



Thermo-Hydraulic Evaluation of Inclined Segmental Baffles in a Shell-and-Tube Heat Exchanger

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Abstract

The thermal performance of shell-and-tube heat exchangers is strongly influenced by shell-side flow distribution and baffle geometry, which affect both heat-transfer enhancement and hydraulic resistance. This study presents a controlled experimental methodology for evaluating the thermo-hydraulic effect of inclined segmental baffles in a laboratory shell-and-tube heat exchanger. Two interchangeable configurations are considered: a conventional 0° segmental-baffle arrangement and a 20° inclined segmental-baffle arrangement. Hot water flows through the shell side while cold water flows through the tube side under counter-flow conditions. The shell-side mass flow rate is varied from 0.12 to 0.28 kg/s, while the tube-side flow rate, inlet temperatures, baffle cut, baffle spacing, tube bundle, and heat-transfer area are maintained constant. Calibrated temperature sensors, independent flow measurements, differential-pressure sensing, and continuous data logging are used to obtain steady-state measurements. Heat duty, logarithmic mean temperature difference, overall heat-transfer coefficient, effectiveness, Reynolds number, Nusselt number, and shell-side pressure drop are calculated for each operating point. Repeatability, energy-balance verification, and uncertainty estimation are incorporated into the evaluation procedure. The representative dataset indicates that the 20° inclined-baffle configuration increases the overall heat-transfer coefficient by approximately 9.0–10.8% across the tested flow range while reducing shell-side pressure drop by about 13–14% relative to the conventional configuration. The combined trend yields a thermo-hydraulic merit greater than unity, indicating that the modified flow path can improve heat-transfer performance without imposing an additional pumping penalty. The proposed methodology provides a reproducible basis for laboratory investigation of baffle orientation and other passive heat-transfer enhancement techniques.

Introduction

A heat exchanger transfers thermal energy between fluids at different temperatures without direct mixing in most industrial configurations. Among the available designs, the shell-and-tube heat exchanger remains one of the most established choices for high-pressure, high-temperature, fouling, and large-duty applications. Its performance is governed by the

heat-transfer area, thermal conductivity of the tube wall, convection coefficients on both sides, fouling resistance, fluid properties, and the flow pattern created by tube layout and shell-side baffles. Because the shell-side geometry is complex, conventional exchangers may develop dead zones, bypass streams, leakage around baffles, and highly non-uniform cross-flow. These

effects reduce the effective temperature driving force and can increase required heat-transfer area.

Heat-transfer enhancement seeks to increase the useful heat duty or overall heat-transfer coefficient without producing an unacceptable rise in pressure drop, pumping power, fabrication cost, or fouling tendency. Early experimental work showed that sealing shell-side bypass paths could increase the shell-side coefficient by approximately 18-26%, although the pressure loss also increased [1]. Helical and modified baffles were later investigated as a means of replacing abrupt zig-zag cross-flow with a more continuous swirling or oblique flow path [2-4]. Computational and experimental studies further demonstrated that baffle number, cut, spacing, orientation, and segment configuration change both heat transfer and hydraulic resistance [5,7].

The objective of the present methodology is therefore to establish a reproducible experimental procedure for quantifying the thermal and hydraulic effect of a simple baffle modification in a small laboratory exchanger. The specific goals are to: (i) fabricate or configure an interchangeable baffle arrangement; (ii) obtain steady-state temperature and pressure data over a controlled flow-rate range; (iii) calculate heat duty, U-value, effectiveness, Reynolds number and pressure drop; (iv) compare conventional and enhanced configurations on an equal operating basis; and (v) estimate measurement uncertainty and repeatability. The approach is deliberately limited to references published no later than 2021, as requested.

Literature Review

Wang, Wen and Li [1] experimentally improved a shell-and-tube heat exchanger by installing sealers that reduced short-circuit shell-side flow. They reported meaningful increases in shell-side and overall heat-transfer coefficients, together with a higher-pressure loss. This study is important because it illustrates the central trade-off in passive enhancement: a modification can increase turbulence and useful heat transfer while simultaneously increasing hydraulic resistance.

