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Article

Comprehensive Numerical Investigation of Helically Coiled Tube's Thermal Efficiency Through Morpho-Hydrodynamic Variations and Global E-NTU Correlation

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Abstract

Helically coiled tube heat exchangers (HCTHEXs) are widely deployed in compact thermal systems, yet reliable effectiveness-NTU (ϵ -NTU) correlations for realistic fluid-to-fluid operation remain scarce. This work presents a comprehensive three-dimensional numerical study of a vertical tube-in-annular-shell HCTHEX under laminar flow on both coil and shell sides, with water as the working fluid in all cases. More than 2400 steady-state CFD simulations in ANSYS Fluent are performed to systematically vary morpho-hydrodynamic parameters, including coil pitch ratio, flow rates, and thermal boundary conditions. The numerical model is verified against established correlations for coil-side Nusselt number and pressure drop, with discrepancies typically below 10%, and is then used to construct a global ϵ -NTU database. For each pitch ratio, three candidate ϵ -NTU correlations are evaluated: a power-law relation in log-log space, a log-quadratic polynomial in $\log(\text{NTU})$, and a nonlinear exponential form of the type $\epsilon = 1 - \exp(-a \text{NTU}^b)$. The log-quadratic and exponential models consistently reproduce the characteristic rising-plateau ϵ -NTU behavior with R^2 values between 0.90 and 0.98, whereas simple power laws underpredict the curvature. A global log-based regression model $\log(\epsilon) = f[\log(\text{NTU}), P]$ captures the overall monotonic trends but attains only moderate accuracy ($R^2 \approx 0.59$ in ϵ -space), highlighting the intrinsic nonlinearity of the ϵ -NTU-pitch surface. To overcome this limitation, generalized additive models (GAM) and bagged decision-tree ensembles are trained using $\log(\text{NTU})$ and pitch as predictors. These machine-learning regressors yield substantially improved agreement with the CFD data, with $R^2 \approx 0.94$ for GAM and $R^2 \approx 0.91$ for the ensemble, while a simple average of both predictions achieves the highest fidelity ($R^2 \approx 0.95$). The resulting pitch-specific closed-form correlations and global GAM/Ensemble surrogate provide practical tools for predicting the effectiveness of helically coiled tube heat exchangers over a broad range of morpho-hydrodynamic conditions.

Keywords: HCTHEX; helical coil; effectiveness; epsilon-NTU

Introduction

HCTHEX is one of the most versatile types of thermal energy exchanges used in the chemical, nuclear, and pharmaceutical industries, and it is also a highly effective device for harnessing solar energy in both residential and commercial buildings [1–8]. Despite their robust popularity among compact heat exchangers, there have not been more than only a few studies focused primarily on the correlations of effectiveness (ϵ) of this kind of HEXs, either experimentally or numerically, which were implemented by the first author of this present work [2,5]. This present work on the other hand, though, has been aiming to investigate the global behavior of HCTHEX by implementing over 2400 simulations covering ranges of thermal, hydraulic, and geometrical features of HCTHEX under laminar flow regimes on both the shell- and coil-side.

Research studies on helically coiled tube heat exchangers primarily focus on specific boundary conditions (B.Cs.), such as constant heat flux, fixed temperature boundaries, or power input through DC current. Some studies also investigate natural convection on the shell side. However, no comprehensive investigations have examined the thermal performance and heat transfer behavior on the shell side of these compact heat exchangers, especially concerning the fluid-to-fluid heat transfer mechanism.

Mirgolbabaei [1,2], Mirgolbabaei et al. [3,6], and Ghorbani et al. [4,5] conducted a series of numerical simulations and experiments to study the heat transfer in helically coiled tube heat exchangers. The experiments in Ghorbani et al. [4,5] were conducted for both laminar and turbulent regimes inside the coil. It was deduced that the ϵ -NTU relation of the mixed convection heat transfer condition – natural and forced convections, can be mirrored by that of a pure counter-flow heat exchanger.

This study aims to provide insights into the thermal performance of widely used industrial heat exchangers. It investigates how various parameter changes affect the effectiveness of helically coiled tube-in-annular-cylindrical shell heat exchangers. To simulate real thermal boundary conditions, a three-dimensional steady-state fluid-to-fluid numerical simulation is conducted. The model includes convection heat transfer within the tube, conduction through the tube wall, and convection on the outer surface of the coiled tube.

Computational Model

This research differs from most studies by using a real fluid-to-fluid simulation of a vertically oriented HEX in ANSYS-FLUENT 2023, licensed to the University of Minnesota. Both sides are modeled with water, with no phase change assumed.

Thermophysical properties:

While temperature-dependent properties could improve accuracy, the complex flow and uneven temperature gradients in the shell side hinder solution convergence. Therefore, the overall average temperature was estimated from prior studies, and water properties were assumed at that temperature.

Flow regimes:

For the shell's flow structure, the most representative length has been discussed in previous studies by the author [1–5]. In this study, the shell-side flow regime was determined using the hydraulic diameter of the shadowed surface. Based on either choice, the Re_{shell} will be smaller than the critical $Re_{cr} = 2300$ for internal flows through a circular pipe, for $\dot{m}_{shell} = 0.01 - 0.15 \text{ kg/sec}$.

The transitional regime of the fluid flow on the coil side is determined based on the study conducted by Schmidt [9]:

$Re_{cr,Coil} = 2300 \left[1 + 8.6 \left(\frac{d_{tube}}{D_{coil}} \right)^{0.45} \right]$	(1)
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The coil flow rate up to $\dot{m}_{coil} = 0.02 \text{ kg/sec}$ remains laminar. To consider shell-side thermal variability, Re and $\dot{m}_{coil} = 0.01 - 0.02 \text{ kg/sec}$ are simulated. Exit configurations include extending the last turn or bending at 90 degrees, but these may disrupt laminar flow. Our models keep coils turning until fluid exits on both sides, with no straight sections, to avoid turbulence.

