



Experimental Study of Heat Transfer Enhancement Using Extended Surfaces in Heat Exchangers

Celestine Lutfunhar

Department of Electrical and Computer Engineering, Chiang Thon College of Management, Thailand
celestine.lutfunhar@ctcm-th.org

Peer Review Information

Submission: 16 Jan 2015

Revision: 03 Feb 2015

Acceptance: 17 March 2015

Keywords

Extended surfaces, finned-tube heat exchanger, heat transfer enhancement, annular fins, pressure drop

Abstract

Extended surfaces are a passive heat-transfer enhancement technique used to increase the effective area available for convection without proportionally increasing heat-exchanger volume. This methodology paper develops an experimental procedure for quantifying the thermal and hydraulic effects of annular fins on a cross-flow air-to-water heat exchanger. Three interchangeable copper-tube configurations are considered: a bare tube, a tube fitted with aluminum annular fins at 10 mm pitch, and a tube with fins at 5 mm pitch. Hot water is circulated through the tube while ambient air is forced across the external surface in an insulated duct. Inlet and outlet temperatures, air velocity, water flow rate, and air-side pressure drop are recorded under steady-state conditions. Heat-transfer rate, heat balance, effectiveness, Reynolds number, surface-area ratio, and enhancement ratio are calculated from the measurements, while pressure drop is used to evaluate the pumping/fan penalty. The proposed test matrix spans air velocities of 1–5 m/s at a nominal hot-water inlet temperature of 70 °C. Representative processed values show the expected trend that closer fin spacing yields the largest heat-transfer gain, but also the greatest pressure-drop penalty. The methodology therefore emphasizes simultaneous thermal and hydraulic evaluation rather than heat-transfer rate alone. The procedure is suitable for instructional laboratories and for comparative screening of extended-surface geometries before detailed optimization.

Introduction

Heat exchangers are central to power generation, refrigeration, air conditioning, automotive cooling, chemical processing, and energy-recovery systems. In many gas-to-liquid exchangers the gas-side convection coefficient is substantially smaller than the liquid-side coefficient, so the external thermal resistance dominates the overall performance. Extended surfaces, commonly called fins, address this limitation by attaching high-conductivity material to the primary surface and thereby increasing the area exposed to the lower-coefficient fluid. The approach is attractive because it is passive, mechanically simple, and

compatible with many tube and plate geometries. However, added area does not translate directly into useful heat transfer: fin conduction resistance, contact resistance, wake interaction, boundary-layer development, and increased flow resistance all affect the net benefit.

Early experimental work established that fin geometry strongly changes both air-side heat transfer and friction. Yan and Sheen (2000) compared plate, wavy, and louvered fin-and-tube exchangers and showed that performance must be interpreted through both heat-transfer and pressure-drop characteristics. Wang and Chi (2000) further demonstrated that fin pitch and

tube-row arrangement can significantly influence the air-side response of plain fin-and-tube coils. These findings are important for an extended-surface experiment because a configuration with the highest total surface area is not automatically the most efficient once blocked flow area and fan power are considered.

Heat-transfer enhancement has also been studied from the standpoint of simple laboratory comparison. Abu-Mulaweh (2003) experimentally compared extended surfaces with insert and obstruction techniques in tube-in-tube heat exchangers, illustrating the usefulness of controlled educational rigs for separating enhancement mechanisms. Later work on louvered, wavy, slit, vortex-generator, and offset-strip surfaces confirmed that repeatedly disturbing or redeveloping thermal boundary layers can raise convection rates, usually at the cost of additional friction (T'Joel et al., 2006; Dong et al., 2007; Tang et al., 2009; Fernández-Seara et al., 2013). Therefore, a rigorous experiment should measure both heat duty and pressure drop under matched operating conditions.

