Physics-informed Neural Networks with Adaptive Dynamic Adjustment for Neutron Transport in simple Geometry

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Summary

- **ADA-PINN**: Adaptive Dynamic Adjustment Physics-Informed Neural Network for the neutron transport equation (NTE)
- **Dynamic loss weighting (ADATL)** automatically balances competing PDE and boundary losses
- Benchmarked on **1D Reed's** and **2D TWIGL** problems → matches reference solutions

Introduction

Background

- The Neutron Transport Equation (NTE) involves six phase-space, making curse of dimensionality.
- Traditional NN had difficulty in confirming that they matched the solution obtained by FDM.

Objective

- Introduce **ADA-PINN**, a mesh-free PINN that autonomously tunes loss weights, solving the NTE accurately and stably without manual hyperparameter tuning.

Methodology

- **ADA-PINN**: mesh-free Physics-Informed Neural Network
- Tailored for the **Neutron Transport Equation (NTE)**
- **Inputs**: spatial coordinates (x, y, z), directional cosines (μ, ϕ), and time (t)
- **Output**: predicted neutron **angular flux ψ(x, y, z, μ, ϕ, t)**

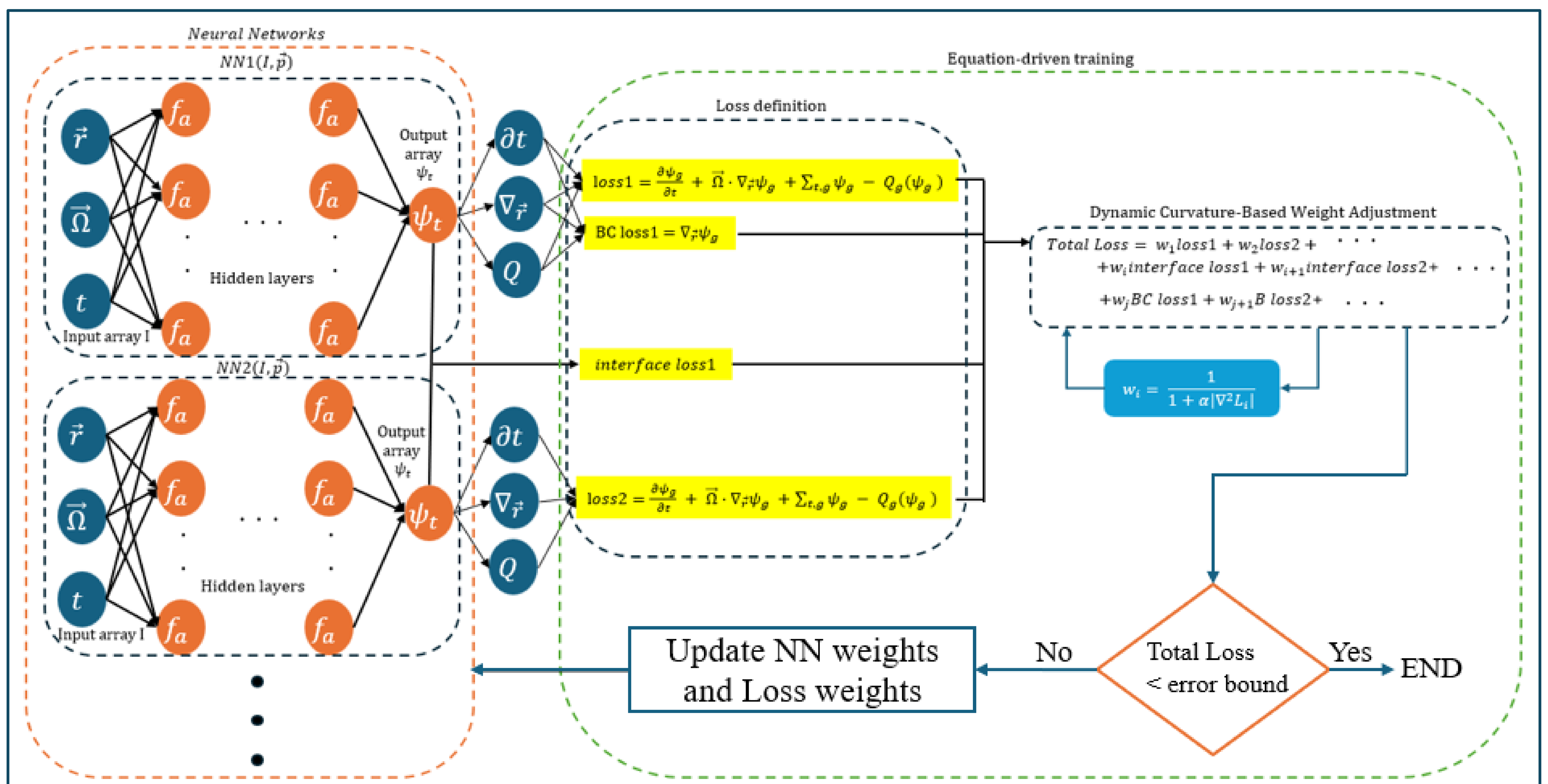


Fig. 1 **Schematic diagram of ADA-PINN**

Key Techniques

- **Adaptive Dynamic Adjustment for Training Loss (ADATL)**
- **Training Set Rearrangement**
- **Multi-group Iteration**
- **Area Decomposition**

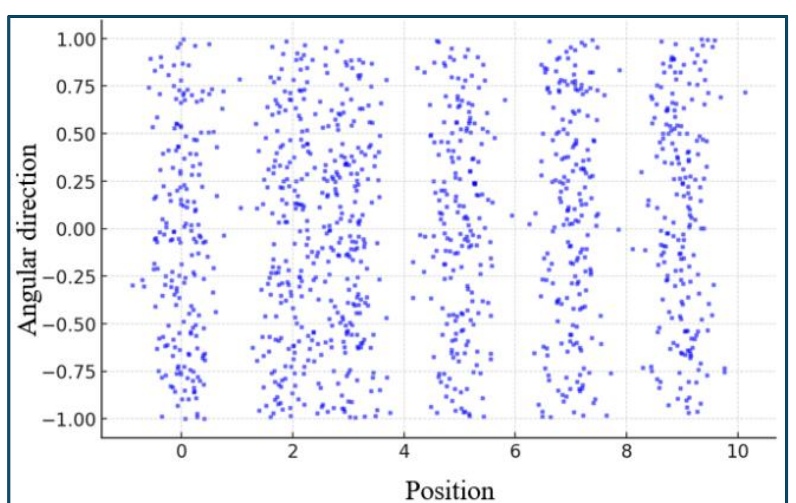
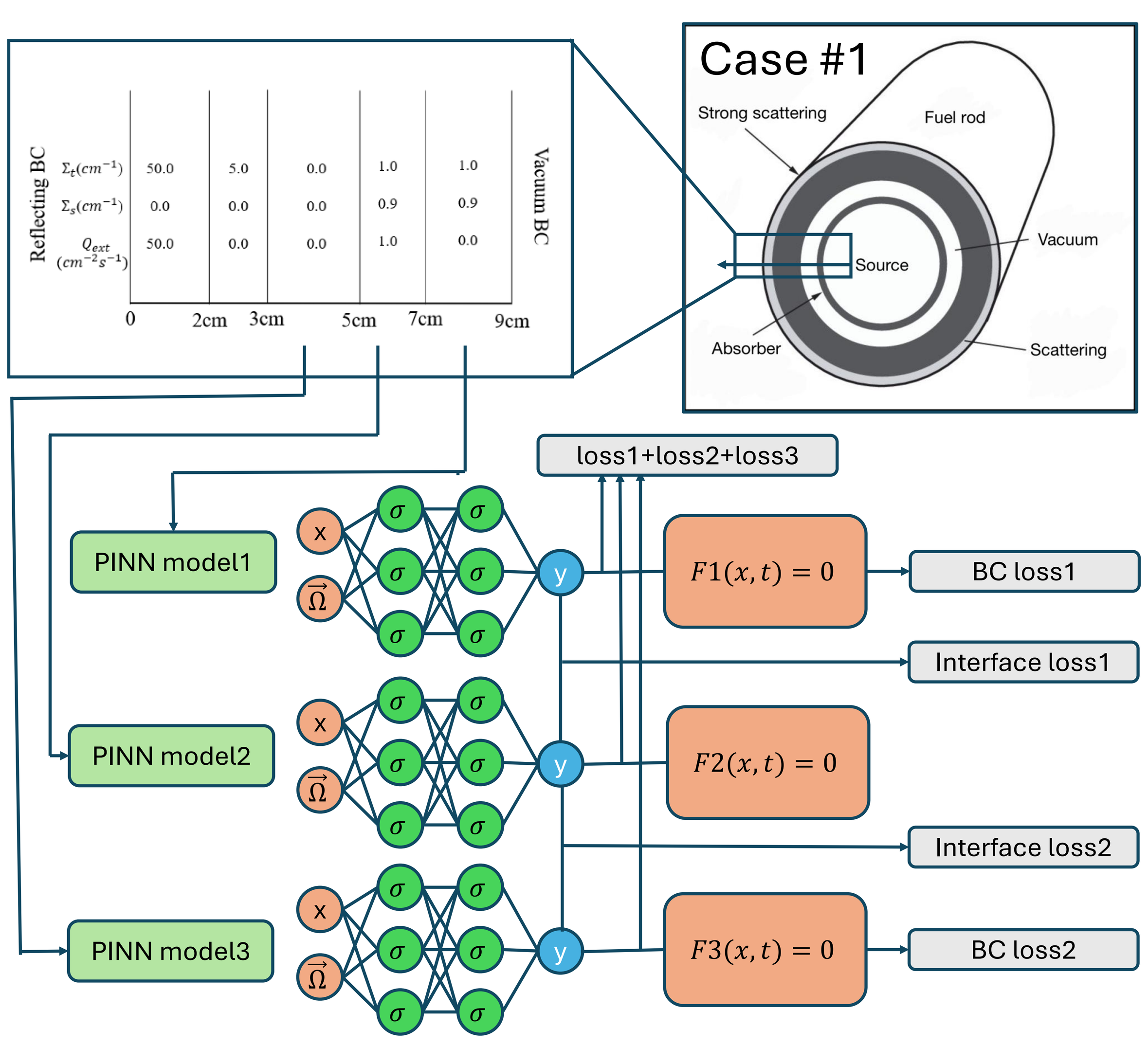