Dimensions of different geometries under study are provided in Table 1. The schematic of the HEX is demonstrated in Figure 1.

The simulation runs under steady-state conditions with a pressure-based 'coupled' algorithm. It uses second-order discretization for the continuity, momentum, and energy equations, with relation factors between models. The coil wall is coupled with its shadow; the coil tube was modeled in Ansys as a 1D wall, using constant copper properties. Artifacts at the coil base were modeled similarly. Protruding coil sections are modeled as adiabatic with zero thickness copper, and shell walls as adiabatic zero-thickness aluminum. The following equations are solved as the continuity, momentum, and energy equations, respectively, for the steady state condition:

$\frac{\partial}{\partial x_i}(\rho u_i) = 0$	(2)
$\frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\mu \frac{\partial u_j}{\partial x_i}\right) + \rho g_i$	(3)
$\frac{\partial}{\partial x_i}(\rho c_p u_i T) = \frac{\partial}{\partial x_i}\left(k \frac{\partial T}{\partial x_i}\right)$	(4)

The computational cells and the type of meshing schemes used in the study are laid out in detail in [6].

Table 1. Coils and shell specifications.

D_{oc} (mm)	D_{ic} (mm)	d_{outer}/d_{inner} (mm/mm)	D_{coil} (mm)	P	N	H (mm)	$A_{coil,outer}$ (mm ²)	D_h (mm)
160	90	9.52/8.001	125	1.8	10.50	180	1.03771e+05	11.57
160	90	9.52/8.001	125	1.85	10.22	180	1.00974e+05	11.84
160	90	9.52/8.001	125	1.90	9.95	180	9.83241e+04	12.10
160	90	9.52/8.001	125	1.95	9.70	180	9.58106e+04	12.35
160	90	9.52/8.001	125	2	9.45	180	9.34230e+04	12.60
160	90	12.5/10.98	125	1.8	7.11	360	0.92330e+05	0.010.17
160	90	12.5/10.98	125	1.9	6.74	360	0.87494e+05	10.74
160	90	12.5/10.98	125	2	6.40	360	0.83142e+05	11.27

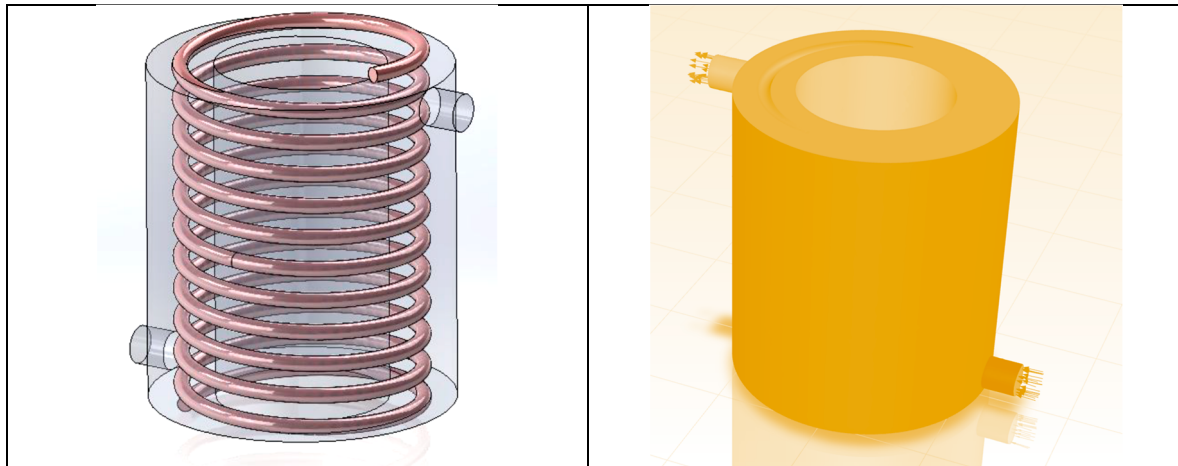


Figure 1. Schematic of HCTHEX and flow directions in shell- and ci-side.

Model Verification

This study validates the numerical model by comparing it to a well-known formula that describes thermal and hydraulic properties on the coil side. The Nusselt number on the coil side is not significantly affected by the pitch; instead, it is primarily influenced by the curvature ratio, as outlined below [10]:

$$\overline{Nu}_{coil} = 3.65 + 0.08 \left[1 + 0.8 \left(\frac{d_{tube}}{D_{coil}} \right)^{0.9} \right] Pr^{\frac{1}{3}} Re^{0.5+0.2903 \left(\frac{d_{inner}}{D_{coil}} \right)^{0.194}} \quad (5)$$

$\overline{Nu}_{coil}$ in our numerical models is calculated as follows:

$$q_{coil} = \dot{m}_c \bar{c}_{p,c} (\bar{T}_{c,out} - \bar{T}_{c,in}) = \bar{h}_{coil} A_{tube,inner} (\bar{T}_{b,c} - \bar{T}_{tube,inner}) \quad (6)$$

$$\overline{Nu}_{coil} = \frac{\bar{h}_{coil} d_{inner}}{k} \quad (7)$$

where $\bar{T}_{b,c}$ and $\bar{T}_{tube,inner}$ are volume-based average temperature of the coil-side medium and overall inner coil surface temperature, respectively.