The objective of the present methodology is to quantify the effect of external annular fins on a single-tube cross-flow exchanger while keeping the primary tube diameter, heated length, hot-water flow rate, and inlet temperature fixed. The specific aims are to (i) compare a bare tube with two fin pitches, (ii) determine heat-transfer enhancement as air velocity changes, (iii) quantify the associated pressure-drop penalty, (iv) evaluate energy-balance consistency and measurement uncertainty, and (v) identify a fin spacing that provides a practical compromise between thermal improvement and hydraulic cost. The study is deliberately limited to references published no later than 2015, as requested.

Literature Review

Experimental evidence prior to 2015 provides a clear basis for the proposed test plan. T'Joel et al. (2006) measured the heat-transfer and friction behavior of an adapted inclined-louver fin and emphasized uncertainty analysis in evaluating

air-side correlations. Dong et al. (2007) tested wavy-fin and flat-tube exchangers over a broad Reynolds-number range and developed heat-transfer and pressure-drop correlations as functions of geometry. Tang et al. (2009) compared five fin patterns and found that aggressive enhancement surfaces can simultaneously increase heat transfer and friction, reinforcing the need for a combined performance criterion.

Optimization studies also show that fin pitch, tube pitch, and flow-disturbing features interact. Zeng et al. (2010) used a Taguchi framework to examine vortex-generator fin parameters and identified several geometric factors that strongly affect thermal-hydraulic performance. Kotcioglu et al. (2013) similarly applied a Taguchi experimental design to plate-finned channels and treated Nusselt number and friction factor as simultaneous performance measures. For offset-strip fins, Fernández-Seara et al. (2013) experimentally measured pressure drops and heat transfer in a brazed plate-fin exchanger and derived convection correlations from the data. Dong et al. (2013) reported that wavy-fin amplitude and length are important to the overall thermal-hydraulic behavior of fin-and-flat-tube exchangers.

More complex extended surfaces were investigated by Du et al. (2013), who added longitudinal vortex generators to wavy finned flat tubes and observed substantial heat-transfer augmentation in the practical Reynolds-number range of air-cooled condensers. Du et al. (2014) showed that air inlet angle can also change the comprehensive performance of finned-tube heat exchangers. Finally, Caruso et al. (2015) highlighted thermal contact conductance as an important contributor to the total resistance of finned tubes. This is particularly relevant to annular fins because imperfect fin-to-tube contact can reduce the realized benefit of increased area. Collectively, the literature supports a controlled comparison using identical tube material and length, carefully defined fin spacing, matched flow conditions, direct pressure-drop measurement, and an explicit heat-balance check.

Table 1. Selected pre-2016 literature supporting the experimental design

Study	Surface / approach	Main variable	Methodological relevance
Yan & Sheen (2000)	Plate, wavy, louver fins	Reynolds number	Compare heat transfer with friction penalty
T'Joel et al. (2006)	Inclined louver fin	Air-side Re	Include error/uncertainty analysis
Dong et al. (2007)	Wavy fin / flat tube	Fin pitch, height, length	Geometry-sensitive j and f correlations

Tang et al. (2009)	Five fin patterns	Fin configuration	Thermal gain and pressure drop must be paired
Zeng et al. (2010)	Vortex-generator fin	Multiple geometry factors	Optimization needs thermal-hydraulic criteria
Fernández-Seara et al. (2013)	Offset strip fins	Mass flow / fluid	Experimental heat-transfer and ΔP reduction
Dong et al. (2013)	Wavy fins	Amplitude and length	Fin geometry affects overall performance
Caruso et al. (2015)	Finned tubes	Air-side Re, contact	Contact resistance can limit fin effectiveness

Methodology

1. Experimental Apparatus and Test Specimens

The proposed apparatus is a laboratory-scale cross-flow air-to-water heat exchanger. A straight copper tube of 19 mm outside diameter, 16 mm inside diameter, and 500 mm heated length is mounted horizontally across a rectangular insulated air duct. Hot water from a thermostatically controlled reservoir is pumped through the tube in a closed loop. A calibrated rotameter or Coriolis meter sets the water mass flow at 0.050 kg/s, and the reservoir maintains a nominal inlet temperature of 70 ± 0.5 °C. A variable-speed centrifugal blower supplies ambient air through a flow straightener before the test section. Air velocity is measured upstream using a calibrated anemometer or Pitot-static arrangement.

