Colburn ‘j’ factor analysis for offset strip fins in compact heat exchangers

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Abstract. Compact heat exchangers frequently utilize offset strip fins to enhance thermal performance in constrained volumes, relying on repeated boundary layer disruption and flow mixing to achieve high convective heat transfer. This paper presents a focused numerical investigation on the *j* factor, aiming to derive correlations that account for variations in key geometric parameters such as lance length (*l*), fin height (*h*), fin thickness (*t*), and fin spacing (*s*). Numerical simulations using computational fluid dynamics were conducted across a broad range of Reynolds numbers spanning laminar, transitional, and turbulent regimes on ANSYS Fluent 2024. Using insights from the data, we derive continuous correlation expressions for *j* in terms of Reynolds number, *Re* and dimensionless geometric parameters. The resulting generalized Colburn *j* factor correlations are applicable across both laminar flow ($300 \leq Re \leq 1500$) and turbulent flow ($2000 \leq Re \leq 6000$) regimes with air being used as the fluid medium and provide a unified predictive model for OSF performance in both flow regimes. These correlations offer improved predictive accuracy and serve as robust tools for optimizing compact heat exchanger performance. The impact of pressure drop, while acknowledged as critical to overall design, is not addressed in this paper and will be explored in future work.

Keywords: Compact Heat Exchangers, Offset Strip Fins, Colburn j factor, ANSYS Fluent.

1 Introduction

Compact heat exchangers (CHEs) are critical in applications ranging from aerospace and automotive thermal management to cryogenics and power generation. Their ability to pack large heat transfer area into a small volume allows high heat transfer rates with minimal size and weight. In plate-fin type CHEs, various fin surface geometries are used to enhance air-side convective heat transfer, including plain straight fins, wavy fins, louvered fins, pin fins, and offset strip fins. Among plate-fin configurations, offset strip fins (OSFs) have gained prominence due to their ability to achieve extremely high air-side heat transfer enhancement performance. It does this by forcing periodic boundary-layer disruption using interrupted fins with offset placement, which promotes mixing between core flow and wall-adjacent fluid thus yielding significantly higher convective heat transfer coefficients compared to continuous fins.

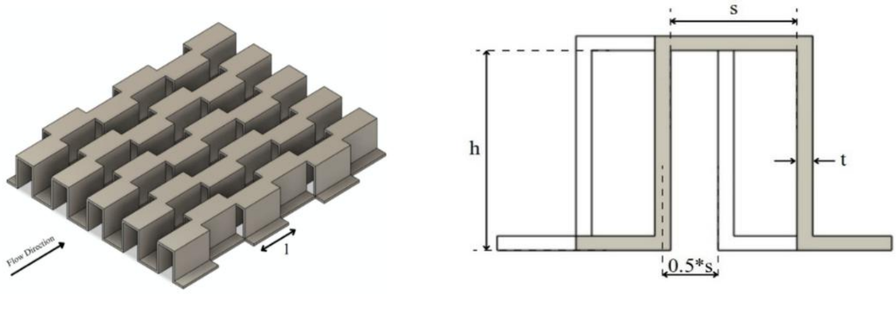
Early work by Wieting (1975) provided multi-variable *j*-factor correlations for 23 OSF geometries. Kays and London (1984) conducted extensive experiments over various plate-fin configurations (including OSFs) and produced classic design correlations. Manglik and Bergles (1995) later developed unified empirical heat-transfer correlations for rectangular OSFs across a wide Reynolds-number range, explicitly including key geometry ratios.

Even though more recent computational efforts have extended their analysis by including more diverse fin topologies, which are made possible by improvements in manufacturing procedures, the existing correlations still fail to capture the interactions between the various geometric features and overlook the complex flow and heat transfer characteristics present in the transitional Reynolds-number range. This study seeks to address these shortcomings by conducting CFD simulations over a large range of Re, while systematically varying geometric parameters to assess their influence on the j factor, with numerical results validated against established experimental benchmarks. From these simulations, generalized continuous correlations are derived as functions of Re and dimensionless parameters.

2 Methodology

2.1 Geometry

The offset strip fin geometry under study is illustrated schematically in Fig. 1. These show the primary geometric parameters of an OSF: lance length (l), height (h), thickness (t), and spacing (s). The combination of these parameters defines the fin surface area density and flow passage geometry, which in turn govern heat transfer and friction characteristics.



(a) (b)

Fig. 1. Geometric parameters of Offset Strip Fin. (a) Isometric view of OSF array, lance length (l); (b) Cross-sectional view, fin height (h), fin thickness (t), fin spacing (s).

For validation and comparison, a baseline geometry was selected from Kays and London's (1984) widely accepted database on compact heat exchanger surfaces. This configuration corresponds to a surface with the following geometric specifications mentioned in Table 1:

Table 1. Geometric parameters used for computational study.

