
DESIGN AND OPTIMIZATION OF A SHELL AND TUBE HEAT EXCHANGER USING PARTICLE SWARM OPTIMIZATION

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ABSTRACT

Heavy-duty haulage vehicles operating in tropical environments experience elevated engine oil temperatures that accelerate lubricant degradation and reduce engine reliability. Although Original Equipment Manufacturer (OEM) stacked-plate oil coolers provide compact thermal management, they are prone to irreversible fouling and limited serviceability under prolonged operation. Conventional shell-and-tube heat exchanger (STHE) retrofits offer improved maintainability but are generally oversized and excessively heavy, resulting in increased parasitic mass and reduced fuel efficiency. This study presents the design and optimization of lightweight STHE oil cooler for a Volvo D13 heavy-duty diesel engine using aluminum Alloy 6061-T6. Particle Swarm Optimization (PSO) was implemented in MATLAB to optimize the exchanger geometry, while the Kern design method was employed to evaluate thermal and hydraulic performance. The optimization objective was to minimize the total core weight subject to a maximum shell-side pressure drop of 50 kPa and an overall exchanger length of 1.5 m. The optimized TEMA E-shell configuration comprised 82 straight tubes (18 BWG), a shell diameter of 0.249m, a tube length of 1.471m, a tube outer diameter of 15.0 mm, and a baffle spacing of 0.064m. The resulting design achieved a total aluminum core weight of 23.80kg while maintaining shell-side and tube-side pressure drops of 49.98 kPa and 3.96 kPa, respectively, both within acceptable hydraulic limits for heavy-duty lubrication systems. The exchanger attained a thermal effectiveness of 83.3% with a Number of Transfer Units (NTU) of 2.37, demonstrating efficient heat transfer with low hydraulic resistance. The results confirm that integrating aluminum Alloy 6061-T6 with PSO-based geometric optimization significantly reduces exchanger weight while maintaining high thermal performance and hydraulic reliability. The proposed design provides a lightweight, maintainable, and locally manufacturable alternative to conventional oil coolers for heavy-duty diesel engines operating under demanding tropical conditions.

Keywords: shell-and-tube heat exchanger; particle swarm optimization; Volvo D13; heavy-duty haulage

1. INTRODUCTION

In Nigeria, heavy-duty haulage trucks are indispensable to the supply chain, facilitating approximately 95% of national freight movement (Federal Ministry of Works, 2025). However, operating in tropical Sub-Saharan environments with ambient temperatures frequently exceeding 35°C accelerates the thermal degradation of engine components. Excessive engine oil temperatures reduce lubricant viscosity, increase component wear, and ultimately shorten engine service life (Çengel & Ghajar, 2020). The Volvo D13 engine utilizes compact Original Equipment Manufacturer (OEM) stacked-plate oil coolers for thermal management; however, these sealed units are highly susceptible to irreversible fouling in dusty environments and cannot be serviced, leading to costly vehicle downtime.

Shell-and-tube heat exchangers (STHEs) provide a highly robust, maintainable alternative recommended for applications involving high operating pressures and severe environmental conditions due to their mechanical strength and serviceability (Shah & Sekulić, 2003). However, conventional STHE design heavily relies on empirical correlations like the Kern method, which utilizes conservative safety margins that frequently produce physically oversized and excessively heavy equipment (Kern, 1950). In automotive applications, this unnecessary structural mass is parasitic, increasing fuel consumption and carbon emissions, which directly conflicts with global climate change mitigation strategies for the transportation sector (IPCC, 2022).

To address these limitations, Particle Swarm Optimization (PSO) a swarm intelligence algorithm mimicking the social behaviour of bird flocks has emerged to effectively solve complex

nonlinear design problems (Kennedy & Eberhart, 1995). Previous studies demonstrate that PSO converges approximately 30% faster than Genetic Algorithms for STHE design (Fesanghary et al., 2009), consistently outperforming conventional deterministic techniques in constrained thermal design (Rao & Patel, 2010). Furthermore, automated MATLAB routines can significantly reduce material requirements within seconds. Balaban and Tadić (2021) developed a MATLAB-based automated shell-and-tube heat exchanger design program based on the Kern method. Their optimization reduced the required heat transfer area from 61.91 m² to 53.27 m², representing a 13.9% reduction in material requirement while obtaining the optimal solution within only a few seconds. Furthermore, recent evaluations of laboratory-scale STHEs operating specifically under northern Nigerian climatic conditions demonstrate the urgent need for robust computational optimisation to maximise thermal effectiveness in local applications (Hassan et al., 2025). Despite these advancements, existing literature frequently focuses on minimizing economic costs for stationary industrial applications (Khorasany & Fesanghary, 2009; Sai & Rao, 2022; Rao & Majethia, 2022). There remains a critical knowledge gap regarding weight minimization for automotive STHEs operating under strict spatial and tropical constraints.