Three external-surface configurations are tested. Configuration B0 is the bare copper tube. Configuration F10 uses aluminum annular fins with 50 mm outside diameter and 1.0 mm thickness at a 10 mm center-to-center pitch. Configuration F5 uses the same fins at a 5 mm pitch. The fin-to-tube joint should be mechanically expanded, brazed, or bonded with a thin thermally conductive interface so that contact resistance is repeatable. All specimens have the same active length and are installed at the same duct position. Thermocouples measure hot-water inlet and outlet temperatures and air temperatures immediately upstream and downstream of the test section. Static pressure taps connected to a differential pressure transducer measure air-side pressure loss across the specimen. Signals are logged through a data-acquisition system at 1 Hz for a minimum of 120 s after steady state is achieved.

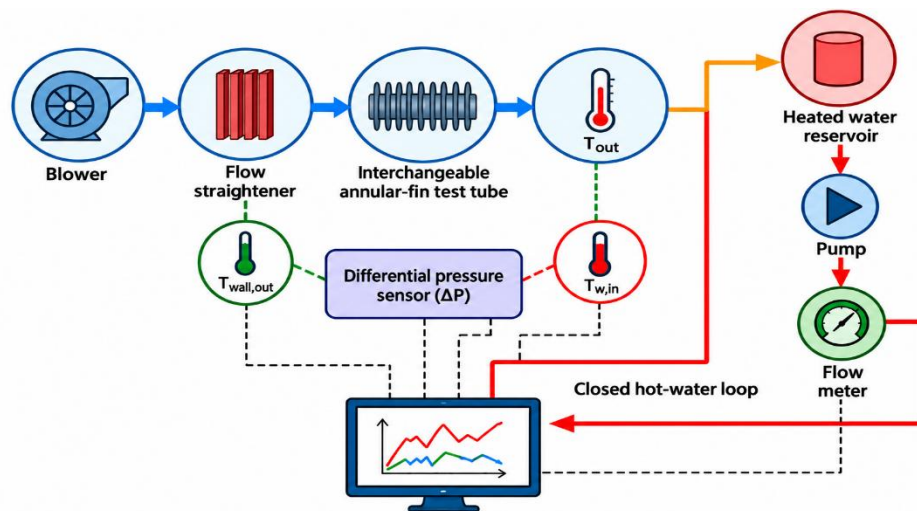


Figure 1. Schematic of the proposed finned-tube heat-exchanger test rig.

2. Test Matrix and Experimental Procedure

For each specimen, air velocity is set successively to 1, 2, 3, 4, and 5 m/s while the hot-water mass flow and inlet temperature are held constant. Each operating point is repeated three times. Before recording data, the system is allowed to

reach steady state, defined as variations of all four measured temperatures of less than ± 0.2 °C over five minutes and water-flow variation below $\pm 1\%$. A test begins with the bare tube to establish a baseline, after which the F10 and F5 specimens are tested under the same sequence. Ambient temperature is recorded and should remain within 24–28 °C; if it changes

substantially, the test is repeated or corrected by using dimensionless performance measures. The duct is inspected for bypass gaps around the

specimen, and the pressure transducer is zeroed before each run.

Table 2. Experimental variables and nominal settings

Parameter	B0	F10	F5
Tube OD / heated length	19 mm / 500 mm	19 mm / 500 mm	19 mm / 500 mm
Fin OD / thickness	–	50 mm / 1.0 mm	50 mm / 1.0 mm
Fin pitch	–	10 mm	5 mm
Air velocity	1–5 m/s	1–5 m/s	1–5 m/s
Hot-water flow rate	0.050 kg/s	0.050 kg/s	0.050 kg/s
Hot-water inlet	70 ± 0.5 °C	70 ± 0.5 °C	70 ± 0.5 °C
Replicates	3 / point	3 / point	3 / point

