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Impact of Cross-Flow Effects on Recuperator Performance: A Two-Dimensional Finite Difference Approach for sCO_2 Recuperator

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1. Introduction

Supercritical carbon dioxide (sCO_2) power cycles have been extensively investigated in recent years as a promising alternative to conventional steam Rankine cycles for advanced energy systems. The unique thermophysical properties of sCO_2, such as high density near the critical point and favorable heat transfer characteristics, enable the realization of highly efficient and compact power conversion systems. For nuclear power plants in particular, sCO_2 cycles are considered attractive due to their potential to achieve high thermal efficiency, reduced plant footprint, and compatibility with wide reactor operating temperature ranges. Consequently, their application has been widely studied in conjunction with advanced nuclear reactor concepts, including sodium-cooled fast reactors, high-temperature gas-cooled reactors, and molten salt reactors.

Within the sCO_2 cycles, the recuperator plays a crucial role in determining overall system performance. By recovering heat from the turbine exhaust stream and preheating the compressor outlet flow, the recuperator substantially reduces the required reactor thermal input and thereby enhances cycle efficiency. Accurate modeling of recuperator performance is therefore essential to achieve reliable design and system optimization.

Previous studies have primarily relied on one-dimensional (1D) finite difference models for recuperator design and analysis. Such approaches generally assume an ideal counter-flow configuration, which simplifies numerical implementation and provides a first-order estimate of thermal performance. However, in actual operation, the flow distribution inside the recuperator is strongly influenced by the headers that connect the manifolds to the parallel channels. This flow arrangement inevitably introduces cross-flow components, leading to non-uniform temperature distributions and deviations from the ideal counter-flow assumption. As a result, 1D counter-flow based models cannot fully capture the complex flow and heat transfer characteristics observed in practical recuperator geometries, which may lead to discrepancies in performance prediction.

To address this limitation, the present study develops a two-dimensional (2D) finite difference method (FDM) model that incorporates cross-flow effects induced by header-to-channel flow distribution. By accounting for the actual flow path, the proposed model enables a more realistic representation of temperature profiles, heat transfer rates, and pressure drop characteristics within the recuperator. Comparative analysis between the conventional 1D counter-flow model and the proposed 2D cross-flow model are conducted to assess the impact of cross-flow heat transfer on recuperator design accuracy. Through this approach, the study aims to provide improved predictive capability for recuperator performance and to support the development of more reliable sCO_2 cycle designs for nuclear application.

2. Methods and Results

2.1 Methods

The target component of this study is the recuperator installed in the Autonomous Brayton Cycle test loop (ABC loop) in KAIST, which represents a prototypic sCO_2 cycle configuration. The recuperator plays a central role in recovering heat from the turbine exhaust and preheating the compressor outlet flow, thereby increasing the turbine inlet temperature to improve the overall cycle efficiency. The design specification of the recuperator used as the reference case, including inlet and outlet conditions for both hot and cold streams, are summarized in Table 1.

Table 1. Design Specification of the reference Recuperator

Parameter	Value
Hot Side	
Inlet/Outlet Temperature [°C]	58.3 / 48.8
Inlet/Outlet Pressure [MPa]	8.7 / 8.55
Mass Flow Rate [kg/s]	1.5
Cold Side	
Inlet/Outlet Temperature [°C]	47.9 / 53.1
Inlet/Outlet Pressure [MPa]	9.13 / 9.0
Mass Flow Rate [kg/s]	1.5

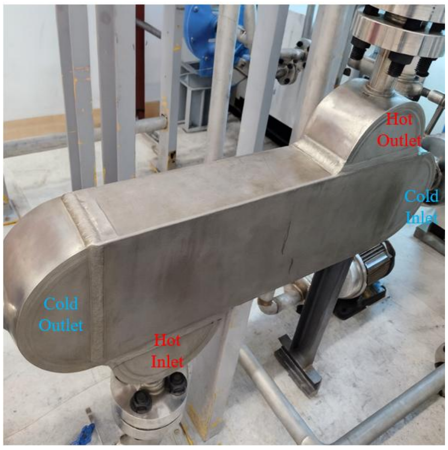

Figure 1. PCHE recuperator in ABC loop

To analyze this component, two modeling approaches are implemented: (1) a 1D FDM model assuming ideal counter-flow arrangement, and (2) a 2D FDM model that accounts for cross-flow effects induced by header-to-channel flow distribution.

