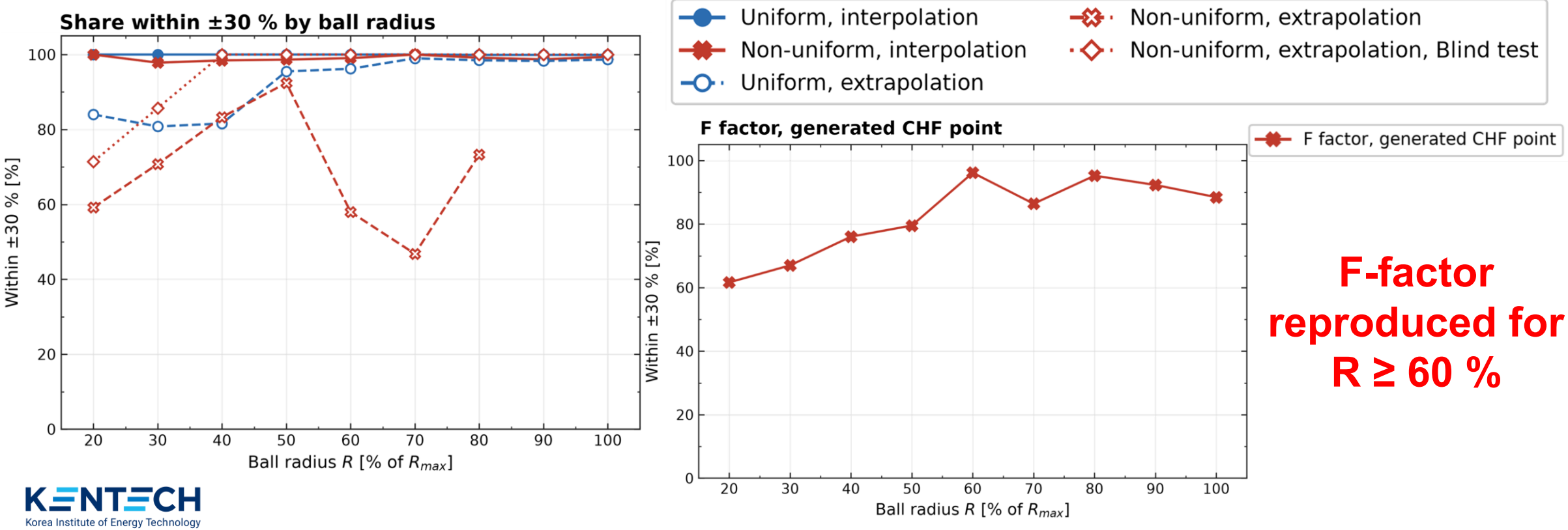
Limited non-uniform extrapolation

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Results: Accuracy vs. R

❑ Uniform and blind-test extrapolation improve with R

- **Interpolation**: ≥ 90 % within ±30 % for both datasets at all R
- **Extrapolation**: uniform from 84 % to 96 % (R = 20–60 %), non-uniform 47–92 %
- **F-factor** within ±30 %: 60–67 % for R ≤ 30 % and 86–96 % for R ≥ 60 %