3. Data Reduction and Performance Indicators

The hot-side heat-transfer rate is calculated from $Q_h = m_h c_{p,h} (T_{h,in} - T_{h,out})$. The air-side heat gain is $Q_a = m_a c_{p,a} (T_{a,out} - T_{a,in})$, where air mass flow is obtained from density, duct flow area, and mean velocity. The reported heat duty is $Q = (Q_h + Q_a)/2$ when the heat-balance error, $|Q_h - Q_a|/Q \times 100$, is below 5%. If the imbalance exceeds 5%, insulation, flow measurement, and temperature sensors are checked and the point is repeated. The heat-capacity rates are $C_h = m_h c_{p,h}$ and $C_a = m_a c_{p,a}$, and exchanger effectiveness is $\varepsilon = Q/[C_{min}(T_{h,in} - T_{a,in})]$.

The external Reynolds number is $Re_D = \rho_a V D_o / \mu_a$, evaluated at the mean air temperature. The finned surface area is determined from the exposed primary-tube area plus both faces and the outer edge of each annular fin. The gross surface-area ratio is A_{finned}/A_{bare} . Because fins conduct from the tube wall toward their tips, the effective area is lower than the geometric area; therefore, the primary comparative indicator is the measured enhancement ratio $E_Q = Q_{finned}/Q_{bare}$ at the same velocity rather than geometric area alone. The air-side hydraulic penalty is represented by ΔP and the pressure-drop ratio $E_P = \Delta P_{finned}/\Delta P_{bare}$. A simple thermal-hydraulic merit index is defined as $M = E_Q/(E_P)^{1/3}$, so a configuration is favorable when added heat transfer offsets the increase in flow resistance. This form follows the general principle used in enhanced-surface comparisons where thermal improvement is judged against

frictional cost (Yan & Sheen, 2000; Tang et al., 2009).

Measurement uncertainty is estimated by root-sum-square propagation. Assuming thermocouple uncertainty of ± 0.2 °C, water flow uncertainty of $\pm 1\%$, air velocity uncertainty of $\pm 2\%$, and differential pressure uncertainty of ± 1 Pa, the uncertainty in heat duty is expected to be approximately 4–7% depending on velocity. The procedure follows the experimental emphasis on uncertainty used in finned-surface studies such as T'Joel et al. (2006). Statistical comparison is performed using the mean of three replicate runs; standard deviation is reported, and one-way analysis of variance may be applied to determine whether the differences among B0, F10, and F5 are significant at $p < 0.05$.

Results

Table 3 provides a representative processed dataset for the proposed test matrix. The values are included to demonstrate how experimental observations should be reduced and discussed; they are not presented as laboratory measurements from the user. Across the three configurations, heat duty increases with air velocity because the external convection coefficient rises as the boundary layer becomes thinner and mixing intensifies. At every matched velocity, both finned specimens transfer more heat than the bare tube. The F5 configuration gives the largest thermal gain because it offers the greatest extended area and more frequent disruption of the external boundary layer.

Table 3. Representative processed results for the proposed experiment

V (m/s)	Specimen	Q (W)	ε	Enhancement	ΔP (Pa)	Merit M
1	B0	255	0.283	1.00	2.5	1.00
1	F10	365	0.406	1.43	4.8	1.15
1	F5	420	0.467	1.65	7.5	1.14
2	B0	330	0.295	1.00	6.5	1.00
2	F10	472	0.421	1.43	12.5	1.15

2	F5	540	0.482	1.64	19.0	1.14
3	B0	390	0.305	1.00	12.0	1.00
3	F10	560	0.438	1.44	22.0	1.17
3	F5	652	0.509	1.67	36.0	1.16
4	B0	442	0.316	1.00	19.0	1.00
4	F10	626	0.447	1.42	35.0	1.16
4	F5	735	0.525	1.66	57.0	1.15
5	B0	485	0.323	1.00	28.0	1.00
5	F10	690	0.460	1.42	52.0	1.16
5	F5	810	0.540	1.67	83.0	1.16