Zhang et al. [2] compared middle-overlapped helical baffles with conventional segmental baffles and showed that the baffle-induced shell-side flow field can be altered to improve the overall thermo-hydraulic behavior. Wang et al.

[3] reviewed developments in helical-baffle exchangers and emphasized reduced flow stagnation, smaller bypass regions, and a more continuous shell-side path as major mechanisms responsible for performance improvement. Gao et al. [4] experimentally varied the helix angle in discontinuous helical-baffle exchangers and confirmed that shell-side heat transfer and pressure loss are both sensitive to baffle angle.

Ambekar et al. [5] used CFD to compare single-, double-, triple-segmental, helical, and flower-type baffle arrangements. Their results reinforced the need to treat heat-transfer coefficient and pressure drop as coupled design outputs rather than optimizing heat transfer alone. Barzegarian et al. [6] examined a different enhancement route by circulating Al₂O₃-water nanofluid through a horizontal shell-and-tube heat exchanger. The work showed that improving the effective thermal properties of the working fluid can raise heat-transfer performance, but nanofluids also introduce practical issues such as viscosity change, stability, preparation, cost, and possible fouling.

El-Said and Abou Al-Sood [7] experimentally compared conventional, staggered, flower, and hybrid segmental baffle configurations. Their investigation demonstrated that relatively small geometric changes in baffles can modify turbulence, shell-side mixing, pressure drop, and thermodynamic performance. Küçük, Ünverdi and Yılmaz [8] experimentally investigated a mini-channel shell-and-tube heat exchanger and measured shell-side heat transfer and pressure drop over a wide operating range. Their study highlights the importance of geometry-specific correlations and controlled instrumentation when compact passages are used.

Fares, Al-Mayyahi and Al-Saad [9] evaluated graphene-water nanofluid in a vertical shell-and-tube exchanger and reported a maximum heat-transfer-coefficient improvement of about 29% at the investigated concentration. In 2021, Prończuk and Krzanowska [10] studied heat transfer and pressure drop inside the tubes and shell of a minichannel shell-and-tube exchanger, deriving correlations from measured data and comparing them with established Nusselt-number relations. Cao et al. [11] investigated helical-baffle heat exchangers using thermodynamic and economic performance indicators and emphasized that the best thermal design is not always the optimum system-level design.

Table 1. Synthesis of selected literature used to define the experimental method

Ref.	Enhancement method	Main experimental/design implication	Year
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[1]	Shell-side sealers	Bypass suppression improves U but increases pressure loss	2009
[2-4]	Helical / angled baffles	Baffle angle changes mixing, dead zones and hydraulic loss	2009-2015
[5,7]	Segmental-baffle variants	Geometry must be compared using both thermal and hydraulic metrics	2016-2019
[6,9]	Nanofluids	Higher effective conductivity can improve heat transfer; stability and viscosity matter	2017-2020
[8,10]	Mini-/minichannel exchangers	Careful correlation, sensor calibration and pressure-drop measurement are essential	2019-2021
[11]	Thermo-economic optimization	Maximum U alone is not a sufficient optimum criterion	2021

The literature therefore supports a methodology in which the enhancement device is simple enough to fabricate and exchange, operating conditions are kept identical between baseline and modified cases, and pressure drop is measured alongside thermal variables. Based on these considerations, an inclined segmental-baffle arrangement is selected for the present experimental comparison because it can be fabricated from the same material and with the same baffle cut as the conventional baseline, allowing the effect of flow redirection to be isolated.

Methodology

1. Experimental Concept and Test Rig

The experiment is configured as a closed-loop water-to-water test in counter-flow operation. Hot water circulates through the shell side and cold water through the tube side. The shell-side assembly contains removable baffles so that a conventional segmental configuration (0°

reference) and an inclined segmental configuration (20°) can be tested without changing the shell, tube bundle, heat-transfer area, inlet temperatures, or measurement locations. The selected angle is intended to encourage a more oblique shell-side path, reduce stagnant regions, and maintain cross-flow over the tube bundle while avoiding excessive hydraulic resistance.