The resultant $\bar{Nu}_{coil}$ values and the values from (5) are reported in Table 2. The discrepancy between 9% and 0.8% is obtained from this comparison.

Table 2. Comparison of the coil-side Nusselt number and equation (5).

Dimensionless pitch	Discrepancies
1.8	7.05%
1.85	4.98%
1.9	8.74%
1.95	0.7%
2	4.42%

The total pressure drop can be approximated using various equations, although these formulas are only applicable within specific ranges of De . All the models in this study utilize the same parameters, so the pressure loss results are consistently compared to a single established formula from existing literature [6,11]. Comparison between the numerically calculated pressure loss on the coil side and the values obtained from the formula in [11] is shown in Table 3.

Table 3. Numerically simulated ΔP_{coil} versus [11] comparison.

Dimensionless pitch	Discrepancies
1.8	7.7%
1.85	9.1%
1.9	5.3%
1.95	3.7%
2	4.4%

Data Reduction

Heat exchanger effectiveness is defined as the ratio of the actual heat transfer rate for a heat exchanger to the thermodynamically limited maximum possible heat transfer rate if an infinite heat transfer surface area were available in a counter-flow heat exchanger:

$$\varepsilon = \frac{q}{q_{max}} = \frac{\int_{T_{shell,i}}^{T_{shell,o}} \dot{m}_{shell} c_{p,shell} \frac{\partial T}{\partial z} dz}{min(\bar{C}_{p,coil}, \bar{C}_{p,shell}; \Delta T_{max} = T_{coil,i} - T_{shell,i}) \int_{T_{shell,i}}^{T_{coil,i}} dT}$$

(5)

q_{max} in this equation is the maximum heat transfer rate that can be hypothetically achieved in a standard counter-flow heat exchanger of infinite length, corresponding to maximum temperature difference for one stream.

Effectiveness-NTU

The number of heat transfer units is described as:

$$NTU = \frac{A_{coil} \bar{U}}{min(\bar{C}_{p,c}, \bar{C}_{p,s}) \times \int_{T_{c,i}}^{T_{h,i}} dT}$$

(6)

The overall heat transfer coefficient is determined as follows:

$$\frac{1}{\bar{U}A} = \frac{1}{h_c A_{inner}} + \frac{ln(d_{outer}/d_{inner})}{2\pi k_{tube} L} + \frac{1}{h_s A_{outer}}$$

(7)

where the are A can be either the area of the inner surface of the tube, A_{inner} , or area of the outer surface of the coil – shell-side heat transfer area, A_{coil} , or the area based on some diameter, $d_{inner} < d < d_{outer}$.

Results & Discussion

The ϵ -NTU distribution in Figure 2 demonstrates the nonlinear dependence of heat exchanger effectiveness on the number of transfer units across all analyzed geometries. At small NTU values, effectiveness increases rapidly, reflecting the strong sensitivity of heat transfer to additional thermal contact area or conductance. As NTU grows, the slope diminishes, indicating that the exchanger approaches its asymptotic thermal limit where further increases in UA produce diminishing performance gains. The five pitch ratios form distinct but parallel bands, showing that geometric variations primarily shift the absolute level of effectiveness while leaving the underlying NTU dependence intact. This consistent rising-plateau structure observed across more than 2,400 simulations supports the use of NTU as the dominant scaling variable for predicting exchanger performance.

Although NTU remains the primary driver of heat exchanger effectiveness, Figure 2 reveals a clear secondary influence from coil pitch. Larger pitches generally correspond to slightly higher effectiveness at a given NTU, suggesting that geometric spacing affects the overall heat transfer conductance (UA) or internal flow development. Nevertheless, all pitch cases follow a similar ϵ -NTU trajectory, indicating that the role of pitch is to modulate the magnitude rather than the functional shape of the ϵ -NTU response. This behavior implies that predictive models must capture both the universal NTU scaling and the modest geometric shifts introduced by pitch variations.

NTU effectively collapses the thermal performance behavior across varied operating conditions, while geometric variations introduce systematic vertical shifts. The smooth, continuous structure of the data confirms its suitability for regression and machine-learning-based modeling, motivating the flexible correlation approaches explored later in this work.