Fig. 2 **Training set Rearrangement**



Total loss:

$w_1$loss1+ w_2 loss2+ w_3 loss3
+
w_4 BC loss1
+
w_5 Interface loss1
+
w_6 Interface loss2
+
w_7 BC loss2

$$w_i = \frac{1}{1+\alpha|\nabla^2 L_i|}$$

ADATL Technique

- **Adaptive Dynamic Adjustment for Training Loss (ADATL)**
  - **Rapidly changing loss (high curvature):** the weight is reduced to prevent over-reaction.
  - **Slowly changing loss (low curvature):** the weight is increased because the term is still under-learned.

- **Multi-group Iteration (Also governing eq. for Case #2)**

$$\begin{cases} \mu\dfrac{\partial\psi_1}{\partial x}+\eta\dfrac{\partial\psi_1}{\partial y}+\Sigma_{t,1}\psi_1=\dfrac{Q_{ext,1}+\Sigma_{s,1\to1}\phi_1+\Sigma_{s,2\to1}\phi_2}{4\pi} \\ \mu\dfrac{\partial\psi_2}{\partial x}+\eta\dfrac{\partial\psi_2}{\partial y}+\Sigma_{t,2}\psi_2=\dfrac{Q_{ext,2}+\Sigma_{s,2\to1}\phi_1+\Sigma_{s,2\to2}\phi_2}{4\pi} \end{cases}$$

Results and Discussion

Case 1: 1D transport problem with scattering(Reed's Problem)

- **Benchmark Purpose**: Commonly used to evaluate and validate neutron transport solvers
- **Geometry**: Features **heterogeneous material layout**
- **Material Types**: Includes **strong absorbers, vacuum regions**, and **scattering zones**
- **Challenge**: Tests solver performance in **complex multi-material environments**

$$\mu\frac{\partial\psi}{\partial x}+\sum\nolimits_t\psi=\frac{Q_{ext}+\Sigma_s\phi}{4\pi}$$

