Last updated: November 1, 2026

🗺️ Four-year roadmap · Year 4, Fall

About this course

This free course has 10 units and 6 labs. Those are the real counts, not a longer syllabus cut short.

A check is one number or code result on a course page that a script recomputes before the page is published. The printed number and the recomputed number have to match.

> This is a free self-study course outline written by Saving Planets. It is not a university course, it carries no academic credit, and no school is involved.
>
> Its scope follows a one-semester senior heat transfer course for engineers. It is modeled on the topics and depth of the free online A Heat Transfer Textbook by Lienhard and Lienhard and MIT 2.51 Intermediate Heat and Mass Transfer (free on MIT OpenCourseWare), which we link where they help. None of those authors, schools or agencies endorses this page.
>
> What we add: every unit ties to real work with a cited public source (NASA's Earth energy budget, Parker Solar Probe and ENERGY STAR heat pumps), every number on the page is re-computed by a checking script before it goes live, and every lab has a free simulation or a spreadsheet.
>
> Work through it in order. Each unit has goals, key ideas, equations, step-by-step examples, practice with full answers, common mistakes, flashcards and a quiz. Your progress is saved only in this browser.

How this course helps save the planet

Earth's climate is a heat transfer problem: sunlight in, thermal infrared out, with convection and evaporation moving heat in between. The same physics decides how much energy our buildings, engines and electronics waste.

Insulation, heat pumps and efficient heat exchangers are some of the cheapest climate solutions. Each unit ends with a short, sourced section. Values that are not from a source are labeled as sample or textbook values.

For instructors

You can teach this course, or let a student work through it alone. It is free. Saving Planets does not give a grade or school credit.

- This page is the whole course: 10 units and 6 labs (AERO 440).
- Plan on 15 weeks, about 6 to 9 hours a week, including the lab weeks.
- Follow the 15-week schedule. Read the unit, do the practice on paper, then open the answer. In a lab week, do the lab or the home version.
- A check is one number or code result on the page that a script recomputes before we publish. The number you see and the recomputed number have to match.
- Use Print this page, or download the PDF study guide. The formula sheet is near the end.
- Ask: how does this unit help people and the planet? Each unit has a green box with a sourced fact.
- Copy the teacher guide template and write in your class name, the time you have, and the questions you will ask. Open the teacher guide template

Before you start

Prerequisites

- Thermodynamics: energy balances and the first and second laws.
- Fluid Mechanics: boundary layers, Reynolds number and pipe flow.
- Differential Equations: first-order ODEs and separation of variables.
- Calculus III: gradients and integrals over areas and volumes.

How to study

- Draw the system and every heat flow arrow before writing an equation.
- Use kelvin for radiation and temperature differences for conduction and convection.
- Turn every problem into a thermal-resistance network when you can.
- Check dimensionless numbers (Bi, Re, Pr, Nu, Ra) to pick the right correlation.
- Compare answers with everyday experience: a warm house, a cooling cup, a hot pan.
- Do every practice problem on paper before opening the answer, and retake the quizzes a few days later.

What you need

- A computer or tablet for the free PhET Energy Forms and Changes, Blackbody Spectrum and Greenhouse Effect simulations.
- Spreadsheet software (any free one works), or Python.
- The free online A Heat Transfer Textbook in a web browser.
- A calculator.

Suggested 15-week schedule

About 6 to 9 hours a week: reading, practice problems and, in lab weeks, the lab.

Week	Unit	Topics	Reading
1	Modes of Heat Transfer and Energy Balances	Modes and energy balances	Lienhard AHTT
2	Steady Conduction and Thermal Resistance	Thermal resistance; Lab A	Lienhard AHTT
3	Cylinders, Spheres and Fins	Cylinders and critical radius	Lienhard AHTT
4	Cylinders, Spheres and Fins	Fins; Lab B	MIT 2.51
5	Transient Conduction	Transient conduction; Lab C	Lienhard AHTT
6	External Forced Convection	Boundary layers	MIT 2.51
7	External Forced Convection	Flat-plate correlations; Lab D; midterm practice	Lienhard AHTT
8	Internal Flow and Heat Exchangers	Internal flow	MIT 2.51
9	Internal Flow and Heat Exchangers	Heat exchangers	Lienhard AHTT
10	Natural Convection and Boiling	Natural convection and boiling	Lienhard AHTT
11	Radiation Fundamentals	Radiation fundamentals; Lab E	NASA Earth Observatory
12	Radiation Exchange and Shields	View factors	Lienhard AHTT
13	Radiation Exchange and Shields	Shields and Parker Solar Probe	NASA Parker Solar Probe
14	Heat Pumps, Buildings and Earth’s Energy Balance	Heat pumps and Earth’s balance; Lab F	ENERGY STAR
15	Heat Pumps, Buildings and Earth’s Energy Balance	Review; final practice	MIT 2.51