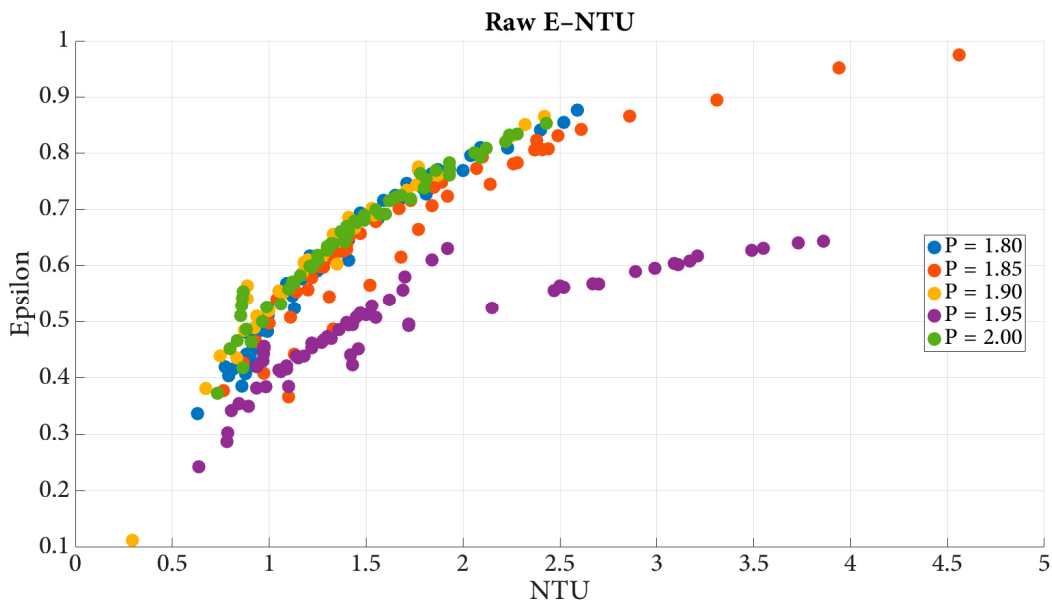
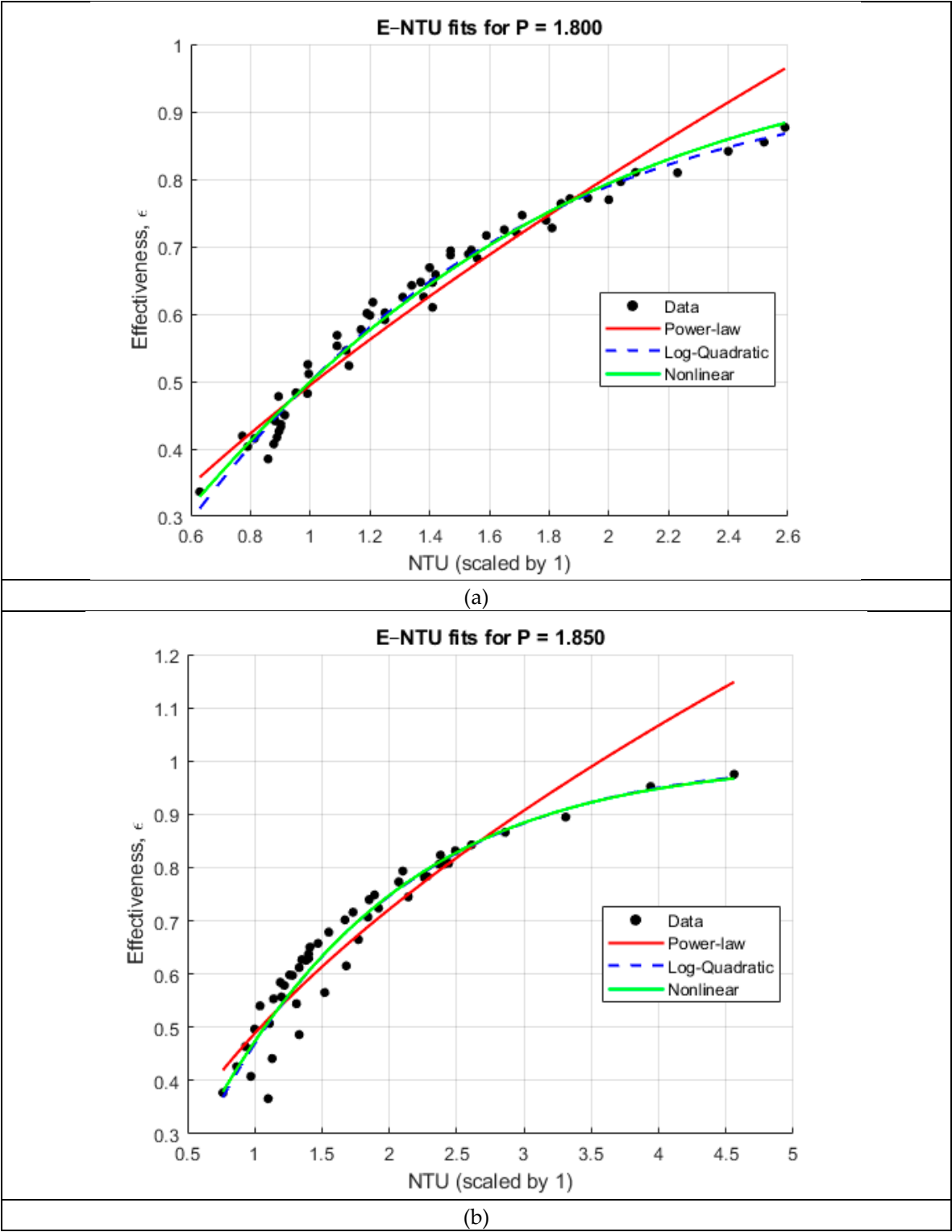
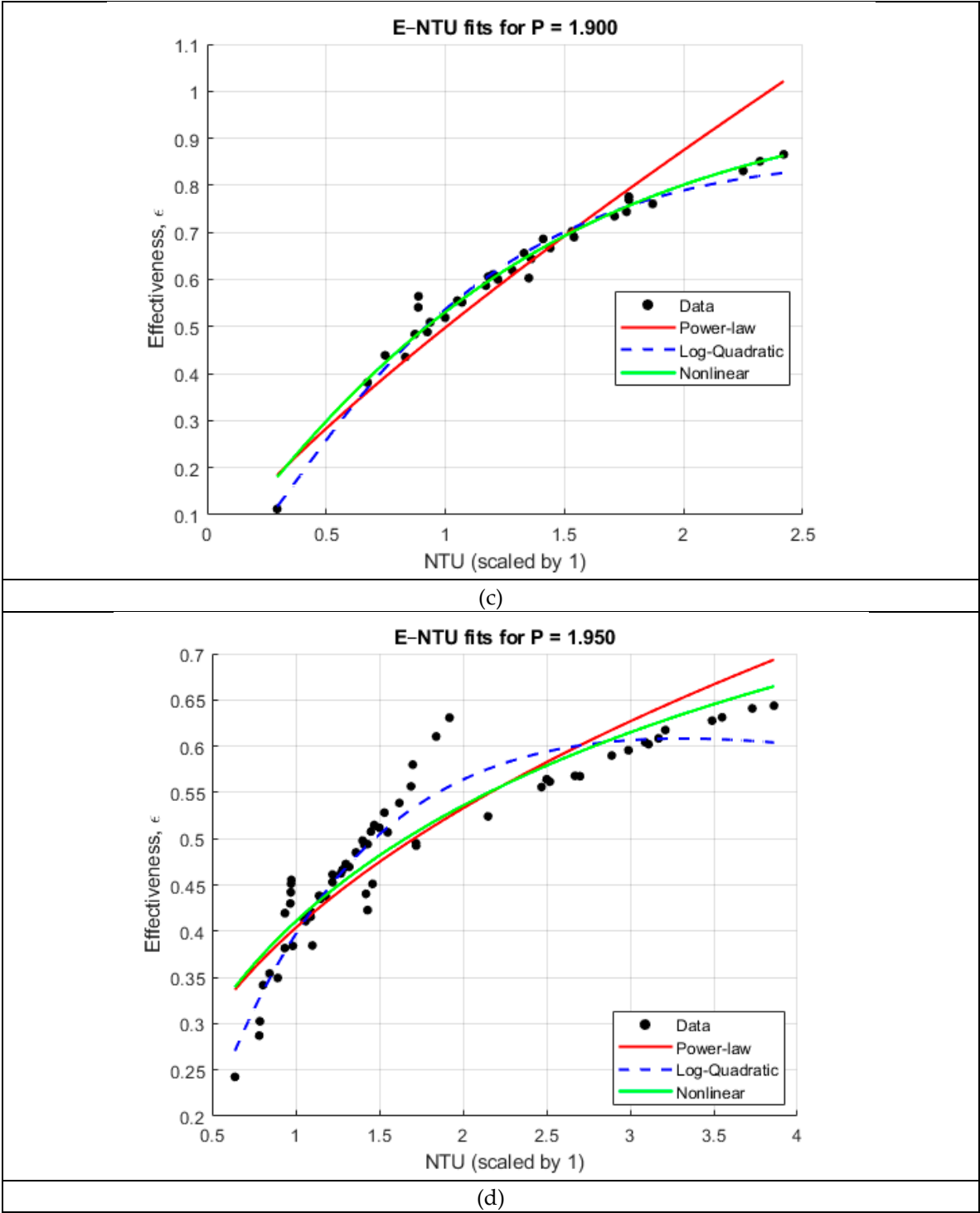