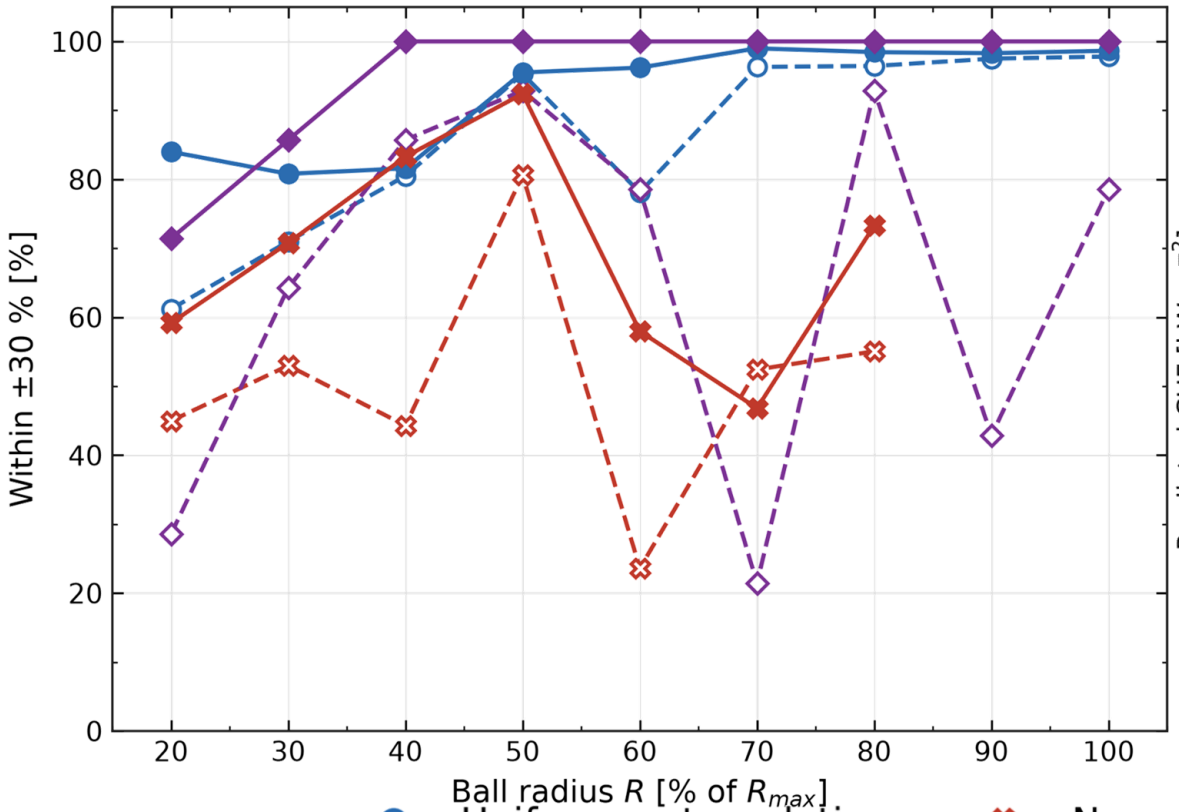
F-factor reproduced for R ≥ 60 %

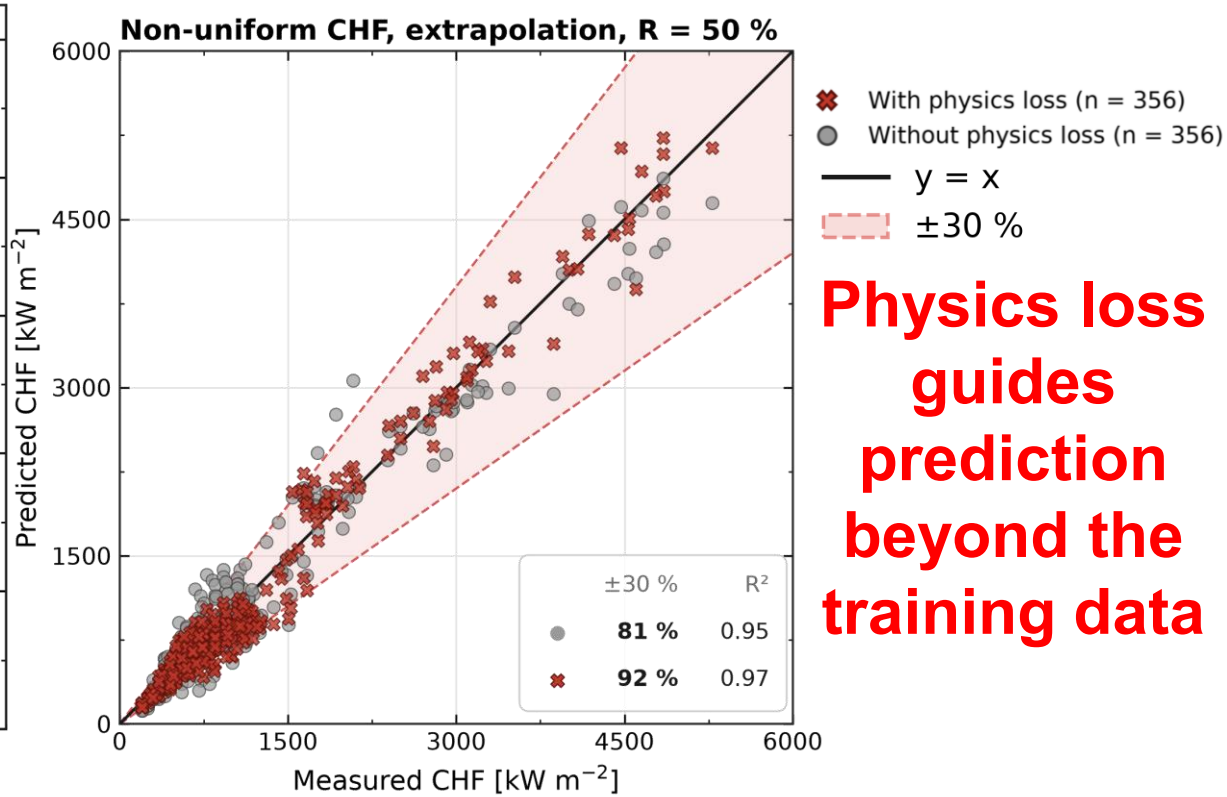
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Results: Effect of Physics Loss