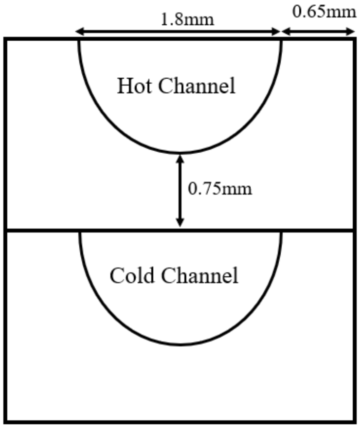

Figure 2. Channel Geometry

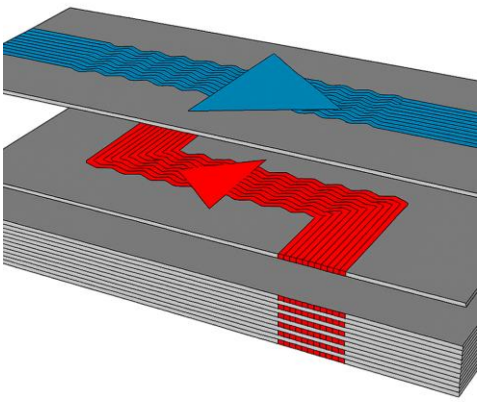

Figure 3. PCHE Flow configuration

ITEM		
TYPE	확산접합형 열교환기	
NAME	CO2 PCHE	
W.O NO.	EN001-20200917	
MANUFACTURING DATE	2020.11.19	
SPECIFICATION		
Division	HOT side	COLD side
Working Fluid	CO2	CO2
Design Temp	100℃ 이하	100℃ 이하
Material Name	STS316L	STS316L
Core Dimension(W•L•H)	250(W)•750(L)•132(H)	
Mass Flow Rate	1.5kg/s	1.5kg/s
Flange Type		

Figure 4. ABC Loop Recuperator Specification

The 1D modeling framework in this study is based on the KAIST-HXD code, which has been developed and validated for PCHE application [1]. In KAIST-HXD, the recuperator is discretized into a series of nodes, with energy balances solved under counter-flow assumption. For each mesh element, the total thermal resistance is calculated as the sum of individual resistances from the hot side fluid, the channel wall, and the cold side fluid. The local heat transfer rate is then obtained from the temperature difference between the two streams and the corresponding thermal resistance. By integrating the heat transfer across all nodes, the overall recuperator performance is determined. The code has been benchmarked against available PCHE experimental data, demonstrating reliable prediction capability under a wide range of operating conditions. In this work, the same 1D modeling approach is applied as the baseline framework for the ABC loop recuperator.

While the 1D model provides a computationally efficient and validated method for recuperator analysis, it inherently neglects cross-flow effects. In practical operation, the flow distribution inside the recuperator is strongly influenced by the header location and configuration, as shown in Figure 3, leading to cross-flow interactions and non-uniform temperature distributions. To capture these phenomena, a 2D FDM model was developed. The governing energy conservation equation is expressed in both axial and transverse directions, with transverse velocity components introduced to represent header-induced flow distribution. The discretization is performed using a structured mesh with second-order central differencing, and an iterative solution procedure is applied until convergence is achieved [2].

Boundary conditions are imposed based on the ABC loop operating parameters: fixed inlet temperature, pressure, and mass flow rate for both streams, with adiabatic wall assumption. Thermophysical properties of sCO_2 are evaluated using the REFPROP database, and correlations are found from the literature review [3].

Finally, the two models are compared in terms of outlet temperature predictions, heat duty, pressure drop, and thermal effectiveness, with particualr emphasis on deviations caused by cross-flow effects. This comparison framework highlights the limitations of simplified 1D counter-flow assumption, and demonstrates the improved fidelity achieved by the 2D approach for the recuperator design.

2.2 Results

Figure 5 to Figure 7 illustrate the temperature distributions obtained from the 1D and 2D recuperator models. The 1D framework provides temperature variations along the flow direction based on a nodal discretization, whereas the 2D FDM model resolves the lateral non-uniformities on both hot and cold sides. As shown in Figure 6 and Figure 7, the 2D analysis captures the local temperature gradients that arise from non-ideal flow paths, including partial cross-flow and transverse mixing, which are absent in the 1D model

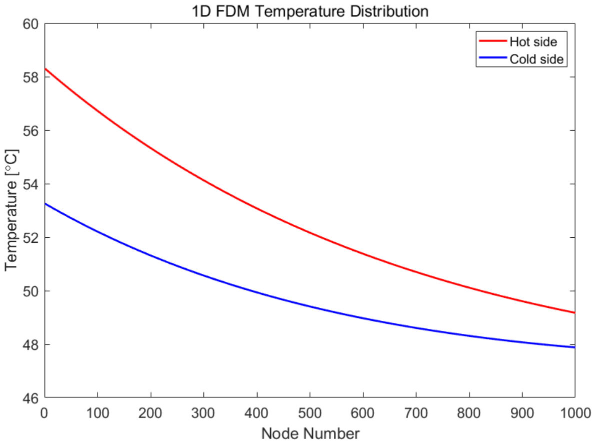

Figure 5. Temperature Distribution predicted by 1D FDM

A key distinction between the two approaches lies in the treatment of hydraulic losses. The 2D model incorporates local form losses at 90° bends and at the junctions between the headers and channels, resulting in slightly larger predicted pressure drops compared to the 1D code. In contrast, the 1D model relies on simplified frictional correlations and idealized counter-flow assumptions, yielding optimistic estimates of both thermal and hydraulic performance.