Your progress

Tick units and labs as you finish them, and take the quizzes. Progress and quiz scores are saved only in this browser, never sent to us.

Units

Modes of Heat Transfer and Energy Balances

Conduction, convection and radiation, their rate equations, and surface and control-volume energy balances.

Learning objectives

By the end of this unit you can:

- Name the three modes and their rate laws.
- Compute conduction, convection and radiation rates.
- Write a surface energy balance.
- Read Earth's energy budget as a heat balance.

Key concepts

- Heat transfer is energy in transit because of a temperature difference; thermodynamics says how much, heat transfer says how fast.
- Conduction moves energy through a solid or still fluid by molecular contact (Fourier's law).
- Convection moves energy between a surface and a moving fluid (Newton's law of cooling, with a heat transfer coefficient h).
- Radiation moves energy by electromagnetic waves, needs no medium, and grows with T^4 in kelvin (Stefan–Boltzmann law).
- A surface stores no energy, so what arrives by one mode must leave by the others.

Key equations

$$q = kA\frac{\Delta T}{L}$$

`q=kA(Δ T)/(L)`

Fourier's law, plane wall

$$q = hA(T_s - T_\infty)$$

`q=hA(T_s-T_∞)`

Newton's law of cooling

$$q = \varepsilon\sigma A(T_s^4 - T_{sur}^4)$$

`q=σ A(T_s^4-T_sur^4)`

Net radiation to large surroundings

$$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_g = \dot{E}_{st}$$

```
E_in- E_out+ E_g= E_st
```

Energy balance

Worked examples, step by step

Example 1.1 A 0.2 m concrete wall (k = 1.4 W/(m·K), sample) of area 10 m² has a 15 K difference across it. Find q.

1. q = 1.4 × 10 × 15/0.2.

Answer: 1050 W.

Example 1.2 A plate with ε = 0.9 at 400 K sits in 300 K surroundings. Net radiation per m²?

1. $0.9\sigma(400^4 - 300^4) = 0.9 \times 5.670374419 \times 10^{-8} \times 1.75 \times 10^{10}$.

Answer: 893 W/m².

Example 1.3 NASA says about 29% of incoming sunlight is reflected and the global average is about 340 W/m². How much is absorbed?

1. Reflected: 0.29 × 340 = 98.6 W/m².
2. Absorbed: 340 − 98.6.

Answer: 241.4 W/m², matching NASA's roughly 240 W/m².

Practice problems

Work each on paper first, then check.

1. Repeat the wall example with k = 0.04 W/(m·K).

   30 W.

2. Convection with h = 25 W/(m²·K), A = 2 m², ΔT = 40 K?

   2000 W.

3. Why must radiation use kelvin?

T^4 depends on absolute temperature.

4. Why is 1360/4 the global average sunlight?

   A sphere's area is 4 times its shadow disk: 1360/4 = 340 W/m².

Common misconceptions

Myth: Heat and temperature are the same.

Actually: Temperature is a state; heat is energy in transit.

Myth: Radiation needs air.

Actually: It travels through vacuum.

Myth: h is a material property.

Actually: It depends on flow and geometry.

Flashcards

Conduction

Molecular energy transfer through matter.

Convection

Surface-to-moving-fluid transfer.

Radiation

Electromagnetic energy exchange.

h

Convection coefficient, W/(m²·K).

k

Thermal conductivity, W/(m·K).

Surface balance

In = out at a surface.

Self-check quiz

1. Concrete wall q...

1050 W

105 W

4200 W

210 W

1050 W. 1.4 × 10 × 15/0.2.

2. Radiation scales with...

T^4 (K)

T (°C)

T^2

√T

T^4 (K). Stefan–Boltzmann.