❑ Physics loss improves and stabilizes extrapolation

- **Extrapolation**: higher at 6 of 7 (non-uniform), equal or higher at all R (uniform)
- **Blind test:** 100 % for R ≥ 40 % with physics loss, 21–93 % without





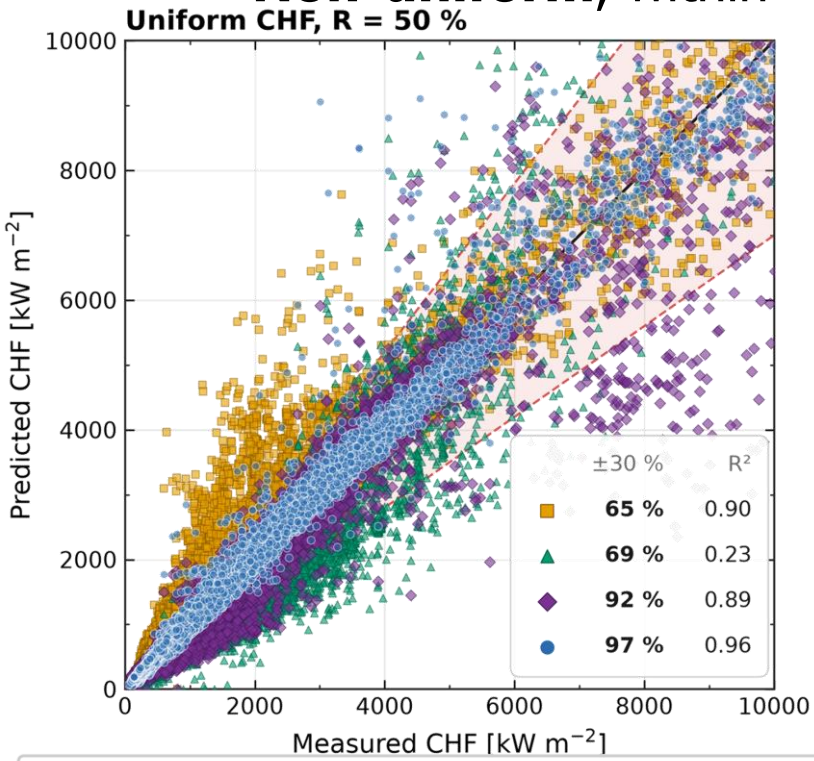
Physics loss guides prediction beyond the training data