Therefore, the aim of this study is to design and computationally optimize a lightweight STHE oil cooler retrofit for a Volvo D13 heavy-duty diesel engine. The specific objectives are to evaluate thermal-hydraulic performance using the Kern method, apply a PSO algorithm in MATLAB to minimize total aluminum core weight under strict pressure drop and spatial constraints, and validate hydraulic reliability using the Bell-Delaware method.

2. METHODOLOGY

2.1 Design Specifications and Material Selection

The shell-and-tube heat exchanger (STHE) was designed as a remote, chassis-mounted oil cooler for the 12.8-liter Volvo D13 heavy-duty diesel engine. The baseline thermal load was established at 63.0 kW, derived from a required temperature drop of 115°C to 90°C for a 1.2 kg/s mass flow rate of 15W-40 engine oil. To prioritize mechanical serviceability, the viscous engine oil was allocated to the shell side to exploit segmental baffle-induced turbulence, while the water-based engine coolant (3.0 kg/s at 85°C) was routed through the tube side because mineral scaling from coolant is effectively removed by passing a mechanical rod directly through the straight tubes, whereas the complex shell-side geometry is largely inaccessible for physical descaling. aluminum Alloy 6061-T6 was specified for both the shell and tube bundle (18 BWG, 1.25 mm wall thickness) to drastically minimize parasitic mass, leveraging its low density (2700 kg/m³) and superior strength-to-weight ratio compared to traditional carbon steel.

2.2 Mathematical Modelling

The Kern method was utilized to evaluate the thermal-hydraulic performance of the heat exchanger during optimization. The clean overall heat transfer coefficient (U_{clean}) was formulated based on the shell-side convective coefficient (h_s), the tube-side convective coefficient (h_t), and the thermal conductivity of the aluminum 6061-T6 tube wall (k_{wall}):

$$U_{clean} = \frac{1}{\frac{1}{h_s} + \frac{d_o}{d_i} \times \frac{1}{h_t} + \frac{d_o \ln\left(\frac{d_o}{d_i}\right)}{2 \times k_{wall}}} \quad (1)$$

To evaluate the hydrodynamic constraints governing the required pumping power, the actual pressure drops for both the tube-side (ΔP_t) and shell-side (ΔP_s) were continuously calculated using the fundamental Kern method equations:

$$\Delta P_s = \frac{(f_s G_s^2 (N_b + 1) D_s)}{(2 \rho_h D_e \phi_s)} \quad (2)$$

$$\Delta P_t = \left(\frac{4 f_t L n_p}{d_i} + 4 n_p \right) \left(\frac{\rho_c v_t^2}{2} \right) \quad (3)$$

Where f_s and f_t are the respective friction factors, G_s is the shell-side mass velocity, N_b is the number of baffles, D_s is the shell inside diameter, ρ_h and ρ_c are the densities of the hot and cold liquid respectively, D_e is the equivalent diameter, φ_s is the viscosity correction factor, L is the tube length, n_p is the number of tube passes, d_i is the internal tube diameter and v_t is the tube-side fluid velocity.

2.3 Optimization Problem Formulation

The objective of the PSO algorithm was to minimize the total structural weight of the STHE core ($f(X)$), expressed as the sum of the shell and tube weights:

$$\text{Minimize } f(X) = W_{\text{tubes}} + W_{\text{shell}} \quad (4)$$

To ensure the physical manufacturability and hydraulic safety of the automotive retrofit, the objective function was subjected to strict inequality constraints:

$$g_1(X) = \Delta P_s - 50 \leq 0$$

$$g_2(X) = \Delta P_t - 30 \leq 0$$

$$g_3(X) = L - 1.5 \leq 0$$

$$g_4(X) = D_s - 0.35 \leq 0$$

2.4 Particle Swarm Optimization (PSO) Implementation

The optimization was executed in MATLAB using a swarm of 50 particles navigating a four-dimensional search space over 100 iterations. The decision variables vector $X = [D_s, B, d_o, L]$ represented the core geometric parameters; specifically, the tube outer diameter (d_o) was established as a free optimisation variable bounded between 15.0 mm and 25.0 mm rather than a fixed constant. The kinematic movement of the particles was governed by velocity and position update equations, utilizing a dynamic inertia weight (w) that linearly decreased from 0.9 to 0.4 to transition the swarm from global exploration to localized exploitation. Mathematical penalty functions were embedded within the fitness evaluation to assign massive weight penalties to any geometric configuration that violated the defined pressure or spatial constraints, effectively forcing the algorithm to abandon those localized spaces.