Parameter	For validation	For numerical study	Unit
Plate Spacing (h)	6.35	5.08, 6.35, and 4.52	mm
Fin Thickness (t)	0.102	0.051, 0.102, and 0.254	mm
Fin Length (l)	3.175	2.54, 3.175, and 4.52	mm
Fin Density	15.61	13.95, 15.61, and 19.86	fins/in
Fin Spacing (s)	1.525	$\frac{25.4}{Fin\ Density} - t$	mm

A total of 1,053 CFD simulations were conducted across 81 fin geometries and 13 Reynolds numbers to assess the thermal–hydraulic performance of offset-strip fin arrays. A parametric study varied four key fin dimensions, guided by manufacturing constraints, practical spacing limits, and literature or catalog references, as detailed in Table 1.

2.2 Empirical Relations for *j*

The Colburn *j* factor is defined as:

$$j = St.Pr^{\frac{2}{3}} \tag{1}$$

Here, St is the Stanton number and *Pr* is the Prandtl number. Stanton number is also a function of Prandtl number, Nusselt number and Reynold number which is given by:

$$St = \frac{Nu}{Pr.Re} \tag{2}$$

$$\mathrm{Pr} = \frac{\mu c_p}{\kappa} \tag{3}$$

Where μ is the dynamic viscosity of the fluid and C_p is the specific heat capacity at a constant pressure of the fluid and k is the thermal conductivity of the fluid.

The Colburn-j factor equation established by Kim et al. (2011) is taken as reference for the numerical study, which is given below:

$$j = \frac{D_h}{4L} Pr^{\frac{2}{3}} \ln\left(\frac{T_w - T_{in}}{T_w - T_{out}}\right) \tag{4}$$

2.3 Governing Equations

As mentioned in Kim and Lee (2011) the standard governing equations are:

$$\frac{\partial}{\partial t}(\rho\emptyset) + \frac{\partial}{\partial x_i}(\rho u_i \emptyset) = \frac{\partial}{\partial x_i}\left(\Gamma_\emptyset \frac{\partial\emptyset}{\partial \dot{x}_i}\right) + S_\emptyset \tag{5}$$

Here, $\Gamma_\emptyset$ and $S_\emptyset$ in the general transport equation are given below in Table 2:

Equation	**$\emptyset$**	**$\Gamma_\emptyset$**	**$S_\emptyset$**
Continuity	1	0	0
u-Momentum	*u*	$\mu + \mu_t$	$-\frac{\partial p}{\partial x}$

v-Momentum	v	$\mu + \mu_t$	$-\frac{\partial p}{\partial y}$
w-Momentum	w	$\mu + \mu_t$	$-\frac{\partial p}{\partial z}$
Energy	T	$\frac{\mu}{Pr} + \frac{\mu_t}{Pr_t}$	$S_T = \frac{1}{C_p}(\mu\Phi + \rho\varepsilon)$

Table 2. Geometric parameters used for validation of computational study.

The flow is treated as steady, incompressible, and Newtonian. The continuity and Navier–Stokes equations, along with the energy equation, were solved with no body forces. Fluid properties were evaluated at the inlet temperature of 300 K. The study considered 5 different RANS turbulence models, which were used to simulate fluid flow through the baseline fin geometry described in Table 1. The k–ω SST model exhibited the lowest deviation of −4.48% when compared to Kays and London (1984) data. As reported in Aujla and Ranganayakulu (2024), the incorporation of blending function F has proven highly accurate results.

2.4 Computational Method

A representative periodic unit cell of the OSF geometry was used as the CFD domain as shown in Fig. 2(a). The side walls and bounding top/bottom planes were treated as symmetry boundaries, and a single module was modelled with periodic boundary conditions in the streamwise direction to reduce the computational effort. A uniform velocity inlet was specified at the entry and a zero-gauge pressure outlet at the exit. All fin surfaces and channel walls were set as no-slip and isothermal at 315 K, while the inlet air was 300 K. Only convective heat transfer in the fluid was considered, neglecting conduction in the fin and radiation.

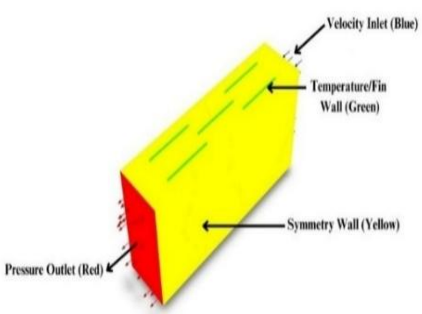


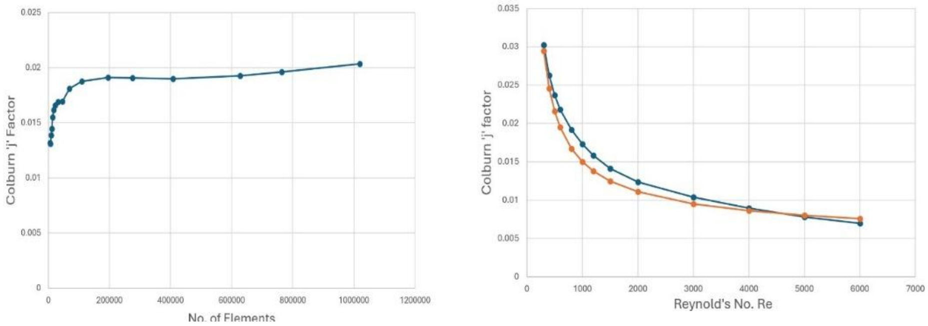
Fig. 2. Computational Domain of OSF with boundary conditions.