Figure 2. Raw effectiveness-NTU (ϵ -NTU) data for 2,400+ helical coil heat exchanger simulations. Effectiveness rises sharply at low NTU and gradually approaches a saturation regime at higher NTU, consistent with classical ϵ -NTU behavior. Pitch-dependent clusters indicate that coil geometry shifts the magnitude of ϵ while preserving the overall NTU-dependent trend.

The pitch-specific and global correlation analyses- Figure 3 and Figure 4, respectively, reveal several important trends regarding the dependence of heat exchanger effectiveness on the number of transfer units (NTU) and the coil pitch ratio P . When the ϵ -NTU relationship is examined separately for each pitch, all five datasets exhibit the characteristic nonlinear rise-plateau behavior predicted by classical heat exchanger theory. This motivates the use of flexible nonlinear functional forms to

correlate effectiveness. Three candidate models were tested for each pitch: a power-law relation expressed in log-log space, a log-quadratic model, and an exponential ϵ -NTU form of the type $\epsilon = 1 - \exp(-a \text{NTU}^b)$. As summarized in Table 2, the log-quadratic and nonlinear exponential models consistently provided the highest coefficient of determination, yielding R^2 values between 0.90 and 0.98 across all pitches. In contrast, the simple power-law form underpredicted the curvature of the ϵ -NTU trend for most cases and exhibited lower fidelity (R^2 between ~ 0.81 and 0.95). These results confirm that effectiveness grows rapidly with NTU at low values but transitions smoothly into a diminishing-returns regime—behavior that is naturally captured by exponential and logarithmic formulations.