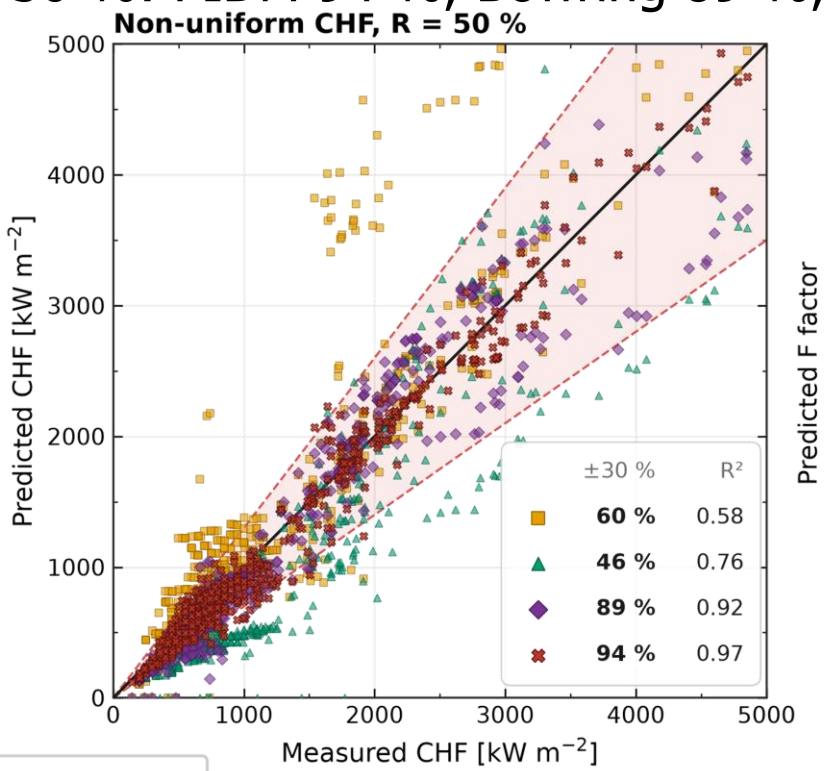
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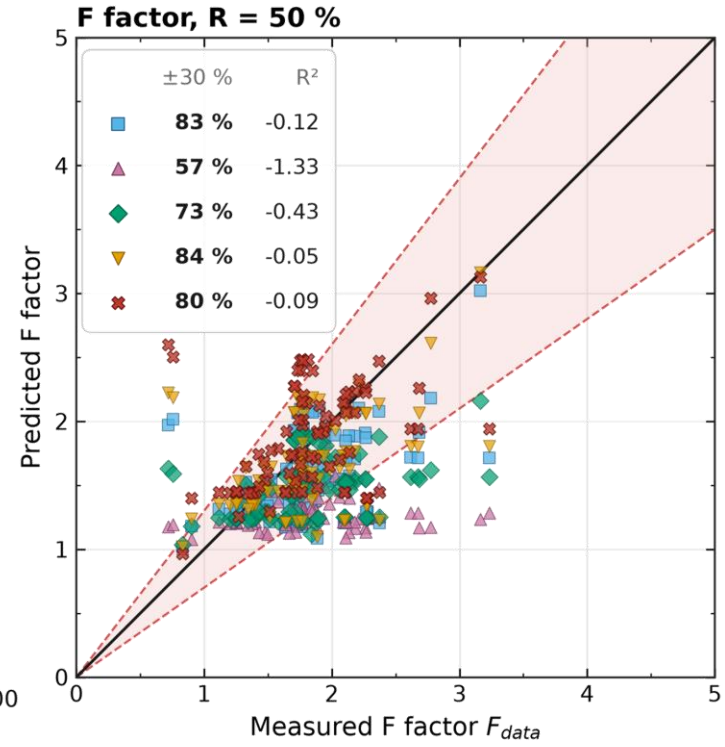
Results: Comparison with Correlations (R=50%)

❑ **PIDM outperforms W-3, B&W-2, and Bowring and it reproduces the F-factor**

- **Uniform**, within ±30 %: PIDM 97 %, Bowring 92 %, B&W-2 69 %, W-3 65 %
- **Non-uniform**, within ±30 %: PIDM 94 %, Bowring 89 %, W-3 60 %, B&W-2 46 %







PIDM (n = 15,110) B&W-2 (n = 15,110) y = x
Bowring (n = 15,110) W-3 (n = 15,110) ±30 %