Simulations were performed in ANSYS Fluent 2024 under steady-state, incompressible flow conditions using the pressure-based solver. The SIMPLE algorithm handled pressure–velocity coupling. Second-order upwind schemes were used for convective terms and second-order central differencing for diffusion terms. For Re ≤ 1500, laminar flow was assumed, whereas for Re ≥ 2000 the *k–ω* SST turbulence model was employed to capture flow separation and recirculation. Convergence was judged by residuals dropping below 10^{-6} for continuity, momentum, and energy equations.

ANSYS Meshing's patch-conforming method was used to generate an unstructured tetrahedral mesh. Inflation layers with a first-layer height ~10^{-4} m were added to achieve a target $y^+ \leq 1$, depending on fin spacing and Reynolds number.

2.5 Grid Independency and Validation

Mesh independence was checked on the baseline geometry, described in Table 1, at *Re* = 800. The test was conducted for several mesh sizes ranging from ∼100,000 elements to ∼500,000 elements, and the resulting Colburn *j* factor was monitored as a function of mesh size. As shown in Fig. 3(a), the *j* factor values converge at 304,947 elements, which corresponds to an optimal element size of 0.15 mm. This mesh provided a reliable balance between accuracy and computational efficiency and was adopted for all subsequent simulations in the parametric study



(a) (b)

Fig. 3. (a) Grid independency test graph for j factor vs No. of elements. (b) Comparison between experimental and numerical results for j factor for offset strip fins.

The CFD model was validated against experimental data from Kays and London (1984) using the baseline OSF geometry (Table 1) over 300 ≤ Re ≤ 6000. Simulated Colburn *j* factors showed good agreement, with deviations within ±8% in the laminar and ±6% in the turbulent regimes (see Fig. 3b). Minor discrepancies stem from boundary condition simplifications and surface irregularities, but overall results confirm the model's accuracy.

3 Results and Discussion

The influence of dimensional parameters is interpreted using the dimensionless groups α = s/h, β = t/s, and γ = t/l, consistent with prior formulations by Manglik and Bergles (1995).The parametric study revealed that narrower fin spacing (lower *s*) and thicker fins (higher *t*) consistently led to higher j factors due to enhanced flow acceleration and frequent boundary layer disruption. Increased lance length (higher *l*) reduced interruption frequency, thereby slightly lowering *j* values. These trends were consistent across the laminar and turbulent regimes, demonstrating the significant role of geometric configuration in shaping thermal performance.

The correlations modelled using power-law expressions are mentioned below:

$$j = 0.4988 \times Re^{-0.5236} \left(\frac{t}{l}\right)^{0.3860} \left(\frac{s}{b}\right)^{-0.2837} \left(\frac{t}{s}\right)^{-0.4424} ; 300 \le Re \le 1500 : laminar\ region \quad (6)$$

$$j = 0.6734 \times Re^{-0.5424} \left(\frac{t}{l}\right)^{0.3830} \left(\frac{s}{b}\right)^{-0.2222} \left(\frac{t}{s}\right)^{-0.4502} ; 1500 \le Re \le 6000 : turbulent\ region \quad (7)$$

The correlations yield an $R^2 > 0.95$ in laminar flow and > 0.85 in turbulent flow, with a maximum deviation of 18% from the CFD analysis as illustrated in Fig. 4. These expressions are continuous across flow regimes and explicitly account for geometric parameters.

4 Conclusion

This work presents a comprehensive numerical investigation into the performance of rectangular offset strip fin in compact heat exchangers, resulting in new empirical correlations for the Colburn *j* factor. The proposed correlations are formulated in terms of Reynolds number, *Re*, and dimensionless geometric parameters, *s/b, t/s,* and *t/l*, and they capture the air-side heat transfer characteristics of OSFs across a wide range of Re in laminar, transition, and turbulent flow regimes. Validation against the classic experimental data of Kays and London (1984) confirms that the CFD-derived correlations accurately reproduce established benchmarks for the *j* factor. Compared to prior correlations in the literature, such as Manglik and Berges (1995), the present correlation framework offers improved accuracy while considering the effects of varying flow length and broader applicability by accounting for a wider range of fin geometries and Re. Thus, enabling more effective optimization of OSF configurations compared to earlier models

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