Governing eq. for Case #1

BC #1: $\nabla\psi(x=0,\mu)=0$
BC #2: $\psi(x=8,\mu<0)=0$

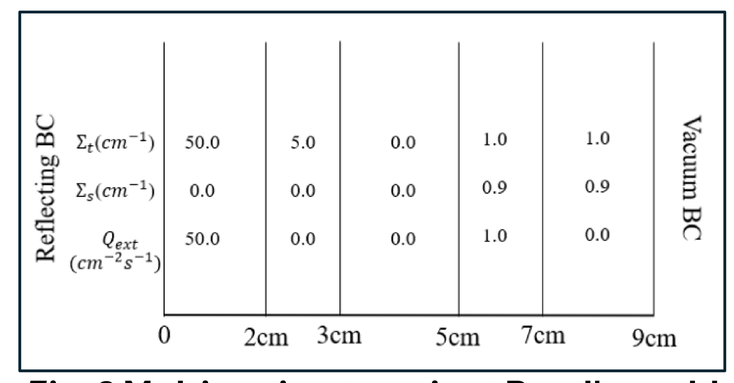


Fig. 3 **Multi-region transient Reed's problem**

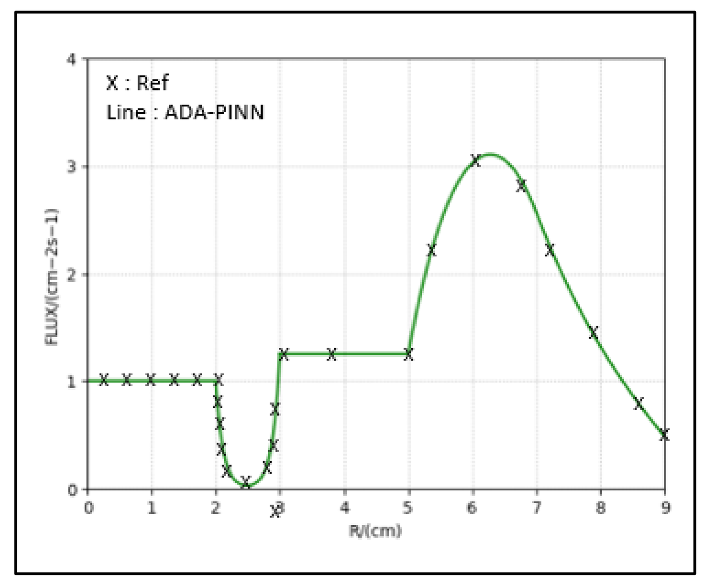


Fig. 4 **Predicted solution comparison between Reference & ADA-PINN**

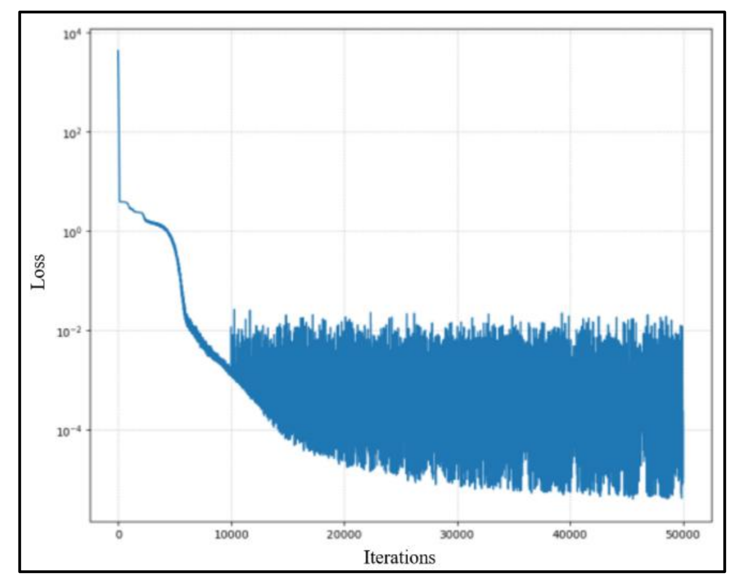


Fig. 5 **Loss history of ADA-PINN for Case1**

Case 2: 2D transport problem with multi-groups (TWIGL Problem)

- **Problem Type**: Steady-state neutron transport equation
- **Materials**: Includes both **absorbing** and **scattering** media
- **External Source**: $Q_{ext,1}$ = Figure below, $Q_{ext,2}$ = 0
- **Benchmark**: Based on the **TWIGL problem**, commonly used to test multigroup transport solvers in heterogeneous domains