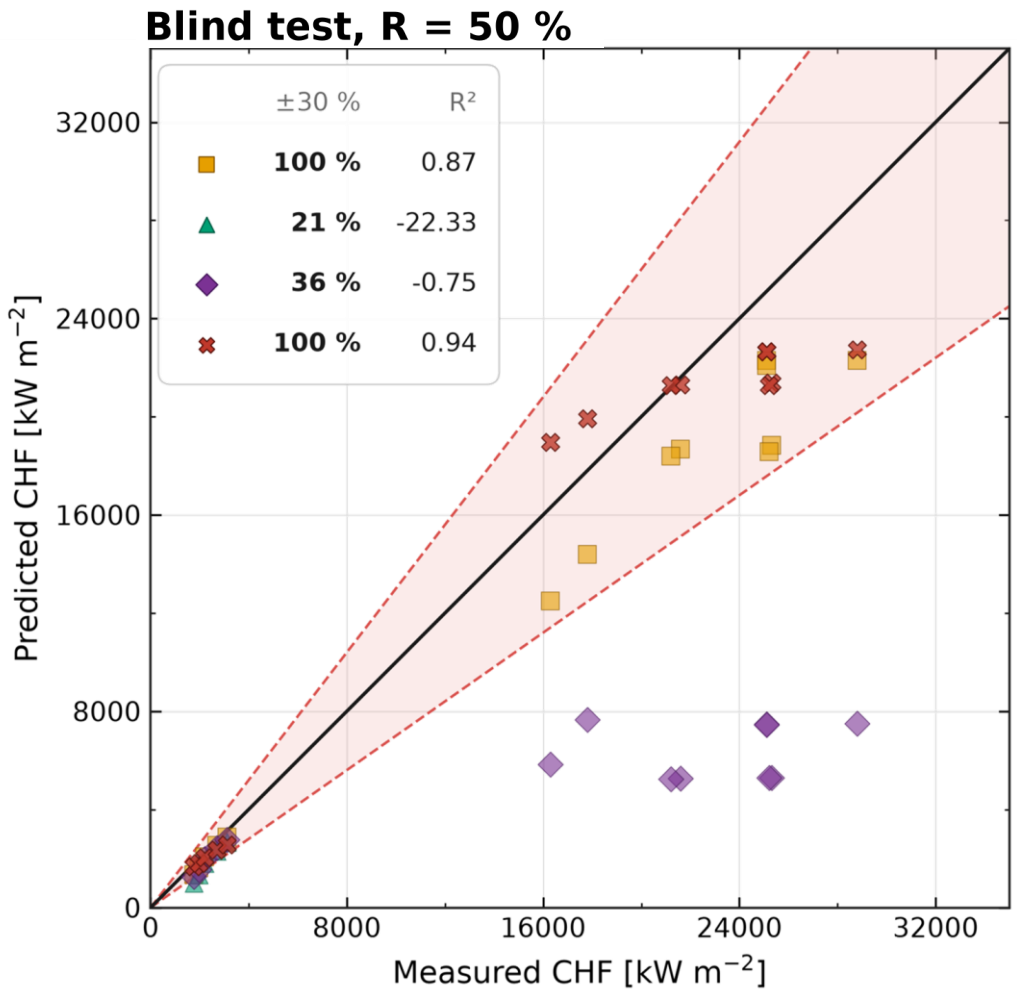
PIDM Hwang F y = x
Groeneveld F Tong F ±30 %
Smolin F