3. Earth absorbs about...

240 W/m²

1360 W/m²

29 W/m²

0.8 W/m²

240 W/m². NASA.

4. Mode needing no medium...

radiation

conduction

convection

boiling

radiation. Waves.

Try this quiz again

How this helps save the planet

NASA's Earth Observatory says total solar irradiance is about 1,360 W/m², averaging about 340 W/m² over the globe; about 29% is reflected, 23% is absorbed by the atmosphere and 48% by the surface, so Earth absorbs about 240 W/m².

For a stable temperature, Earth must radiate the same 240 W/m² back to space as thermal infrared, the heat balance this course returns to in Unit 10.

On Saving Planets: Earth Observation · Thermodynamics

Sources: NASA Earth Observatory: Climate and Earth's Energy Budget (https://earthobservatory.nasa.gov/features/EnergyBalance)

Free learning resources

- J. H. Lienhard IV and J. H. Lienhard V, A Heat Transfer Textbook (free online edition) (https://ahtt.mit.edu/): Free textbook, Chapter 1.
- NASA Earth Observatory: Climate and Earth's Energy Budget (https://earthobservatory.nasa.gov/features/EnergyBalance): NASA explainer.

☐ **I finished this unit**

Steady Conduction and Thermal Resistance

The heat equation, one-dimensional steady conduction, thermal-resistance networks, composite walls and insulation.

Learning objectives

By the end of this unit you can:

- State the heat equation and its 1D steady form.
- Build series and parallel resistance networks.
- Compute heat loss through a composite wall.
- Quantify the savings from insulation.

Key concepts

- The heat equation balances conduction, generation and storage; at steady state with no generation, a plane wall has a linear temperature profile.
- Each layer acts like an electrical resistor: R = L/(kA) for conduction, 1/(hA) for convection.
- Series resistances add; heat flow equals overall ΔT divided by total resistance, like current.
- The largest resistance controls the heat flow, which is why insulation (low k) matters most.
- Contact resistance between layers can add surprising resistance in electronics and joints.

Key equations

$$\nabla \cdot (k \nabla T) + \dot{q} = \rho c \frac{\partial T}{\partial t}$$

```
·(k T)+ q=ρ c( T)/( t)
```

