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FINNED ELLIPTIC TUBES HEAT EXCHANGERS IN THE TURBULENT REGIME CONSTRUCTAL DESIGN

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This work seeks numerically the heat exchanger structure direction of evolution in time, i.e., the general optimal that maximizes the total heat transfer rate between a fixed volume arrangement of finned tubes and a turbulent external flow governed by a pressure difference, Δp_∞, both for circular and elliptic tube arrays. In this way, the dynamic, ever-changing heat exchanger design that provides easier access to the currents that flow through it is sought for any time reality (*e.g.*, geometry, materials, environment), according to Constructal law. The optimization procedure began by recognizing the limited availability of the design space as a fixed volume constraint. The three-way optimized (3wo) arrangement concerning tube-to-tube distance, eccentricity, and fin density was found as $(S/2b, e, \phi_f)_{3wo} \cong (0.5; 0.4; 0.094)$. A relative heat transfer gain of up to *38%* was noted with the elliptic compared to the 3wo circular arrangement, demonstrating that elliptical tube arrangements have potential for considerably better performance and lower cost than traditional circular arrangements.

Keywords: Heat transfer; Numerical simulation; Refrigeration; Tube banks.

1. INTRODUCTION

Human society depends heavily on the utilization of finned tube heat exchangers. For example, they are the main components of Heating, Ventilation, Air Conditioning, and Refrigeration (HVAC-R) systems that require 13.2%, 14.9%, and 3.7% (residential, commercial, and industrial sectors, respectively) of the US consumed electrical power, adding up to 31.8% of total US electricity consumption in 2019 [1]. Therefore, in recent decades, in this area, many studies have been carried out on modeling, simulation, design, and operating parameters optimization aimed at achieving the highest possible efficiency for reaching the minimum possible cost and resource waste [2].

This study broadens such optimization efforts with the Constructal law: "For a finite-size flow system to persist in time, it must evolve with freedom such that it provides greater and easier access to its flows" [3, 4]. So, the entropy generation minimization (EGM) method could predict the system's optimal structural design and energy

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flow organization for minimum losses [5] for any time reality (*e.g*., geometry, materials, environment). For that, a quasi-steady process [6] is assumed, *i.e*., the dynamic design phenomenon is modeled by a succession of periods (time steps) where, in each of them, the optimal design remains practically unchanged, "…like the images in a movie at the cinema…" [3]. The quasi-steady assumption is justified because the duration of each time step is much shorter than the evolution timescale since evolution never ends. The changing rate of optimal designs points to the direction of heat exchangers evolution in time, *i.e.*, the constructal design.

2. MATERIALS AND METHODS

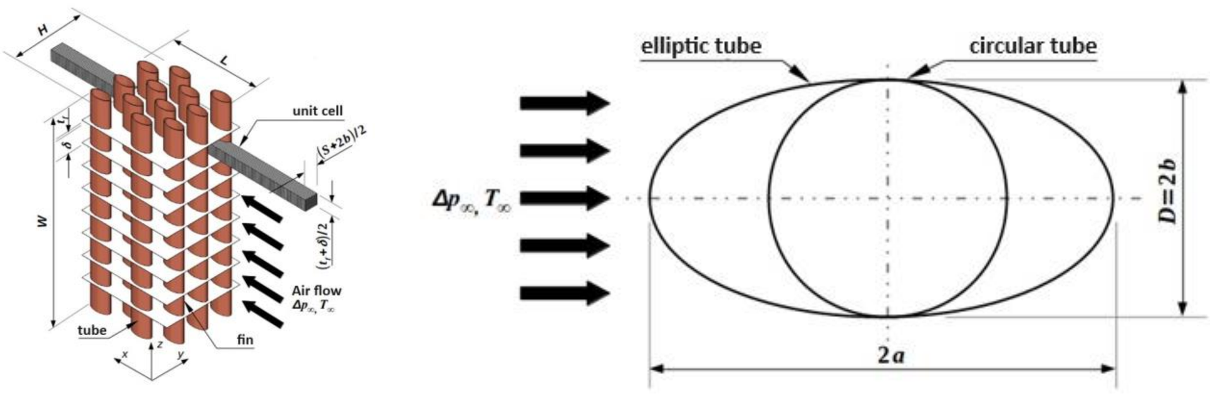
The mathematical model was developed for the turbulent flow regime external to elliptical finned tubes driven by a pressure difference Δp_∞. The finite volume method was used to discretize the governing equations. The model was written for the domain of the unit cell in Fig. 1a, considering all system symmetries.

Figure 1b shows the finned elliptical (or circular) tube arrangement. The comparison criterion was to use the same tube section in the flow direction [7], *i.e*., the same free-flow obstruction area.

The adopted simplifying assumptions were forced convection, Newtonian fluid, incompressible flow, steady-state, and constant fluid properties. The fluid flow and heat transfer governing equations are based on the mass, momentum, and energy conservation principles and are listed as follows:

$$\nabla \cdot \vec{V} = 0 \,; \; \rho \frac{D\vec{V}}{Dt} = -\nabla p + \mu \nabla^2 \vec{V} + \vec{F} \text{, and } \rho c_p \frac{DT}{Dt} = k\nabla^2 T + \mu \Phi \,, \tag{1}$$

where $\vec{V} = (u, v, w)^T$ is the velocity vector, $\vec{F} = (X, Y, Z)^T$ the body force vector per unit volume and Φ the viscous dissipation function.