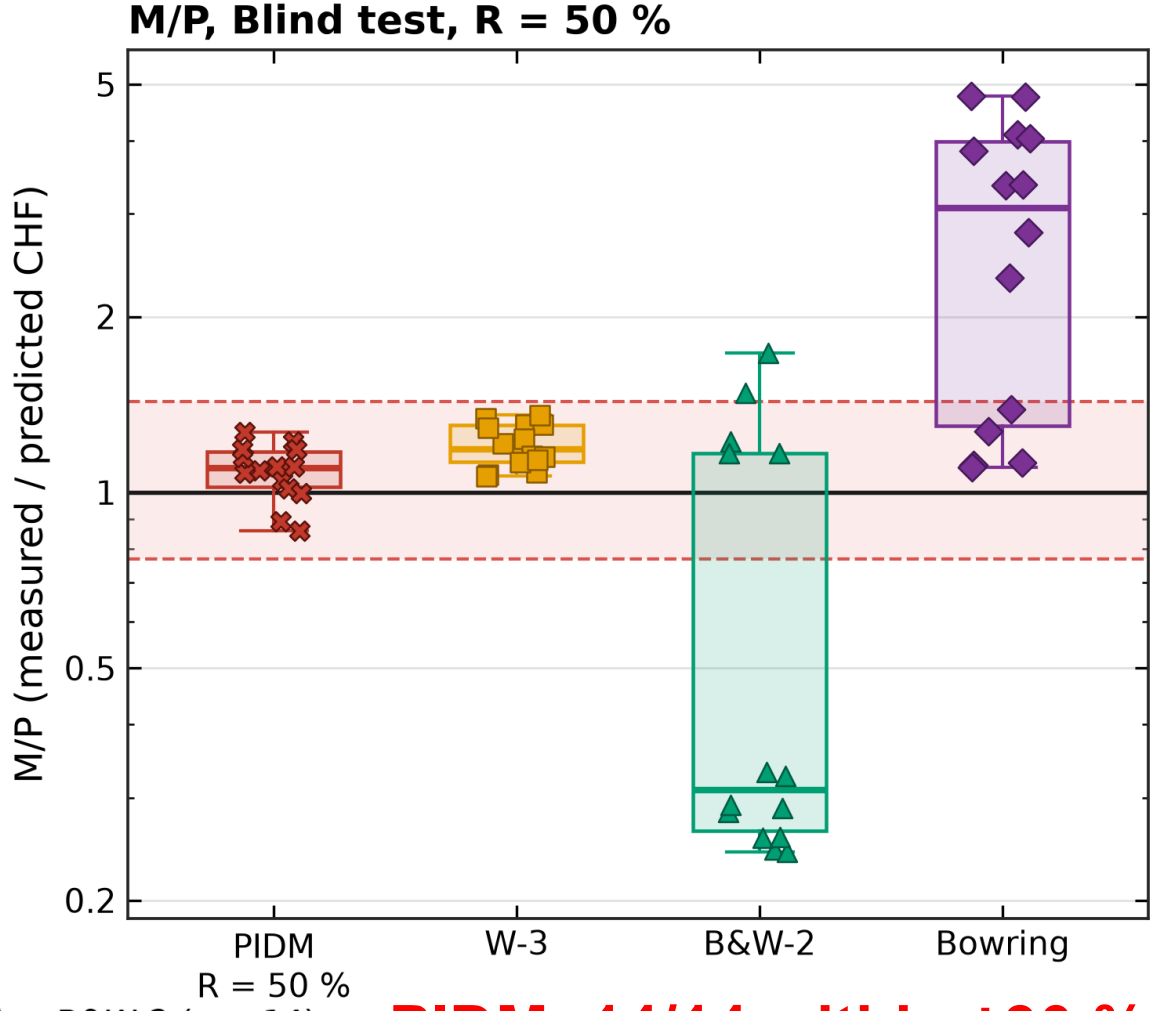
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F-factor reproduced without training on it

Results: Compare with Existing Correlation (R=50%)

❑ **Blind tests (n = 14): PIDM and W-3 keep all 14 within ±30 %**





PIDM: 14/14 within ±30 %

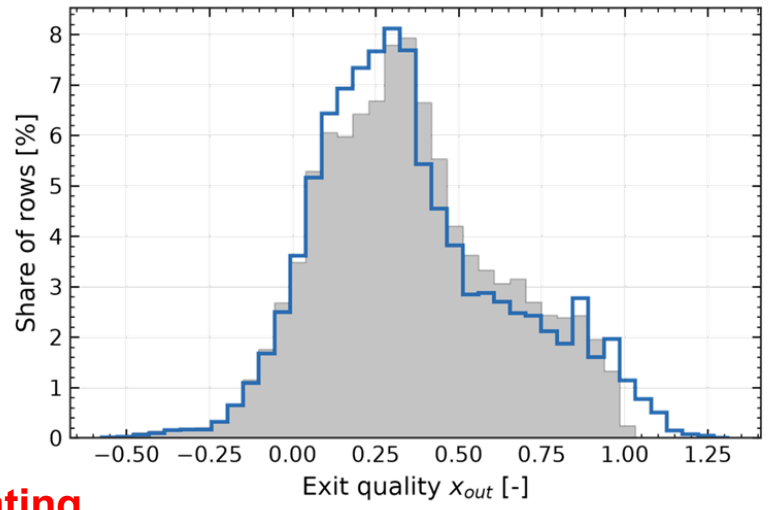
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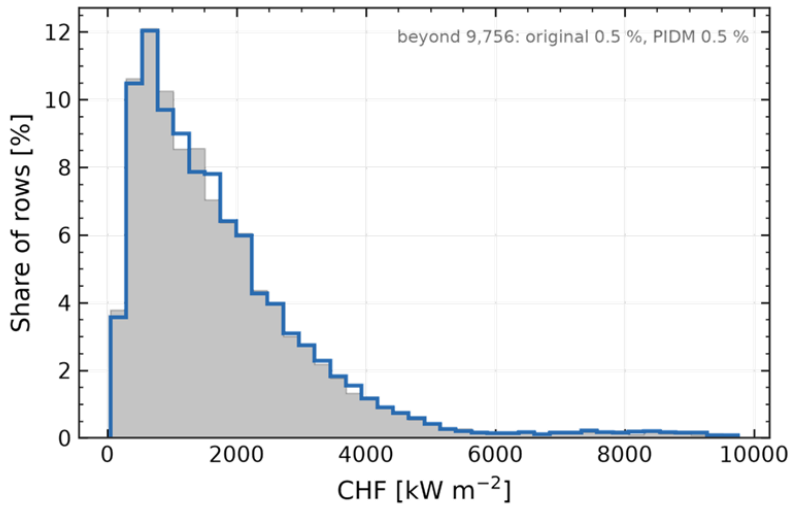
Results: Distribution Reproduction (R=50%)