Heat equation

$$R_{cond} = \frac{L}{kA}$$

```
R_cond=L/kA
```

Conduction resistance

$$R_{conv} = \frac{1}{hA}$$

```
R_conv=1/hA
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Convection resistance

$$q = \frac{T_{\infty,1} - T_{\infty,2}}{\sum R}$$

q=_∞,1-T_∞,2 R

Series network

Worked examples, step by step

Example 2.1 A wall has inside air (h = 8), 0.1 m insulation (k = 0.04), 0.1 m brick (k = 0.7) and outside air (h = 25), all sample values. Find the resistance per m².

1. 1/8 + 0.1/0.04 + 0.1/0.7 + 1/25 = 0.125 + 2.5 + 0.1429 + 0.04.

Answer: 2.808 m²·K/W.

Example 2.2 With 20 K between inside and outside, find the heat flux and the loss through 100 m².

1. q" = 20/2.808 = 7.12 W/m².
2. q = 100 × 7.12.

Answer: 712 W.

Example 2.3 Remove the insulation. How much does the loss grow?

1. R" = 0.3079 m²·K/W.
2. q" = 20/0.3079 = 64.97 W/m².

Answer: About 9.1 times; insulation cuts the loss by 89.0%.

Practice problems

Work each on paper first, then check.

1. Double the insulation to 0.2 m. New q"?

   R" = 5.308, q" = 3.77 W/m².

2. Which layer dominates the original wall?

   The insulation, 2.5 of 2.808 m²·K/W.

3. Write R for two layers in parallel.

   $1/R = 1/R_1 + 1/R_2$.

4. Shape of T(x) in a plane wall at steady state?

   Linear.

Common misconceptions

Myth: Thin layers never matter.
Actually: A low-k thin layer can dominate.

Myth: Resistances in series multiply.
Actually: They add.

Myth: Air films add nothing.
Actually: Convection resistance is real.

Flashcards

Thermal resistance

ΔT per unit heat flow.

Heat equation

Energy balance in a solid.

Composite wall

Layers in series.

Insulation

Low-k material.

Contact resistance

Resistance at an interface.

U-value

Overall coefficient, 1/R".

Self-check quiz

1. Total R"...

2.808 m²·K/W

2.5

0.308

28.08

2.808 m²·K/W. Sum the layers.

2. Heat loss through 100 m²…

712 W

71 W

6497 W

2000 W

712 W. 100 × 7.12.

3. Insulation savings…

89.0%

50%

9.1%

25%

89.0%. 1 − 0.3079/2.808.

4. Series resistances…

add

multiply

average

cancel

add. Circuit analogy.

Try this quiz again

How this helps save the planet

ENERGY STAR says a typical U.S. household energy bill is around $1,900 a year and almost half of that goes to heating and cooling.

This unit's sample wall shows why sealing and insulating comes first: adding insulation cut the conduction loss by about 89%, so any heating system has far less heat to replace.

On Saving Planets: Solutions · Thermodynamics

Sources: ENERGY STAR: Air-Source Heat Pumps (https://www.energystar.gov/products/air_source_heat_pumps)

Free learning resources

- J. H. Lienhard IV and J. H. Lienhard V, A Heat Transfer Textbook (free online edition) (https://ahtt.mit.edu/): Free textbook, Chapter 2.
- MIT OpenCourseWare 2.51 Intermediate Heat and Mass Transfer (Fall 2008) (https://ocw.mit.edu/courses/2-51-intermediate-heat-and-mass-transfer-fall-2008/): Free MIT lectures.

☐ **I finished this unit**

Cylinders, Spheres and Fins

Radial conduction, pipe insulation and the critical radius, extended surfaces, fin efficiency and electronics cooling.

Learning objectives

By the end of this unit you can:

- Compute radial conduction resistance.
- Find the critical insulation radius.
- Compute fin parameter m and fin efficiency.
- Estimate heat from a fin.

Key concepts

- In a cylinder, area grows with radius, so the temperature profile is logarithmic and R = ln(r_2/r_1)/(2πkL).
- Adding insulation to a small wire can increase heat loss until the outer radius passes the critical radius k/h.
- Fins add area where h is low (usually gases), as on engine cylinders, heat sinks and radiators.
- The fin parameter m = √(hP/(kA_c)) sets how fast the fin temperature decays from its base.
- Fin efficiency compares actual heat to the heat if the whole fin were at the base temperature.

Key equations

$$R_{cyl} = \frac{\ln(r_2/r_1)}{2\pi k L}$$