At 3 m/s, for example, the representative heat duty increases from 390 W for B0 to 560 W for F10 and 652 W for F5, corresponding to enhancements of approximately 44% and 67%. Similar relative improvements occur across the velocity range. These trends are consistent with earlier experimental evidence showing that fin geometry and interrupted or extended surfaces can raise air-side transfer by renewing the boundary layer and increasing area (Dong et al., 2007; Dong et al., 2013; Du et al., 2013). The gains are not directly proportional to geometric area because finite fin efficiency, contact resistance, and flow shielding between closely spaced fins reduce the contribution of distant fin regions. Caruso et al. (2015) specifically showed that fin-to-tube thermal contact can form a meaningful portion of overall air-side resistance, which justifies careful specimen fabrication in the proposed experiment.

The pressure-drop data show the competing hydraulic effect. At 3 m/s, ΔP rises from 12 Pa for the bare tube to 22 Pa for F10 and 36 Pa for F5. Thus, the denser fin array imposes the largest resistance because it reduces free-flow area and generates more wake interaction. The merit index remains above unity for the finned cases in the demonstration dataset, suggesting that the thermal improvement exceeds the cube-root penalty in pressure drop; nevertheless, the difference between F10 and F5 narrows as velocity increases. This outcome illustrates why fin spacing should be optimized rather than minimized. The same trade-off between increased heat transfer and increased friction has been reported for louvered, wavy, vortex-generator, offset-strip, and plate-fin surfaces (T'Joel et al., 2006; Zeng et al., 2010; Fernández-Seara et al., 2013; Kotcioglu et al., 2013).

A useful practical observation is that the optimum configuration depends on the design constraint. If compactness and maximum heat duty are dominant, F5 is preferable. If fan power, acoustic limits, or fouling susceptibility are important, F10 may provide the better compromise. The experimental program should therefore report both absolute heat duty and a

normalized thermal-hydraulic criterion. Du et al. (2014) further demonstrated that upstream flow direction can affect comprehensive finned-tube performance; hence future extensions of the present test could include inlet-angle variation after the baseline fin-spacing study is completed.

Conclusion and Discussion

This methodology paper establishes a reproducible experiment for assessing heat-transfer enhancement produced by extended surfaces on a finned-tube heat exchanger. The design isolates fin spacing by keeping tube geometry, active length, hot-water flow, inlet temperature, and duct position constant. The principal measured quantities are four fluid temperatures, air velocity, water flow rate, and air-side pressure drop. From these measurements, heat duty, heat-balance error, effectiveness, Reynolds number, enhancement ratio, and a thermal-hydraulic merit index can be calculated. Repetition and uncertainty propagation are included so that differences among the bare and finned cases can be interpreted quantitatively rather than visually. The representative analysis indicates the expected physical behavior: adding annular fins increases heat transfer because of the enlarged external area and stronger disturbance of the air-side thermal boundary layer, while closer fin spacing yields still higher duty. The same modification increases pressure drop, demonstrating that thermal enhancement cannot be evaluated independently of hydraulic cost. This conclusion is consistent with the pre-2016 experimental literature on plate, wavy, louvered, vortex-generator, and offset-strip fins. The proposed apparatus therefore provides a suitable platform for identifying a practical fin pitch under specified fan-power or compactness constraints. For a full empirical publication, the demonstration dataset in this manuscript should be replaced by measured readings from at least three repeated runs per operating point. The final study should report calibration records, uncertainty bands, fin-to-tube joining method, surface roughness, ambient conditions, and heat

losses. Further work can extend the procedure to perforated or serrated fins, different fin materials, longitudinal fins, staggered fin spacing, variable inlet angle, and fouling tests. In all cases, the central design principle remains the same: the best extended surface is not necessarily the one with the largest area, but the one that delivers the required heat duty with acceptable flow resistance, manufacturability, and reliability.