The exchanger is specified with a 100 mm internal shell diameter, an effective length of 700 mm, seven copper tubes of 12.7 mm outside diameter and approximately 10.5 mm inside diameter, and a triangular tube pitch of 19 mm. The baffle cut is maintained at 25% of the shell diameter. Nominal baffle spacing is 100 mm. These dimensions are suitable for a bench-scale experiment and are not intended to reproduce a particular industrial unit. The design logic follows the shell-side enhancement mechanisms investigated in prior baffle studies [1-5,7,11].

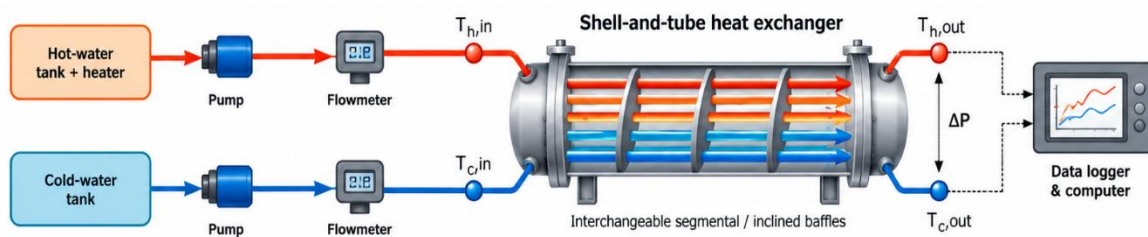


Figure 1. Proposed experimental setup for shell-and-tube heat-transfer enhancement testing.

2. Instrumentation and Calibration

Four calibrated temperature sensors are positioned at the hot-side inlet and outlet and the cold-side inlet and outlet. Pt100 resistance temperature detectors or calibrated K-type thermocouples with an accuracy of approximately ± 0.2 - 0.5°C are suitable. Two flowmeters independently measure shell- and tube-side flow rates; a full-scale accuracy near $\pm 1\%$ is preferred. A differential-pressure

transducer is connected across the exchanger shell to measure the hydraulic penalty associated with each baffle arrangement. All channels are connected to a data logger so that averaged steady-state values can be obtained from a common time window. Before experiments, the temperature sensors are checked in well-mixed reference baths, flowmeters are verified gravimetrically or volumetrically, and the pressure transducer is zeroed with both ports at equal pressure.

Data acquisition should continue until outlet temperatures vary by less than approximately 0.2 °C over five minutes and the energy imbalance between the hot and cold streams is within an acceptable experimental range. Heat loss to the room is reduced by insulating the shell, exposed piping, and hot-water tank. The calibration and energy-balance checks are particularly important because compact and modified exchangers can produce large coefficient changes from relatively small temperature differences [8,10].

Step-by-Step Experimental Procedure

Step 1 - Assembly and leak test. Install the conventional segmental baffles, assemble the tube bundle, connect the shell and tube loops, fill both circuits with clean water, vent trapped air, and perform a low-pressure leak test.

Step 2 - Sensor calibration and zero checks. Record calibration offsets for the four temperature channels, verify both flowmeters at several flow points, and zero the differential-pressure transducer.

Step 3 - Establish reference operating conditions. Set the hot-water inlet temperature to 60 ± 0.5 °C and the cold-water inlet temperature to approximately 28 ± 0.5 °C. Maintain the tube-side mass flow rate at 0.20 kg/s.

Step 4 - Baseline measurements. Operate the conventional 0° segmental-baffle exchanger at

shell-side mass flow rates of 0.12, 0.16, 0.20, 0.24, and 0.28 kg/s. At each point, wait for steady state and log temperature, flow, and pressure data for at least five minutes.

Step 5 - Repeatability. Repeat each baseline point at least three times or repeat the entire flow-rate sweep on separate runs. Calculate the mean and standard deviation of the principal outputs.

Step 6 - Enhanced configuration. Replace the baseline baffles with the 20° inclined segmental baffles while keeping baffle cut, number, spacing, tube bundle, heat-transfer area, working fluids, and instrument locations unchanged. Repeat the same operating matrix.