(a) (b)

Fig. 1 – (a) Finned tubes heat exchanger arrangement and (b) Circular and elliptic tubes comparison criterion.

For brevity, the full description of all variables and the SST k-w (Shear Stress Transport) turbulence model used to solve the problem are not shown here but can be found in Pereira [7].

3. RESULTS

The results of Fig. 2 investigate the existence of optima concerning tube-to-tube distance, S/2b, eccentricity, e, and fin density, $\phi_f = t_f/(t_f+\delta)$. The airflow covered the range $1\,240 \le Re_{2b} \le 28\,180$, where Re_{2b} is the Reynolds number based on 2b. Numerical results were validated against published data for flow in tubes and bundles of tubes in the laminar and turbulent regime [7]. The Nusselt number, Nu, was calculated and validated with empirical correlations, in good agreement, with a 2.8% error for $Re_D = 5\,000$ and 18.3% for $Re_D = 30\,000$.

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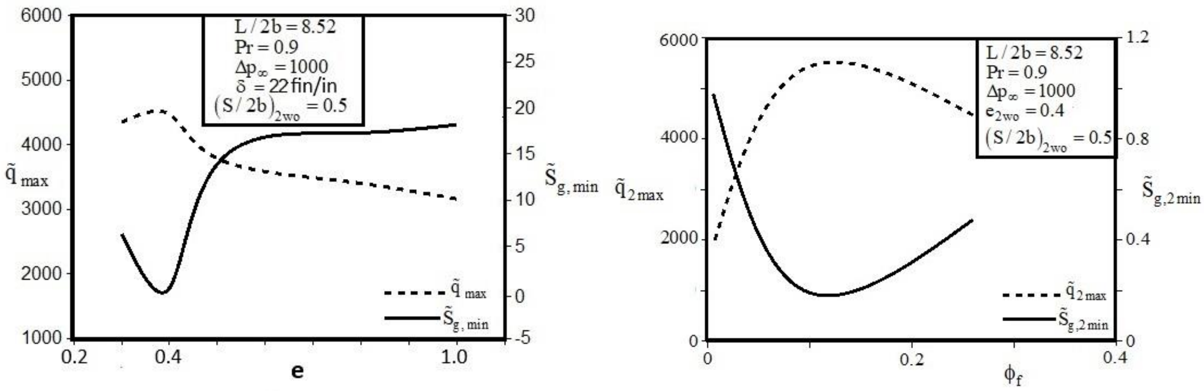

(a) (b)

Fig. 2 – The finned heat exchanger two- (a) and three-way (b) optimization.

The three-way optimized (3wo) arrangement was found as $(S/2b, e, \phi_f)_{3wo} \cong (0.5; 0.4; 0.094)$. The heat transfer gain was up to *38%* for the 3wo elliptic arrangement in comparison to 3wo circular one. The calculation of the system total entropy generation allowed for obtaining both 3-way maximized heat transfer and 3-way minimized entropy generation, $\tilde{q}_{3\max}$ and $\tilde{S}_{g,3\min}$, respectively, for $(S/2b, e, \phi_f)_{3wo} \cong (0.5; 0.4; 0.094)$ for the arrangement.

4. DISCUSSION AND CONCLUSIONS

In sum, it is reasonable to state that the heat exchanger constructal design has been achieved by minimizing the system's total entropy generation, which simultaneously minimizes the system's thermal and flow resistances.

REFERENCES

1. Matos R.S., Vargas J.V.C., Rossetim M.A., Pereira M.V.A., Pitz D.B., Ordonez J.C., Performance comparison of tube and plate-fin circular and elliptic heat exchangers for HVAC-R systems, *Applied Thermal Engineering*, **184**, p. 116288 (2021).
2. Macchitella S., Colangelo G., Starace G., Performance Prediction of Plate-Finned Tube Heat Exchangers for Refrigeration: A Review on Modeling and Optimization Methods, *Energies*, **16**, p. 1948 (2023).
3. Bejan A., Lorente S., Constructal law of design and evolution: Physics, biology, technology, and society, *J. Appl. Phys.*, **113**, p. 151301 (2013).

4. Bejan A., Tsatsaronis G., Purpose in thermodynamics, *Energies*, **14**, *2*, p. 408 (2021).
5. Bejan A., *Entropy Generation Minimization*, CRC Press, Boca Raton, Florida, USA, 1995.
6. Martinho L.C.S., Vargas, J.V.C., Balmant W., Ordonez J.C., A single stage absorption refrigeration system dynamic mathematical modeling, adjustment and experimental validation, *Int. J. Refrigeration*, **68**, pp. 130–144 (2016).
7. Pereira M.V.A., *Modeling, Simulation and Optimization of Finned Tubes Heat Exchangers in Turbulent Regime*, PhD Dissertation, Federal University of Parana, Curitiba, Brazil, 2018.