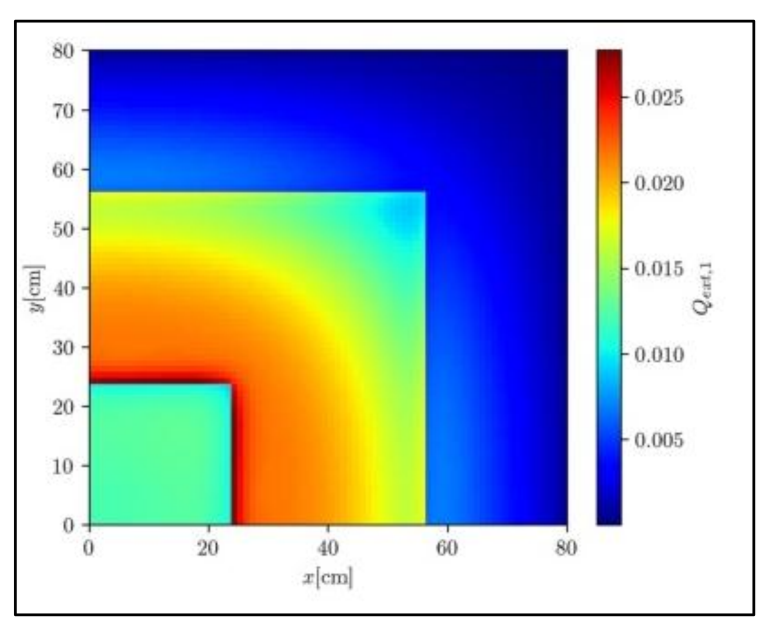


Fig. 6 **$Q_{ext,1}$ Graph**

$$\mu\frac{\partial\psi_1}{\partial x}+\eta\frac{\partial\psi_1}{\partial y}+\Sigma_{t,1}\psi_1=\frac{Q_{ext,1}+\Sigma_{s,1\to1}\phi_1+\Sigma_{s,2\to1}\phi_2}{4\pi}$$
$$\mu\frac{\partial\psi_2}{\partial x}+\eta\frac{\partial\psi_2}{\partial y}+\Sigma_{t,2}\psi_2=\frac{Q_{ext,2}+\Sigma_{s,2\to1}\phi_1+\Sigma_{s,2\to2}\phi_2}{4\pi}$$