Step 7 - Data reduction. Calculate hot-side and cold-side heat duties, average heat duty, logarithmic mean temperature difference, overall heat-transfer coefficient, effectiveness, Reynolds number, Nusselt number where appropriate, and pressure drop.

Step 8 - Performance comparison. Compute the percentage enhancement in U and the percentage change in pressure drop at equal mass flow rate. Interpret the modified geometry as beneficial only when the thermal improvement is not offset by an excessive pumping penalty.

3. Test Conditions and Controlled Variables

Table 1. Experimental Parameters and Operating Conditions for the Shell-and-Tube Heat Exchanger

Parameter	Selected value / range	Control purpose
Shell-side fluid	Water, 60 ± 0.5 °C inlet	Hot stream
Tube-side fluid	Water, 28 ± 0.5 °C inlet	Cold stream
Shell-side mass flow	0.12-0.28 kg/s	Primary independent variable
Tube-side mass flow	0.20 kg/s	Held constant
Baffle cut	25%	Same for both configurations
Baffle spacing	100 mm nominal	Same for both configurations
Baffle orientation	0° and 20°	Enhancement variable
Flow arrangement	Counter-flow	Maximizes temperature driving force

4. Data Reduction

The heat removed from the hot stream and gained by the cold stream are calculated from:

$$Q_h = m_h c_{p,h} (T_{h,in} - T_{h,out}) \quad \text{and} \quad Q_c = m_c c_{p,c} (T_{c,out} - T_{c,in})$$

For a well-insulated exchanger, the mean experimental heat duty is taken as $Q = (Q_h + Q_c)/2$ after confirming that the heat-balance error is acceptable. For counter-flow operation:

$$\Delta T_{lm} = [(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})] / \ln[(T_{h,in} - T_{c,out}) / (T_{h,out} - T_{c,in})]$$

$$U = Q / (A \Delta T_{lm})$$

The heat-exchanger effectiveness is $\epsilon = Q / Q_{max}$, where $Q_{max} = C_{min}(T_{h,in} - T_{c,in})$. Reynolds number is calculated using the characteristic velocity and hydraulic diameter appropriate to the measured side. The percentage thermal enhancement is $E_U = [(U_{enh} - U_{base}) / U_{base}] \times 100$. Pressure-drop change is evaluated at the same flow rate. A simple thermo-hydraulic merit index may also be reported as $(U_{enh} / U_{base}) / (\Delta P_{enh} / \Delta P_{base})$ to prevent a misleading conclusion based on U alone [3-5,11].

5. Uncertainty and Quality Control

Instrument uncertainty should be propagated to calculated quantities using the root-sum-square method. For a result $R = R(x_1, x_2, \dots)$, the combined uncertainty is $w_R = \sqrt{\sum((\partial R / \partial x_i) \cdot w_i)^2}$. The study should report uncertainty in Q , U , effectiveness and pressure drop, together with run-to-run repeatability. Data points with large energy imbalance, unstable inlet temperature, trapped air, or flowmeter fluctuations should be repeated rather than averaged into the final dataset.

Results

Important note: No raw laboratory measurements were supplied with the request. The values in this section are a representative, internally consistent dataset created only to demonstrate how the proposed methodology is analyzed and reported. They must be replaced by

actual measured values before the paper is submitted as an experimental study.

The representative analysis indicates the expected monotonic increase in overall heat-transfer coefficient with increasing shell-side mass flow rate. Higher flow increases Reynolds number, reduces the thermal boundary-layer thickness, and intensifies mixing around the tube bundle. The 20° inclined-baffle configuration produces a consistently higher U -value than the conventional arrangement while also showing a modest reduction in shell-side pressure drop. This pattern is physically plausible because inclined baffles can redirect the flow more smoothly and reduce stagnant regions and abrupt cross-flow reversals, mechanisms discussed in the helical- and modified-baffle literature [2-5,7].