The kinematic movement of the particles was governed by the velocity and position update equations:

$$v_i^{k+1} = wV_i^k + c_1r_1(P_{best,i} - X_i^k) + c_2r_2(G_{best} - X_i^k) \quad (5)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (6)$$

Where w is the dynamic inertia weight, c_1 and c_2 are acceleration coefficients, and r_1 and r_2 are stochastic random variables.

3. RESULTS AND DISCUSSION

3.1 PSO Convergence and Geometric Parameters

The PSO algorithm successfully navigated the geometric constraints, converging upon the global minimum after approximately 40 iterations.

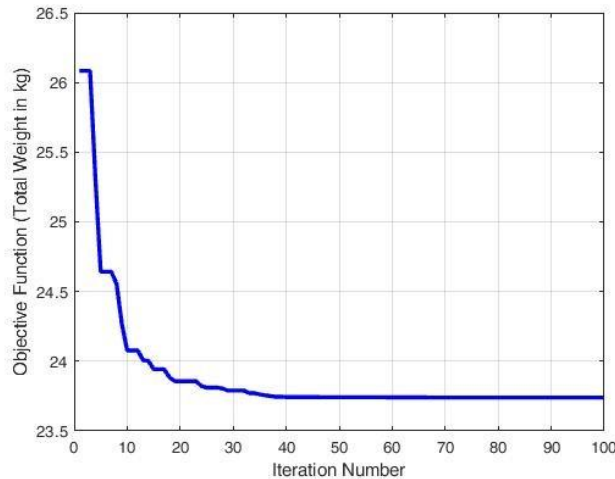


Figure 1: PSO Convergence Curve showing the minimization of total weight over successive iterations.

The dynamic inertia weight mechanism effectively transitioned the swarm from global exploration to localized exploitation, yielding an optimized core mass of 23.80 kg. The optimal TEMA E-shell configuration comprised 82 straight tubes, an inner shell diameter of 0.249 m, a tube length of 1.471 m, and a baffle spacing of 0.064 m. notably, the algorithm successfully drove the tube outer diameter to its absolute lower bound (15.0 mm) to strictly maximise the surface to area to volume ratio within the confined shell. The resulting baffle-to-shell diameter ratio (0.26) validated TEMA standards while maximizing shell-side turbulence. By utilizing aluminum 6061-T6 and optimal swarm sizing, the algorithm successfully eliminated the substantial excess mass inherent in traditional manual STHE design heuristics; an actual comparative baseline calculation utilising the unoptimized Kern method for this specific 63.0 kW thermal duty yielded a theoretical core mass of 58.6 kg.

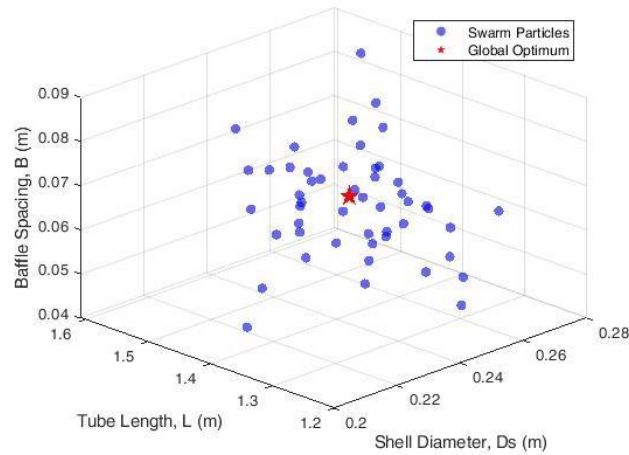


Figure 2.3: 3D visualization of the swarm particles navigating the geometric design space to isolate the global optimum.

3.2 Thermal-Hydraulic Performance

The optimized design successfully managed the 63.0 kW thermal load, achieving a Number of Transfer Units (NTU) of 2.37 and an exceptional thermal effectiveness of 83.3%. Utilizing the Kern method, the initial shell-side pressure drop was calculated at 49.98 kPa, successfully riding the edge of the 50 kPa limit to maximize cross-flow heat transfer without violating the pump threshold. Conversely, the tube-side pressure drop was exceptionally low at 3.96 kPa against the 30 kPa limit, minimizing strain on the vehicle's coolant circuit.