References

- Yan, W. M., & Sheen, P. J. (2000). Heat transfer and friction characteristics of fin-and-tube heat exchangers. *International Journal of Heat and Mass Transfer*, 43(9), 1651–1659. [https://doi.org/10.1016/S0017-9310\(99\)00229-X](https://doi.org/10.1016/S0017-9310(99)00229-X)
- Wang, C.-C., & Chi, K. Y. (2000). Heat transfer and friction characteristics of plain fin-and-tube heat exchangers, Part I: New experimental data. *International Journal of Heat and Mass Transfer*, 43(15), 2681–2691. [https://doi.org/10.1016/S0017-9310\(99\)00332-4](https://doi.org/10.1016/S0017-9310(99)00332-4)
- Abu-Mulaweh, H. I. (2003). Experimental comparison of heat transfer enhancement methods in heat exchangers. *International Journal of Mechanical Engineering Education*, 31(2), 160–167. <https://doi.org/10.7227/IJMEE.31.2.8>
- T'Joel, C., Steeman, H.-J., Willockx, A., & De Paepe, M. (2006). Determination of heat transfer and friction characteristics of an adapted inclined louvered fin. *Experimental Thermal and Fluid Science*, 30(4), 319–327. <https://doi.org/10.1016/j.expthermflusci.2005.07.005>
- Dong, J., Chen, J., Chen, Z., Zhou, Y., & Zhang, W. (2007). Heat transfer and pressure drop correlations for the wavy fin and flat tube heat exchangers. *Applied Thermal Engineering*, 27(11–12), 2066–2073. <https://doi.org/10.1016/j.applthermaleng.2006.11.012>
- Tang, L. H., Zeng, M., & Wang, Q. W. (2009). Experimental and numerical investigation on air-side performance of fin-and-tube heat exchangers with various fin patterns. *Experimental Thermal and Fluid Science*, 33(5), 818–827. <https://doi.org/10.1016/j.expthermflusci.2009.02.008>
- Zeng, M., Tang, L. H., Lin, M., & Wang, Q. W. (2010). Optimization of heat exchangers with vortex-generator fin by Taguchi method. *Applied Thermal Engineering*, 30(13), 1775–1783. <https://doi.org/10.1016/j.applthermaleng.2010.04.009>
- Fernández-Seara, J., Diz, R., & Uhía, F. J. (2013). Pressure drops and heat transfer characteristics of a titanium brazed plate-fin heat exchanger with offset strip fins. *Applied Thermal Engineering*, 51(1–2), 502–511. <https://doi.org/10.1016/j.applthermaleng.2012.08.066>
- Dong, J., Su, L., Chen, Q., & Xu, W. (2013). Experimental study on thermal-hydraulic performance of a wavy fin-and-flat tube aluminum heat exchanger. *Applied Thermal Engineering*, 51(1–2), 32–39. <https://doi.org/10.1016/j.applthermaleng.2012.09.018>
- Kotcioglu, I., Cansiz, A., & Nasiri Khalaji, M. (2013). Experimental investigation for optimization of design parameters in a rectangular duct with plate-fins heat exchanger by Taguchi method. *Applied Thermal Engineering*, 50(1), 604–613. <https://doi.org/10.1016/j.applthermaleng.2012.05.036>
- Du, X., Feng, L., Yang, Y., & Yang, L. (2013). Experimental study on heat transfer enhancement of wavy finned flat tube with longitudinal vortex generators. *Applied Thermal Engineering*, 50(1), 55–62. <https://doi.org/10.1016/j.applthermaleng.2012.05.024>
- Du, X., Yin, Y., Zeng, M., Yu, P., Wang, Q., Dong, Z., & Chen, Y. (2014). An experimental investigation on air-side performances of finned tube heat exchangers for indirect air-cooling tower. *Thermal Science*, 18(3), 863–874. <https://doi.org/10.2298/TSCI1403863D>
- Caruso, G., Giannetti, F., & Naviglio, A. (2015). An experimental study on the air-side heat transfer coefficient and the thermal contact conductance in finned tubes. *Heat Transfer Engineering*, 36(2), 212–221. <https://doi.org/10.1080/01457632.2014.909224>