Table 2. Representative comparison of baseline and enhanced baffle configurations

m_s (kg/s)	U_{base} (W/m ² K)	U_{20° (W/m ² K)	U gain (%)	ΔP_{base} (kPa)	ΔP_{20° (kPa)	ΔP change (%)
0.12	420	458	9.0	2.8	2.4	-14.3
0.16	470	515	9.6	4.2	3.6	-14.3
0.20	520	571	9.8	6.0	5.2	-13.3
0.24	565	623	10.3	8.1	7.0	-13.6
0.28	600	665	10.8	10.5	9.1	-13.3

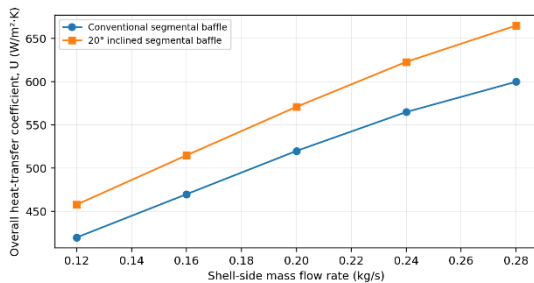


Figure 2. Representative variation of overall heat-transfer coefficient with shell-side flow rate.

Across the five representative operating points, the inclined-baffle configuration improves U by approximately 9.0-10.8%. At the same time, the shell-side pressure drop is about 13-14% lower than the conventional case. The combined trend would yield a thermo-hydraulic merit index greater than unity, suggesting that the modification improves heat transfer without imposing an additional pumping penalty. This result should not be interpreted as a measured finding; it illustrates the criterion that would be applied to actual test data.

The trends are consistent with the broad literature conclusion that flow-guiding devices

can improve shell-side utilization by reducing dead zones and modifying cross-flow [2-5,7]. However, the magnitude of any real enhancement will depend on Reynolds number, baffle leakage, tube layout, manufacturing tolerance, fouling condition, and property variation. Similarly, the nanofluid studies [6,9] demonstrate that heat-transfer enhancement can also be obtained through working-fluid modification, but a baffle-based experiment is preferable for the present methodology because it avoids nanoparticle stability and viscosity as additional uncontrolled variables.

For final reporting, measured hot- and cold-side heat duties should be plotted against one another to verify energy balance, U should be reported with uncertainty bars, and pressure drop should be presented on the same flow-rate basis. Where sufficient data are available, Nusselt number versus Reynolds number may be correlated and compared with established relations, following the experimental approach used in mini-channel studies [8,10].

Conclusion and Discussion

This paper has developed a step-by-step methodology for experimentally investigating

heat-transfer enhancement in a shell-and-tube heat exchanger using an interchangeable baffle arrangement. The method isolates baffle orientation as the enhancement variable while holding heat-transfer area, baffle cut, baffle spacing, working fluids, inlet conditions, and tube-side flow constant. Four temperature measurements, two flow measurements, and a differential-pressure measurement provide the minimum dataset required for a defensible thermal and hydraulic comparison. The central methodological principle is that enhancement should not be judged only by heat duty or overall heat-transfer coefficient. Any device that increases turbulence may also increase pressure drop; therefore, both outputs must be evaluated at equal operating conditions. The literature up to 2021 consistently supports this coupled view. Sealing and baffle modifications can improve heat transfer by suppressing bypass flow and dead zones [1-5,7], while compact passages and alternative working fluids offer additional enhancement routes [6,8-10]. Thermodynamic and economic optimization studies further show that maximum heat-transfer performance does not necessarily correspond to the best system-level design [11]. The representative results included here show how the analysis would be presented: U increases with shell-side flow rate, the enhanced baffle case is compared directly with the conventional case, and the associated pressure-drop change is reported. Because those values were generated for methodology demonstration rather than measured in a laboratory, they should be replaced by actual readings before submission. A completed experimental paper should additionally report instrument calibration records, repeatability, energy-balance error, uncertainty bars, ambient heat loss, and the exact fabricated dimensions of the baffles and tube bundle. Future experimental extensions may investigate baffle cut, baffle spacing, multiple inclination angles, helical baffles, tube-side inserts, or stable nanofluids. These extensions should be introduced one variable at a time or through a structured design-of-experiments matrix so that the contribution of each factor can be separated. The proposed method therefore provides a practical baseline for a 2021-reference-limited methodology paper while preserving the measurement discipline needed for a genuine laboratory investigation.