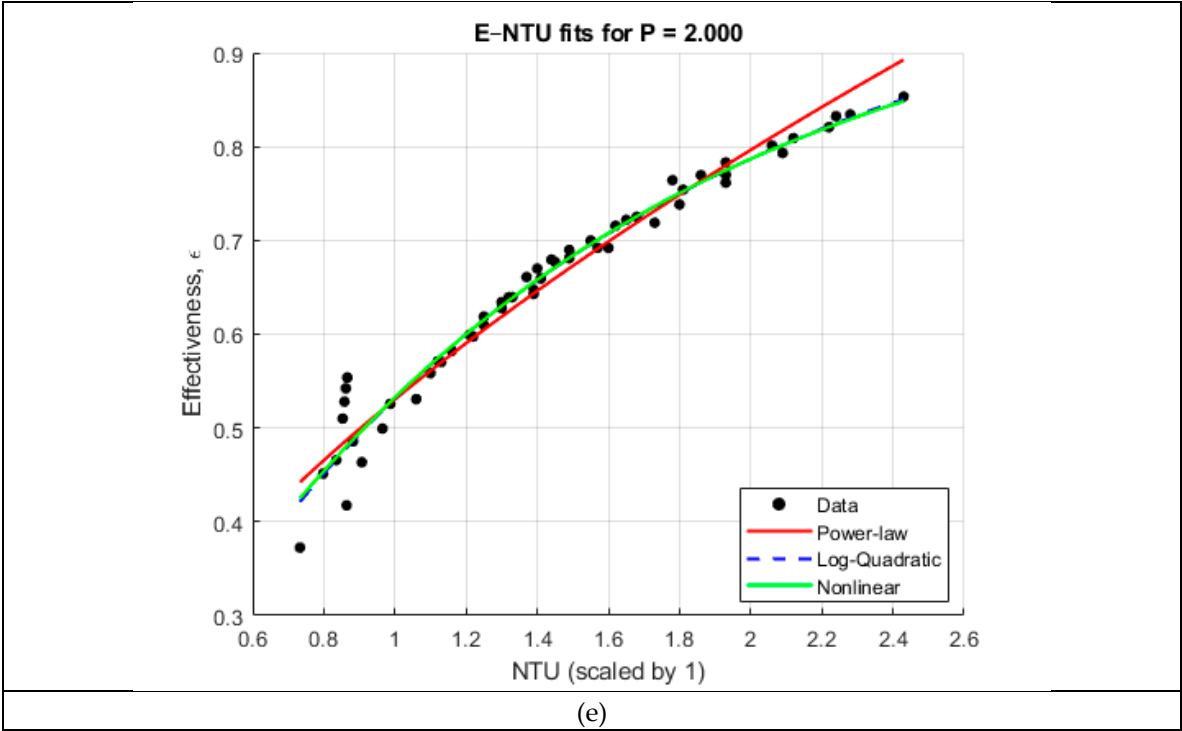


Figure 3. Pitch-specific ϵ -NTU curve-fitting results for (a) $P = 1.80$, (b) $P = 1.85$, (c) $P = 1.90$, (d) $P = 1.95$, and (e) $P = 2.00$. For each pitch, the raw effectiveness data are compared against three candidate models: a power-law relation in log-log form, a log-quadratic polynomial in $\log(\text{NTU})$, and a nonlinear exponential ϵ -NTU expression of the form $\epsilon = 1 - \exp(-a \text{NTU}^b)$.

P	Model	Correlation	Constants	R ²
1.80	Power-law	$E = \exp(-0.7083) * \text{NTU}^{0.7011}$	$A=\exp(-0.7083)$, $B=0.7011$	0.9419
1.80	Log-Quadratic	$\log(E) = -0.6938 + 0.8775 \log(\text{NTU}) - 0.3132(\log(\text{NTU}))^2$	$c0=-0.6938$, $c1=0.8775$, $c2=-0.3132$	0.9814
1.80	Nonlinear	$E = 1 - \exp(-0.6919 * \text{NTU}^{1.19})$	$a=0.6919$, $b=1.19$	0.9789
1.85	Power-law	$E = \exp(-0.7167) * \text{NTU}^{0.5635}$	$A=\exp(-0.7167)$, $B=0.5635$	0.8708
1.85	Log-Quadratic	$\log(E) = -0.757 + 0.8329 \log(\text{NTU}) - 0.2338(\log(\text{NTU}))^2$	$c0=-0.757$, $c1=0.8329$, $c2=-0.2338$	0.9306
1.85	Nonlinear	$E = 1 - \exp(-0.6411 * \text{NTU}^{1.104})$	$a=0.6411$, $b=1.104$	0.9305
1.90	Power-law	$E = \exp(-0.6972) * \text{NTU}^{0.8128}$	$A=\exp(-0.6972)$, $B=0.8128$	0.8503
1.90	Log-Quadratic	$\log(E) = -0.6225 + 0.8049 \log(\text{NTU}) - 0.3577(\log(\text{NTU}))^2$	$c0=-0.6225$, $c1=0.8049$, $c2=-0.3577$	0.9709
1.90	Nonlinear	$E = 1 - \exp(-0.7572 * \text{NTU}^{1.093})$	$a=0.7572$, $b=1.093$	0.9729
1.95	Power-law	$E = \exp(-0.9076) * \text{NTU}^{0.4010}$	$A=\exp(-0.9076)$, $B=0.4010$	0.8134
1.95	Log-Quadratic	$\log(E) = -0.9247 + 0.714 \log(\text{NTU}) - 0.2981(\log(\text{NTU}))^2$	$c0=-0.9247$, $c1=0.714$, $c2=-0.2981$	0.8906
1.95	Nonlinear	$E = 1 - \exp(-0.5283 * \text{NTU}^{0.538})$	$a=0.5283$, $b=0.538$	0.8454
2.00	Power-law	$E = \exp(-0.6339) * \text{NTU}^{0.5861}$	$A=\exp(-0.6339)$, $B=0.5861$	0.9570
2.00	Log-Quadratic	$\log(E) = -0.6312 + 0.6937 \log(\text{NTU}) - 0.1859(\log(\text{NTU}))^2$	$c0=-0.6312$, $c1=0.6937$, $c2=-0.1859$	0.9669
2.00	Nonlinear	$E = 1 - \exp(-0.7603 * \text{NTU}^{1.024})$	$a=0.7603$, $b=1.024$	0.9668

A global correlation incorporating both NTU and pitch, parameterized in the form $\log(\epsilon) = f[P, \log(\text{NTU})]$, was also developed (Figure 4 & Table 3), as follows:

$$\log(\epsilon) = \beta_0 + \beta_1 \log(\text{NTU}) + \beta_2 P + \beta_3 [\log(\text{NTU})P]$$

(8)