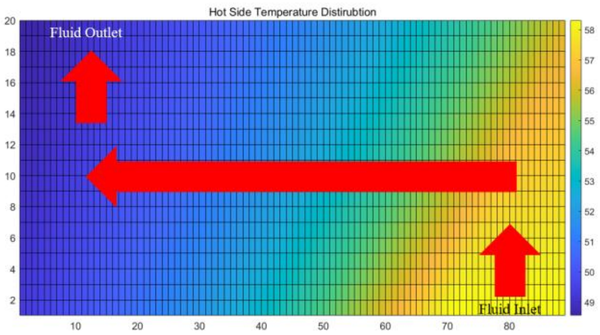

Figure 6. Hot Side Temperature Distribution predicted by 2D FDM

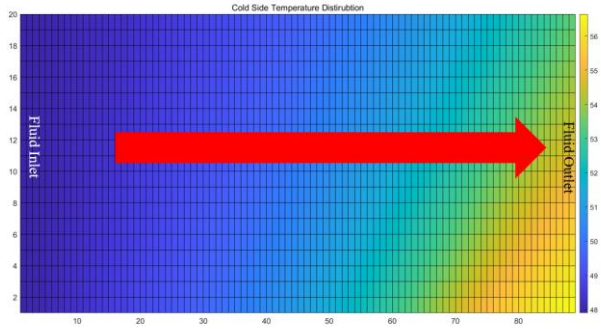

Figure 7. Cold Side Temperature Distribution predicted by 2D FDM

Table 2 summarizes the comparative results of the 1D and 2D analysis alongside the reference design values corresponding to the recuperator currently nstalled in the ABC loop. At first glance, the 1D predictions appear to align more closely with the reference design in terms of heat load and pressure drops. However, this apparent agreement originates from the fact that the ABC loop recuperator was originally designed based on the 1D methodology. The 1D predictions therefor inherently reproduce the design targets, rather than independently verifying them.

By contrast, the 2D model, which accounts for realistic flow effects and geometric details, predicts larger pressure dcrops and a slightly reduced heat load, together with a larger required core volume. While these results deviate from the 1D-based design specifications, they provide a more physically realistic representation of thermal-hydraulic behavior in compact PCHEs. This comparison highlights that although the 1D code remains a valuable tool for preliminary sizing and optimization, higher-fidelity 2D simulations are essential to evaluate the true performance of recuperators, particualry under nuclear sCO_2 cycle conditions where cross-flow and form losses cannot be neglected.

Table 2. Comparison of 1D and 2D Recuperator Design.

Parameter	1D	2D	Reference Design (ABC Loop)
Effectiveness [%]	89.7	83.94	88.39
Volume [m^3]	0.012	0.017	0.023
Length [m]	0.750	0.750	0.750
Cross-sectional Area [m^2]	0.009	0.02	0.03
Total Number of fluid channel	3000	3000	3000
Hot Side Pressure Drop [kPa]	117.5	203.3	150
Cold Side Pressure Drop [kPa]	100.1	173.0	130
Heat Load [kWth]	36.0	28.8	35.7

In summary, the 1D model systematically predicts higher heat transfer and lower pressure losses due to its idealized counter-flow assumption, while the 2D model reveals more conservative performance with larger core size and higher hydraulic resistance. The reference recuperator aligns more closely with the 1D results, reflecting its design origin, but the 2D framework is expected to capture operational behavior more realistically.

3. Conclusions

This study examined recuperator performance in an sCO2 power cycle by comparing a simplified 1D KAIST-HXD code with an extended 2D finite-difference model. The 1D framework offered computational efficiency and reproduced the design targets of the ABC loop recuperator, as expected from its role in the original design process. However, this agreement was achieved by assuming ideal counter-flow and neglecting cross-flow and form losses, leading to optimistic predictions.

In contrast, the 2D model incorporated these non-ideal flow features, yielding more conservative estimates with larger pressure drops, slightly reduced heat load, and increased core size. While such results deviate from the 1D-based design data, they provide a more realistic representation of the complex flow and thermal interactions within compact PCHEs.

Overall, the findings emphasize the complementary roles of the two approaches: the 1D code remains useful for rapid preliminary design and optimization, while the 2D model enhances predictive fidelity and is better suited for detailed performance assessments. Future work will focus on incorporating detailed header geometries and validating the numerical predictions against experimental data from the ABC loop recuperator, thereby strengthening the credibility of the high-fidelity modeling framework for nuclear sCO_2 applications.

ACKNOWLEDGEMENT

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