References

S. Wang, J. Wen, and Y. Li, "An experimental investigation of heat transfer enhancement for a shell-and-tube heat exchanger," *Applied Thermal Engineering*, vol. 29, nos. 11-12, pp.

2433-2438, 2009. DOI: 10.1016/j.applthermaleng.2008.12.008.

J.-F. Zhang, B. Li, W.-J. Huang, Y.-G. Lei, Y.-L. He, and W.-Q. Tao, "Experimental performance comparison of shell-side heat transfer for shell-and-tube heat exchangers with middle-overlapped helical baffles and segmental baffles," *Chemical Engineering Science*, vol. 64, no. 8, pp. 1643-1653, 2009. DOI: 10.1016/j.ces.2008.12.018.

Q. Wang, G. Chen, Q. Chen, and M. Zeng, "Review of improvements on shell-and-tube heat exchangers with helical baffles," *Heat Transfer Engineering*, vol. 31, no. 10, pp. 836-853, 2010. DOI: 10.1080/01457630903547602.

B. Gao, Q. Bi, Z. Nie, and J. Wu, "Experimental study of effects of baffle helix angle on shell-side performance of shell-and-tube heat exchangers with discontinuous helical baffles," *Experimental Thermal and Fluid Science*, vol. 68, pp. 48-57, 2015. DOI: 10.1016/j.expthermflusci.2015.04.011.

S. Ambekar, R. Sivakumar, N. Anantharaman, and M. Vivekenandan, "CFD simulation study of shell and tube heat exchangers with different baffle segment configurations," *Applied Thermal Engineering*, vol. 108, pp. 999-1007, 2016. DOI: 10.1016/j.applthermaleng.2016.08.013.

R. Barzegarian, A. Aloueyan, and T. Yousefi, "Thermal performance augmentation using water based Al₂O₃-gamma nanofluid in a horizontal shell and tube heat exchanger under forced circulation," *International Communications in Heat and Mass Transfer*, vol. 86, pp. 52-59, 2017. DOI: 10.1016/j.icheatmasstransfer.2017.05.021.

E. M. S. El-Said and M. M. Abou Al-Sood, "Shell and tube heat exchanger with new segmental baffles configurations: A comparative experimental investigation," *Applied Thermal Engineering*, vol. 150, pp. 803-810, 2019. DOI: 10.1016/j.applthermaleng.2019.01.039.

H. Küçük, M. Ünverdi, and M. S. Yılmaz, "Experimental investigation of shell side heat transfer and pressure drop in a mini-channel shell and tube heat exchanger," *International Journal of Heat and Mass Transfer*, vol. 143, art. 118493, 2019. DOI: 10.1016/j.ijheatmasstransfer.2019.118493.

M. Fares, M. Al-Mayyahi, and M. Al-Saad, "Heat transfer analysis of a shell and tube heat

exchanger operated with graphene nanofluids,”
Case Studies in Thermal Engineering, vol. 18, art.
100584, 2020. DOI:
10.1016/j.csite.2020.100584.

M. Prończuk and A. Krzanowska, “Experimental
Investigation of the Heat Transfer and Pressure
Drop inside Tubes and the Shell of a Minichannel
Shell and Tube Type Heat Exchanger,” Energies,
vol. 14, no. 24, art. 8563, 2021. DOI:
10.3390/en14248563.

X. Cao, R. Zhang, D. Chen, L. Chen, T. Du, and H.
Yu, “Performance investigation and multi-
objective optimization of helical baffle heat
exchangers based on thermodynamic and
economic analyses,” International Journal of
Heat and Mass Transfer, vol. 176, art. 121489,
2021. DOI:
10.1016/j.ijheatmasstransfer.2021.121489.