Heat Transfer Analysis: Conduction, Convection, and Fins

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Abstract

This report presents computational analysis of heat transfer mechanisms including conduction through composite walls, convection correlations, fin analysis, and heat exchanger design. Python-based computations provide quantitative analysis with dynamic visualization of temperature distributions and heat flux.

Contents

1 Introduction to Heat Transfer

Heat transfer is the thermal energy in transit due to a temperature difference. The three modes are:

- Conduction: Energy transfer through molecular interactions
- Convection: Energy transfer by fluid motion
- Radiation: Energy transfer by electromagnetic waves

2 Conduction Heat Transfer

2.1 Fourier's Law

The rate of heat conduction is proportional to the temperature gradient:

$$q = -k\frac{dT}{dx} \tag{1}$$

where k is thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$).

2.2 Composite Wall Analysis

For a composite wall with convection on both sides:

$$q = \frac{T_i - T_o}{R_{total}} = \frac{T_i - T_o}{\frac{1}{h_i A} + \sum \frac{L_j}{k_j A} + \frac{1}{h_o A}} \tag{2}$$

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Figure 1: Composite wall analysis: temperature profile and thermal resistance breakdown.

Heat flux through wall: $q = 10.4\ \mathrm{W\,m^{-2}}$

3 Convection Heat Transfer

3.1 Convection Correlations

The heat transfer coefficient depends on the Nusselt number:

$$h = \frac{Nu \cdot k}{L_c} \tag{3}$$

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Figure 2: Convection heat transfer correlations for external and internal flows.

4 Extended Surfaces (Fins)

4.1 Fin Temperature Distribution

For a fin with adiabatic tip:

$$\frac{\theta}{\theta_b} = \frac{\cosh[m(L-x)]}{\cosh(mL)} \tag{4}$$

where $m = \sqrt{\frac{hP}{kA_c}}$ and $\theta = T - T_\infty$.

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Figure 3: Fin analysis: temperature distribution, efficiency, and heat transfer rate.

Table 1: Fin Performance Parameters

Parameter	Value	Units
Fin parameter m	10.49	1/m
Product mL	1.05	–
Fin efficiency	74.5	%
Heat transfer rate	30.7	W

5 Heat Exchanger Analysis

5.1 LMTD Method

For counter-flow heat exchangers:

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} \tag{5}$$

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Figure 4: Heat exchanger analysis: temperature profiles and effectiveness-NTU curves.

Heat duty: $Q = 60.0$ kW, $UA = 801$ W/K

6 Transient Conduction

6.1 Lumped Capacitance Method

When $Bi = hL_c/k < 0.1$:

$$\frac{T - T_\infty}{T_i - T_\infty} = \exp\left(-\frac{hA_s}{\rho V c_p}t\right) = \exp\left(-\frac{t}{\tau}\right) \tag{6}$$

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Figure 5: Transient conduction analysis using lumped capacitance method.

Biot number: $Bi = 0.004$ (lumped model valid since $Bi < 0.1$)

7 Radiation Heat Transfer

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Figure 6: Radiation heat transfer: blackbody emission and emissivity effects.

8 Conclusions

This analysis demonstrates key aspects of heat transfer:

1. Composite walls require thermal resistance network analysis
2. Convection correlations depend on flow geometry and regime
3. Fin efficiency decreases with length but total heat transfer increases
4. Heat exchanger design uses LMTD or effectiveness-NTU methods
5. Lumped capacitance applies when $Bi < 0.1$
6. Radiation becomes dominant at high temperatures