```
R_cyl=((r_2/r_1))/(2π kL)
```

Radial resistance

$$r_{cr} = \frac{k}{h}$$

```
r_cr=k/h
```

Critical radius (cylinder)

$$m = \sqrt{\frac{hP}{kA_c}}$$

```
m=(hP)/(kA_c)
```

Fin parameter

$$\eta_f = \frac{\tanh(mL_c)}{mL_c}$$

_f=((mL_c))/(mL_c)

Fin efficiency

Worked examples, step by step

Example 3.1 Pipe insulation from r = 0.05 to 0.1 m, k = 0.04 W/(m·K), 1 m long, 100 K across it (sample values). Find R and q.

1. R = ln 2/(2π × 0.04) = 2.758 K/W.
2. q = 100/2.758.

Answer: 36.3 W per meter.

Example 3.2 An aluminum pin fin (k = 200) is 5 mm across with h = 50 W/(m²·K) and a 20 mm effective length. Find η.

1. m = √(4h/(kD)) = √(200/1) = 14.14 m⁻¹.
2. mL = 0.2828.
3. η = tanh(0.2828)/0.2828.

Answer: 0.974.

Example 3.3 Heat from that fin with a 50 K base excess?

1. A_f = πDL = 3.142 × 10⁻⁴ m².
2. q = ηhA_fθ = 0.974 × 50 × 3.142 × 10⁻⁴ × 50.

Answer: 0.765 W.

Practice problems

Work each on paper first, then check.

1. Critical radius for k = 0.04 and h = 8?

   5 mm.

2. Fin efficiency at L = 40 mm?

mL = 0.566, η = 0.905.

3. Why do fins suit air more than water?

   Air’s low h makes area the bottleneck.

4. Profile shape in a cylinder wall?

   Logarithmic.

Common misconceptions

Myth: More insulation always helps.
Actually: Not below the critical radius.

Myth: Longer fins always help a lot.
Actually: Efficiency drops with length.

Myth: Fins work in any medium.
Actually: They pay off where h is low.

Flashcards

Critical radius

k/h for cylinders.

Fin

Extended surface.

Fin efficiency

Actual over ideal fin heat.

m

Fin decay parameter.

Heat sink

Array of fins.

Log profile

Cylinder steady temperature.

Self-check quiz

1. Pipe R...

2.758 K/W

0.276

27.6

1.0

2.758 K/W. ln 2/(2π × 0.04).

2. Critical radius...

5 mm

50 mm

0.5 mm

200 mm

5 mm. k/h.

3. Fin efficiency...

0.974

0.5

0.283

1.2

0.974. tanh(mL)/mL.

4. Fin heat...

0.765 W

7.65 W

76.5 W

0.0765 W

0.765 W. ηhAθ.

Try this quiz again

How this helps save the planet

Heat moves the same way in a pipe wall as in a planet's crust: from hot to cold, through resistances in series.

Insulating hot-water and steam pipes is one of the simplest efficiency steps in buildings and industry. All values in this unit are sample textbook values.

On Saving Planets: Solutions · Circuits

Sources: J. H. Lienhard IV and J. H. Lienhard V, A Heat Transfer Textbook (free online edition) (https://ahtt.mit.edu/)

Free learning resources

- J. H. Lienhard IV and J. H. Lienhard V, A Heat Transfer Textbook (free online edition) (https://ahtt.mit.edu/): Free textbook, Chapter 4.
- MIT OpenCourseWare 2.51 Intermediate Heat and Mass Transfer (Fall 2008) (https://ocw.mit.edu/courses/2-51-intermediate-heat-and-mass-transfer-fall-2008/): Free MIT lectures.

☐ **I finished this unit**

Transient Conduction

The Biot number, the lumped-capacitance model, time constants, and when spatial temperature gradients matter.

Learning objectives

By the end of this unit you can:

- Compute the Biot number.
- Use the lumped model when Bi < 0.1.
- Compute a thermal time constant.
- Find the time to reach a target temperature.

Key concepts

- The Biot number compares internal conduction resistance to external convection resistance.
- When Bi < 0.1, the body is nearly uniform in temperature and the lumped model works.
- In the lumped model, the temperature excess decays exponentially with time constant τ = ρcV/(hA).
- For larger Bi, use one-term series solutions or charts (Heisler) or a numerical method.
- High heat capacity slows response: oceans and thick walls are thermal flywheels.

Key equations

$$Bi = \frac{hL_c}{k},\ L_c = V/A$$

`Bi=(hL_c)/(k),\ L_c=V/A`

Biot number

$$\tau = \frac{\rho c V}{hA}$$

`τ=(ρ cV)/(hA)`

Time constant

$$\frac{T - T_\infty}{T_i - T_\infty} = e^{-t/\tau}$$

`(T-T_∞)/(T_i-T_∞)=e^-t/τ`

Lumped response

$$t = \tau \ln \frac{\theta_i}{\theta}$$

`t=τ(θ_i)/(θ)`

Time to a target

Worked examples, step by step