❑ Generated marginals reproduce the experimental distributions

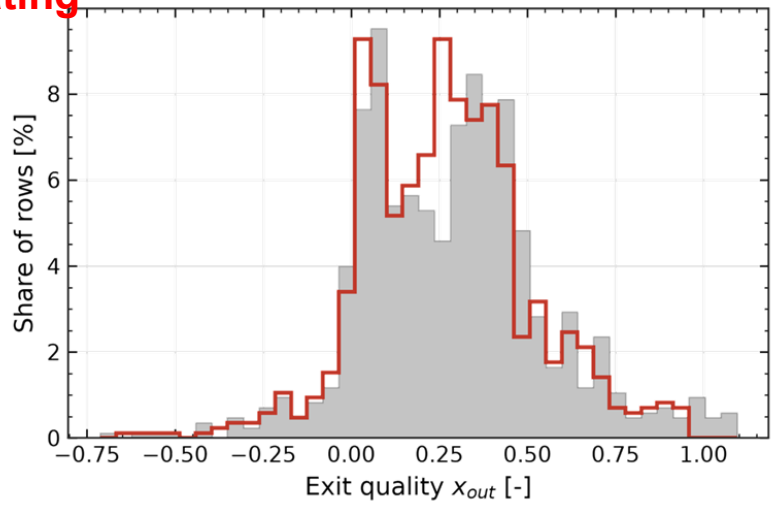
- Exit-quality and CHF distributions are reproduced for both datasets

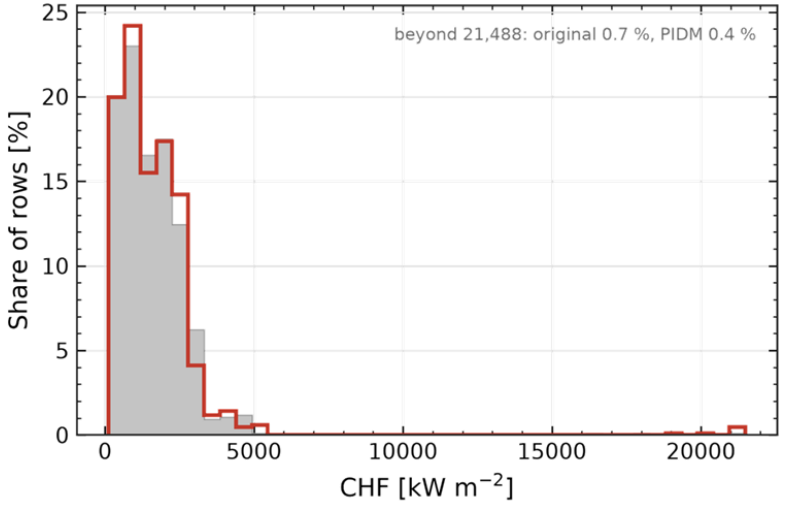
Uniform heating





Non-uniform heating





Original

PIDM, Uniform

PIDM, Non-uniform

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Summary

- **PIDM: a single physics-informed model for uniform and non-uniform CHF**
  - Energy balance and physical bounds via differentiable IAPWS-97 surrogates
- **Results**
  - **Interpolation**: ≥ **98 %** within ±30 % for both datasets at all R
  - **Extrapolation**: uniform ≥ **95 %** for R ≥ 50 %; non-uniform up to **92 %** (R = 50 %); blind tests **14/14** for R ≥ 40 %
  - **Physics loss:** higher and more stable extrapolation than data loss only (non-uniform **92 % vs 81 %** at R = 50 %)
  - F-factor reproduced without training: **80 %** within ±30 % (R = 50 %), **86–96 %** for R ≥ 60 %
- **Limitations and Future Work**
  - Non-uniform extrapolation varies with R **(47–92 %)**
  - Evaluate CHF location and F-factor outside R