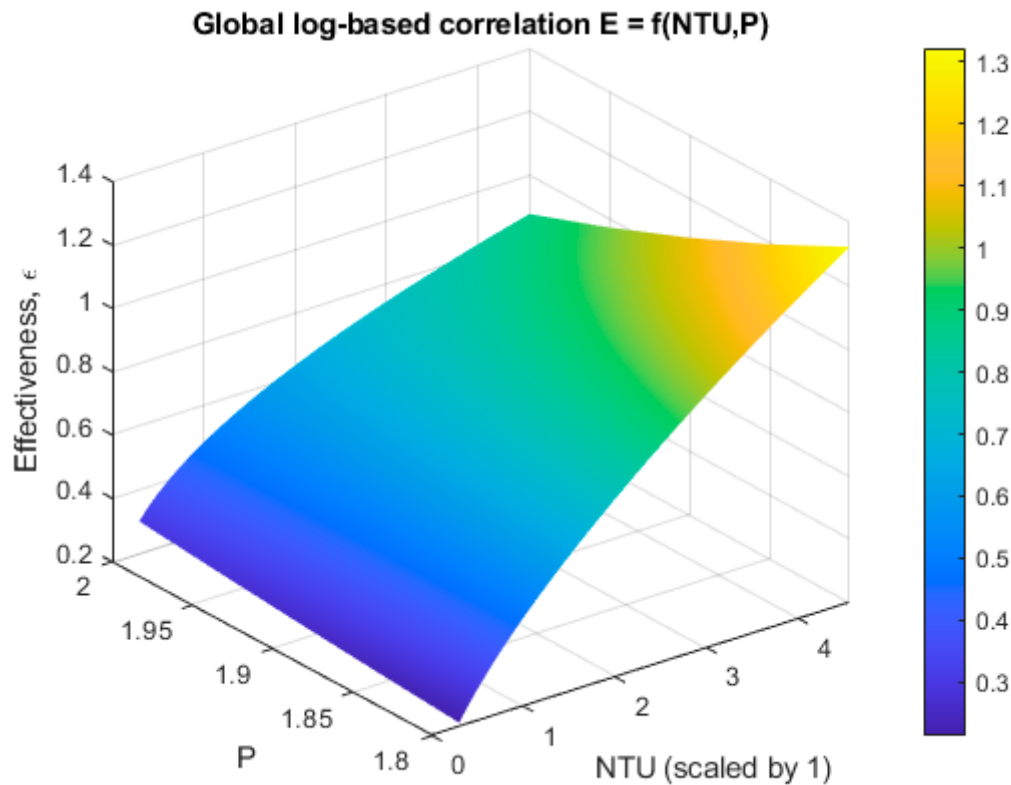


Figure 4. Global log-based regression surface obtained from the model $\log(\epsilon) = \beta_0 + \beta_1 \log(\text{NTU}) + \beta_2 P + \beta_3 [\log(\text{NTU})P]$. The surface illustrates the monotonic increase of effectiveness with NTU and the upward shift associated with larger pitch ratios. Although the model captures the overall trend, the predicted surface exhibits smooth averaging and underestimates localized nonlinear curvature, resulting in moderate global accuracy ($R^2 = 0.5883$ in ϵ -space).

Table 3. Global ϵ -NTU- P correlation coefficients for the log-based regression model.

Term	Estimate (β)	Std. Error	t-Statistic	p-Value
Intercept (β_0)	-0.77347	0.35255	-2.1939	0.029154
$\log(\text{NTU})$ (β_1)	3.1351	0.74153	4.2278	3.30×10^{-5}
P (β_2)	0.024367	0.1853	0.1315	0.89549
$\log(\text{NTU}) \cdot P$ (β_3)	-1.3723	0.38933	-3.5248	0.00050325
Model Summary				
Metric		Value		
Root Mean Squared Error (RMSE)		0.162		
R^2 (log-space)		0.633		
Adjusted R^2		0.629		
R^2 (converted to ϵ -space)		0.5883		
F-statistic p-value		1.33×10^{-54}		

While the linear log-based model successfully reproduced the general monotonic dependence of ϵ on NTU and the upward shift associated with increasing pitch, its overall predictive capability

($R^2 \approx 0.63$ in ϵ -space) is significantly weaker than that of the pitch-specific nonlinear fits. The relatively modest performance of the global linear model suggests that the ϵ -NTU- P relationship is inherently nonlinear in both variables and cannot be fully captured by a first-order log-linear regression.

To address this limitation, machine-learning-based regressors—Generalized Additive Models (GAM) and bagged decision-tree ensembles—were applied using $\{\log(\text{NTU}), P\}$ as predictors. These models provided substantially improved accuracy, achieving R^2 values of 0.91 (Ensemble) to 0.94 (GAM), with a combined GAM-Ensemble predictor producing the highest fidelity ($R^2 = 0.945$), as demonstrated in Figure 5 with the analytical formulations in Table 4. The machine-learning models effectively reproduced the nonlinear ϵ -NTU curvature and the subtle pitch-dependent variations without imposing a restrictive analytical structure. Their predictive smoothness and low residual errors confirm that the underlying functional relationship is moderately complex and exhibits mild interaction between NTU and pitch—features that the GAM and Ensemble frameworks are well suited to represent.

Taken together, these results indicate that (i) pitch-specific exponential/logarithmic correlations provide the most accurate closed-form predictive models, (ii) the ϵ -NTU- P surface is globally nonlinear and not easily captured by simple algebraic expressions, and (iii) modern regression techniques (GAM/Ensemble) offer high predictive accuracy for surrogate modeling or reduced-order simulations. The correlation coefficients, best-fit parameters, and performance metrics shown in Table X provide a compact summary of the model forms and their relative merits for engineering use.