Governing eq. for Case #2

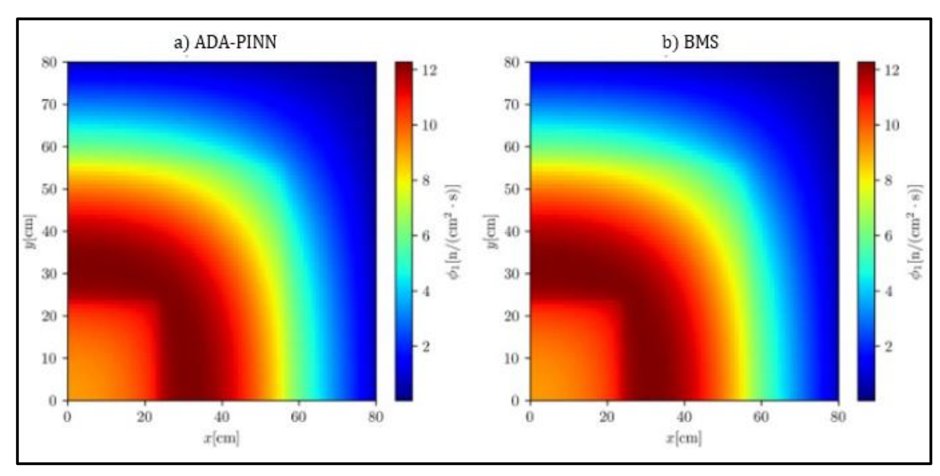


Fig. 8 **Global comparison of ϕ_1 in Case 2.**

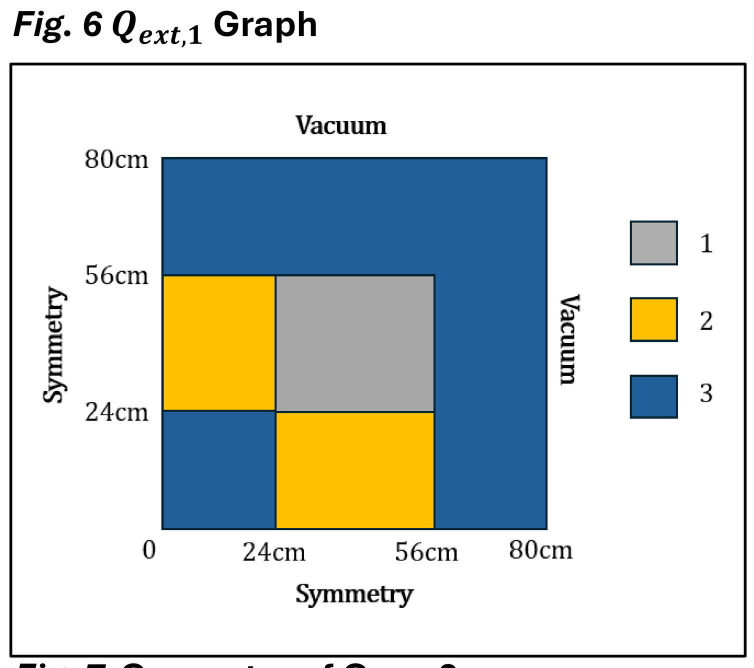


Fig. 7 **Geometry of Case 2**

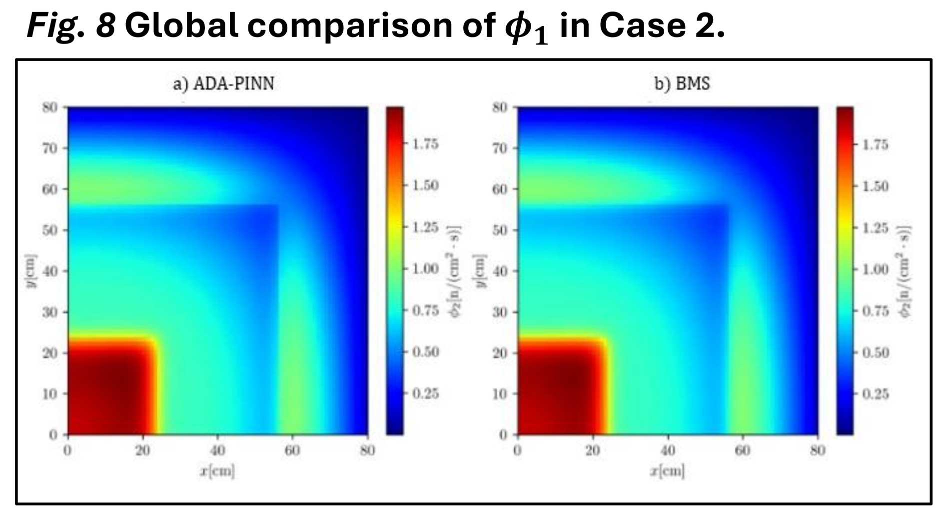


Fig. 9 **Global comparison of ϕ_2 in Case 2**

Region	Group, g	Σ_t	$\Sigma_{s,g\to g}$	$\Sigma_{s,g\to g'}$
1	1	0.2380	0.218095	0.01
	2	0.8333	0.68333	0
2	1	0.2380	0. 218095	0.01
	2	0.8333	0.68333	0
3	1	0.2564	0.23841	0.01
	2	0.6666	0.616667	0

Table 1 **Physical parameters of Case 2**

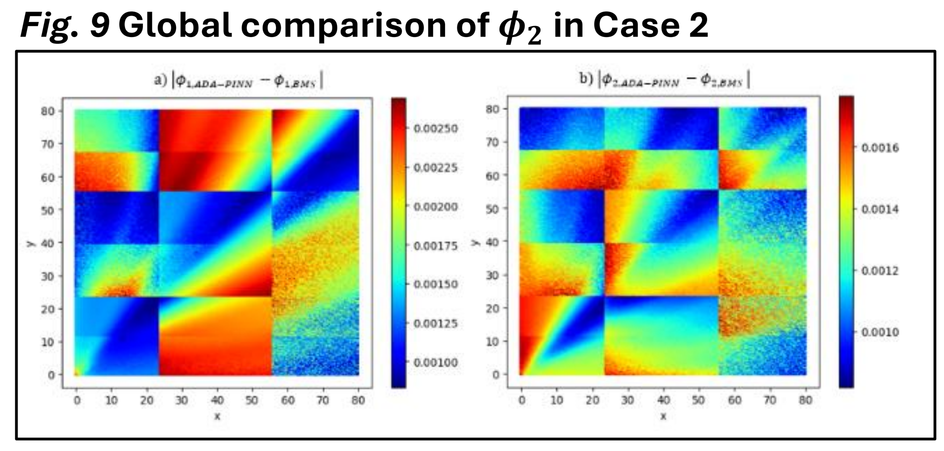


Fig. 10 **Difference values between ADA-PINN and BMS over the geometry**

Conclusion

- **Model**: ADA-PINN enhanced with ADATL and training-set rearrangement
- Solves NTE with high accuracy on **1D Reed** and **2D TWIGL** benchmarks
- Achieves **fast/thermal flux errors ≈ 0.0017 / 0.0011**
- **Mitigates ray effects** and **boundary-related errors**
- **No manual tuning** of hyperparameters required
- **Outlook**: Will be extended to **transient**, **multi-group**, and **anisotropic** transport cases for broader applicability in reactor simulations

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