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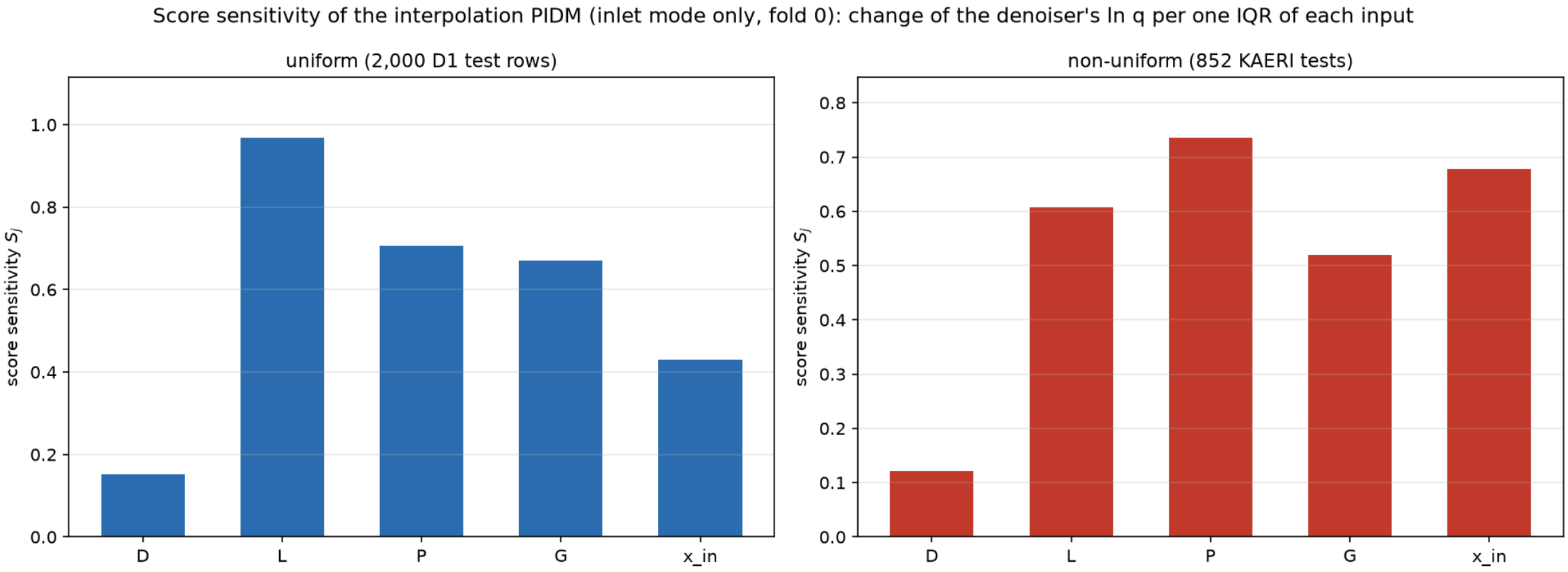
Thank you

Hyunjun Jang, Kyung Mo Kim*

Intelligent Reactor for Innovative Safety (IRIS Lab.)

A1. Input Parameter Sensitivity

❑ L, P, G have top sensitivity in PIDM



A2. Other Performance Metrics

Test set	n	Within ±30 % [%] (outside)	R^2	MAPE [%]	Median P/M
Uniform, interpolation	2,363	100 (0)	0.995	2.6	1.001
Uniform, extrapolation	9,627	95.7 (416)	0.920	8.0	1.011
Non-uniform, interpolation	74	98.6 (1)	0.982	3.3	0.998
Non-uniform, extrapolation	356	92.4 (27)	0.968	14.0	0.949
Blind test	14	100 (0)	0.939	10.9	0.910
F factor, generated CHF point	88	79.5 (18)	−0.09	21.0	1.037
F factor, measured CHF point	105	100 (0)	0.986	2.3	1.014