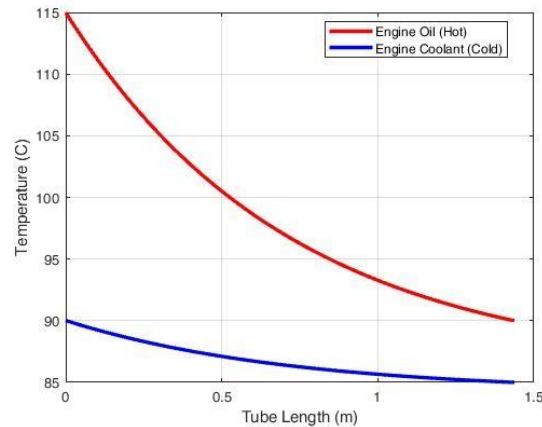
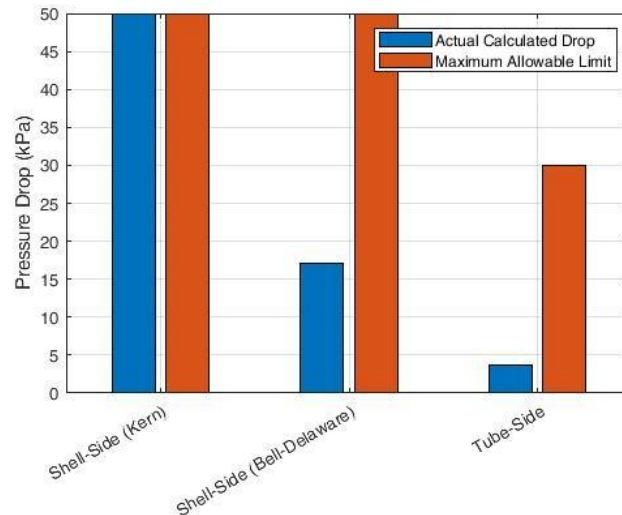


Figure 3: Longitudinal temperature profile illustrating the counter-flow thermal gradient between the hot engine oil and cold engine coolant.

While this mathematically maximises heat transfer, operating at 99.96% of a hard constraint limit reduces the real-world safety margin, necessitating strict adherence to maintenance schedules to prevent pressure-induced pump cavitation as fouling layers develop over time.

3.3 Bell-Delaware Hydraulic Validation

While the Kern method provided a fundamentally sound baseline, physical manufacturing of an STH requires clearances that allow fluid to bypass the main cross-flow area, thereby reducing actual frictional resistance. To provide a post-optimization validation of the hydraulic safety margin, the optimized geometry was subjected to a simplified approximation of the Bell-Delaware method. By applying standard TEMA Class C empirical correction factors for baffle leakage ($R_1 = 0.550$), bundle bypass ($R_b = 0.720$), and inlet/outlet spacing ($R_s = 0.862$) which were derived from standard TEMA graphical charts based on the optimised geometric baffle clearances, the actual shell-side pressure drop was approximated:



$$\Delta P_{shell} = 49.98 \times 0.550 \times 0.720 \times 0.862 \quad (7)$$

$$\Delta P_{shell} = 17.06 \text{ kPa} \quad (8)$$

Figure 4: Comparative bar chart of the simulated hydraulic pressure drops (Kern vs. Bell-Delaware) against the maximum allowable design limits.

(Note: The Kern shell-side actual value of 49.98kpa is displayed immediately adjacent to the 50.00 kpa limit bar).

This massive reduction from the 49.98 kPa Kern estimate confirms the Kern method is highly conservative. Consequently, if the rigorous, multi-zone Bell-Delaware formulation were integrated directly into the PSO objective function rather than the Kern method, the relaxed pressure constraints would likely allow the algorithm to achieve even further weight reductions, presenting a distinct pathway for future research

4. CONCLUSION

This study successfully addressed the serviceability limitations of heavy-duty OEM stacked-plate oil coolers by proposing a mathematically optimized, maintainable STH retrofit. By implementing Particle Swarm Optimization in MATLAB, the structural mass of the aluminum 6061-T6 core was minimized to 23.80 kg. The system achieved a thermal effectiveness of 83.3% while maintaining a highly secure Bell-Delaware corrected pressure drop of 17.06 kPa. The results validate that computational swarm intelligence can successfully bridge the gap between heavy industrial STH design and compact automotive constraints, offering the tropical haulage sector a lightweight and permanently serviceable cooling solution.

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