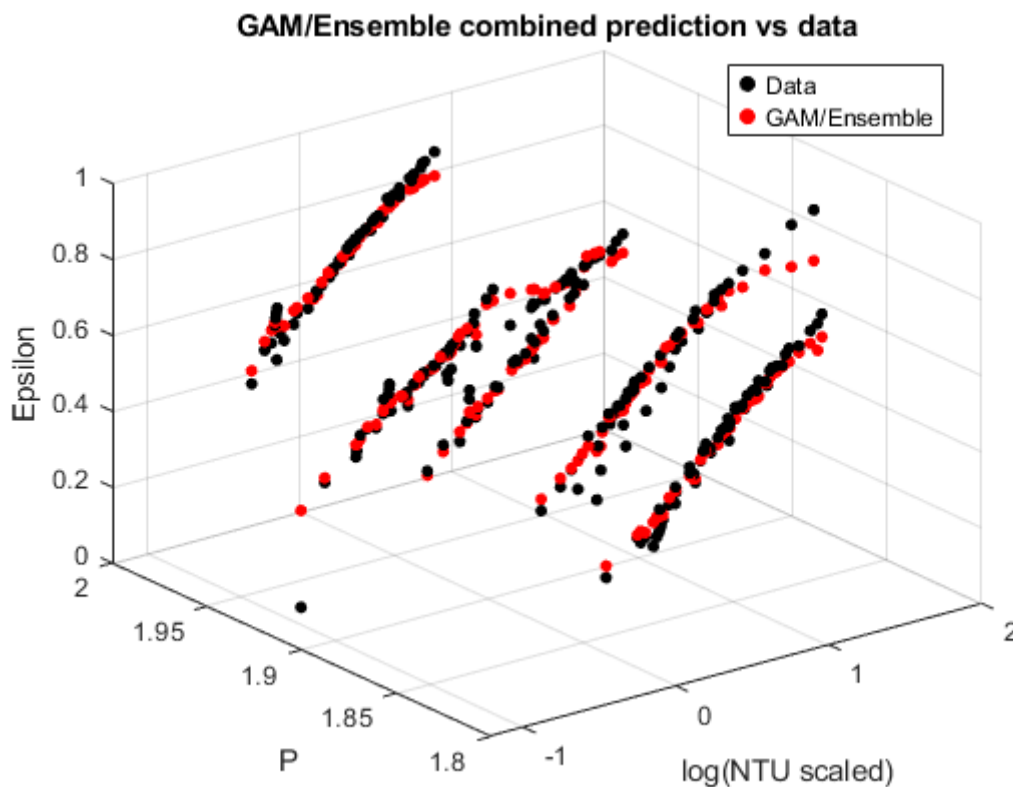


Figure 5. Comparison of data (black markers) and combined GAM/Ensemble predictions (red markers) in the $(\log \text{NTU}, P, \epsilon)$ domain. The GAM model achieves $R^2 = 0.9444$, while the Bagged Ensemble achieves $R^2 = 0.9138$; their averaged prediction attains the highest overall fidelity ($R^2 = 0.9453$). The combined model accurately reproduces both the nonlinear ϵ -NTU curvature and the pitch-dependent separation between curves, demonstrating the superiority of flexible machine-learning models over linear log-based regression for global correlation of effectiveness.

Table 4. Summary of Global GAM and Ensemble Correlation Models for $\epsilon = f(\log(\text{NTU}), P)$.

Model	Predictors	Functional Description	Performance
GAM (Generalized Additive Model)	$\log(\text{NTU}), P$	$\epsilon(x,p) = s_1(x) + s_2(p) + s_3(x,p)$ $x = \log(\text{NTU})$ s_1 : smoothing spline (edf ≈ 3.9) s_2 : smoothing spline (edf ≈ 1.0) s_3 : tensor-product spline (edf ≈ 3.0)	$R^2 = 0.9444$ RMSE = 0.085
Ensemble (Bagging Regression Trees)	$\log(\text{NTU}), P$	Bagged CART regression trees (~100 trees) MinLeafSize tuned tree depth 6–12	$R^2 = 0.9138$ RMSE = 0.109
Combined GAM + Ensemble Model	$\log(\text{NTU}), P$	$\epsilon_{\text{comb}} = 0.5 \cdot \epsilon_{\text{GAM}} + 0.5 \cdot \epsilon_{\text{Ens}}$ (average of two ML predictions)	$R^2 = 0.9453$ RMSE = 0.078

Concluding Remarks

This study has established a numerically validated ϵ –NTU database for helically coiled tube-in-shell heat exchangers based on more than 2,400 laminar CFD simulations, enabling a detailed assessment of how morpho-hydrodynamic variations shape global thermal performance. Across all geometries, effectiveness exhibits the classical rising–plateau dependence on NTU, while coil pitch primarily introduces vertical shifts in ϵ rather than altering the overall trend. This structure is captured accurately by pitch-specific log-quadratic and exponential ϵ –NTU correlations, which achieve R^2 levels up to 0.98 and offer closed-form models suitable for engineering design and sensitivity studies. At the same time, attempts to represent the full ϵ –NTU–pitch surface using a simple log-linear regression reveal only moderate predictive capability, confirming that the global response is inherently nonlinear and includes weak but non-negligible interactions between NTU and geometry. By contrast, generalized additive models and bagged ensembles trained on $\log(\text{NTU})$ and pitch replicate both the nonlinear ϵ –NTU curvature and pitch-dependent offsets with high accuracy, and their combined prediction provides a robust, low-error surrogate for the entire dataset. Together, these results suggest a two-tier modeling strategy: use the compact pitch-specific correlations when closed-form expressions are required, and employ the GAM/Ensemble surrogate when maximum predictive accuracy is needed for optimization, uncertainty quantification, or system-level integration of helically coiled tube heat exchangers.

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