Overview

This work presents a CFD-based investigation of laminar forced convection through a staggered tube heat exchanger. The aim is to study how variations in inlet mass flow rate affect the flow field, temperature distribution, and overall heat transfer performance. Velocity and temperature contours are used for qualitative analysis, while Reynolds and Nusselt numbers are extracted to quantify heat transfer trends.
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Mass flow rate $\dot{m}$	Heat transfer coeff. h	Max velocity U_{max}	Reynolds Number Re	Nusselt Number Nu	Temp. Max C^o	Temp. Min C^o
0.05	433.515	0.01282	127.543	7.225	70	5.946
0.1	512.005	0.02927	291.313	8.533	76.096	10.807
0.15	741.121	0.05384	535.844	12.352	70	12.250

Table 1 All quantities are in SI units except the max and min temperatures.

Quantitative Results and Trends

Increasing mass flow rate leads to higher Reynolds numbers, reflecting stronger inertial effects relative to viscous forces. Correspondingly, the Nusselt number and convective heat transfer coefficient increase, consistent with classical forced convection theory. The rise in maximum velocity contributes to increased wall shear and improved heat exchange. Temperature data further supports these trends, showing enhanced heat transfer at higher flow rates.

Validation and Numerical Reliability

The numerical results exhibit trends consistent with classical forced convection theory, with a monotonic increase in Nusselt number as Reynolds number increases. This qualitative agreement provides physical validation of the simulations.
Numerical reliability was ensured through:
•**Mesh quality assessment**, with an average element quality of **0.907** and average skewness of $\mathbf{4.72 \times 10^{-2}}$, indicating a high-quality mesh suitable for CFD analysis
•**Residual convergence monitoring**, with absolute convergence criteria set to $\mathbf{10^{-16}}$ for all governing equations
•Consistent solution stability observed across multiple mass flow rates
Although no experimental data was used for comparison, the combination of good mesh quality, strict convergence criteria, and agreement with theoretical trends suggests that the results are physically meaningful and numerically robust.

Key Takeaways

- Increasing mass flow rate increases velocity and Reynolds number
- Higher Reynolds number leads to improved convective heat transfer
- Temperature and velocity contours visually confirm theoretical heat transfer trends
- CFD provides a powerful tool to link flow behaviour with thermal performance

Velocity Contours | Temperature Contours

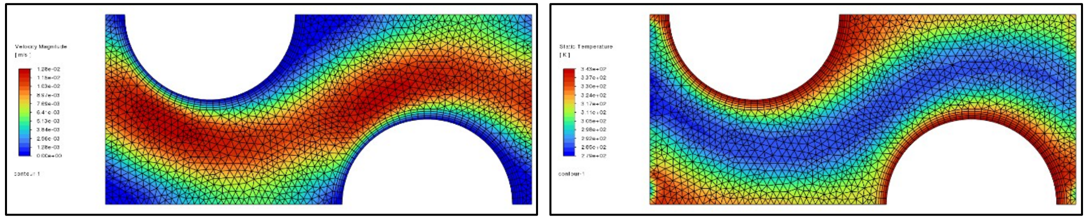

Figure 1 mass flow rate of 0.05kg/s

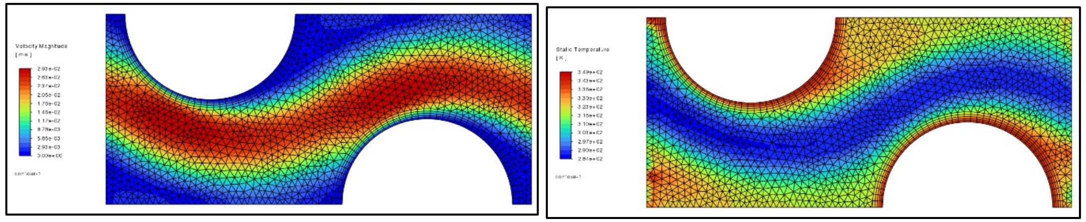

Figure 2 mass flow rate of 0.1 kg/s

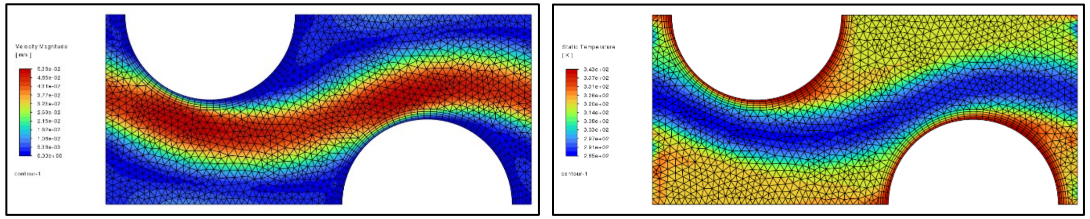

Figure 3 mass flow rate of 0.15 kg/s

Velocity Contours

Velocity contours show acceleration of the fluid in the narrow passages between staggered tubes due to flow constriction, with lower velocities in wider downstream regions. As the mass flow rate increases from 0.05 kg/s to 0.15 kg/s, velocity magnitudes and near-wall gradients increase, indicating stronger shear effects and enhanced momentum transport. The flow remains laminar in all cases, but higher mass flow rates lead to more pronounced velocity redistribution around the tubes.

Temperature Contours

Temperature contours illustrate heat transfer from the tube surfaces to the flowing fluid. High temperatures are observed near the heated tube walls, while cooler regions persist in the core flow. Increasing mass flow rate results in thinner thermal boundary layers and smoother temperature gradients, indicating improved convective heat transfer. Despite reduced residence time at higher velocities, enhanced mixing leads to more effective heat removal from the tube surfaces.