Example 4.1 A 10 mm aluminum sphere (k = 237, ρ = 2700, c = 900) cools in air with h = 50. Find Bi.

1. L_c = D/6 = 1.667 × 10^{-3} m.
2. Bi = 50 × 1.667 × 10^{-3}/237.

Answer: 3.52 × 10^{-4}, so the lumped model works.

Example 4.2 Find τ for that sphere.

1. τ = 2700 × 900 × 1.667 × 10^{-3}/50.

Answer: 81 s.

Example 4.3 How long to cool from 300 °C to 50 °C in 20 °C air?

1. θ_i = 280 K, θ = 30 K.
2. t = 81 ln(280/30) = 81 × 2.234.

Answer: 181 s.

Practice problems

Work each on paper first, then check.

1. Fraction of the excess left after one τ?

   e^{-1} = 0.368.

2. Time to halve the excess?

   τ ln 2 = 56.1 s.

3. Bi = 0.5. Is lumped valid?

No; use series or numerical solutions.

4. Double h. What happens to τ?

   It halves to 40.5 s.

Common misconceptions

Myth: Bi is the Nusselt number.
Actually: Bi uses the solid's k; Nu uses the fluid's.

Myth: Lumped works for any size.
Actually: Only when Bi < 0.1.

Myth: Cooling is linear in time.
Actually: It is exponential.

Flashcards

Biot number

Internal over external resistance.

Lumped capacitance

Uniform-temperature model.

Time constant

ρcV/(hA).

Heisler chart

One-term transient solution chart.

Thermal mass

Heat capacity that slows change.

L_c

V/A characteristic length.

Self-check quiz

1. Time constant...

81 s

8.1 s

810 s

181 s

81 s. ρcV/(hA).

2. Cooling time to 50 °C...

181 s

81 s

56 s

300 s

181 s. τ ln(280/30).

3. Lumped valid when...

Bi < 0.1

Bi > 1

Re > 5×10^5

Nu < 1

Bi < 0.1. Uniform body.

4. After one τ...

36.8% left

50% left

0% left

63.2% left

36.8% left. e^{-1}.

Try this quiz again

How this helps save the planet

NASA's Earth Observatory notes that Earth's surface averages about 15 °C, more than 30 °C warmer than it would be with no atmosphere.

In this unit's language, a large heat capacity means a long time constant; the oceans' heat capacity gives Earth's climate a slow response (a textbook idea, not a NASA figure).

On Saving Planets: Oceans · Earth Observation

Sources: NASA Earth Observatory: Climate and Earth's Energy Budget (https://earthobservatory.nasa.gov/features/EnergyBalance)

Free learning resources

- J. H. Lienhard IV and J. H. Lienhard V, A Heat Transfer Textbook (free online edition) (https://ahtt.mit.edu/): Free textbook, Chapter 5.
- MIT OpenCourseWare 2.51 Intermediate Heat and Mass Transfer (Fall 2008) (https://ocw.mit.edu/courses/2-51-intermediate-heat-and-mass-transfer-fall-2008/): Free MIT lectures.

☐ **I finished this unit**

External Forced Convection

Boundary layers, Reynolds, Prandtl and Nusselt numbers, flat-plate correlations and flow over cylinders.

Learning objectives

By the end of this unit you can:

- Compute Re, Pr and Nu.
- Use the laminar flat-plate correlation.
- Find h and the heat rate.
- Check transition at Re ≈ 5 × 10⁵.

Key concepts

- Velocity and thermal boundary layers form on a surface; heat crosses the thin layer of slow fluid by conduction.
- The Nusselt number Nu = hL/k is the dimensionless heat transfer coefficient.
- The Prandtl number compares momentum and thermal diffusivity (about 0.7 for air, about 7 for water near room temperature, textbook values).
- On a flat plate, flow is usually laminar below Re ≈ 5 × 10⁵; turbulence raises h.
- Correlations are fits to experiments; use them inside their stated ranges.

Key equations

$$Re_L = \frac{VL}{\nu}$$

`Re_L=(VL)/(ν)`

Reynolds number

$$Nu_L = \frac{\bar{h}L}{k}$$

`Nu_L=( hL)/(k)`

Nusselt number

$$\overline{Nu}_L = 0.664 Re_L^{1/2} Pr^{1/3}$$

`_L=0.664Re_L^1/2Pr^1/3`

Laminar flat plate (average)

$$\overline{Nu}_L = 0.037 Re_L^{4/5} Pr^{1/3}$$

_L=0.037Re_L^4/5Pr^1/3

Turbulent flat plate (average)

Worked examples, step by step

Example 5.1 Air (ν = 1.5 × 10⁻⁵, k = 0.026, Pr = 0.71) flows at 5 m/s over a 0.5 m plate. Find Re.

1. Re = 5 × 0.5/1.5 × 10⁻⁵.

Answer: 166,667, laminar.

Example 5.2 Find the average Nu and h.

1. Nu = 0.664 × 166,667^½ × 0.71^⅓ = 0.664 × 408.2 × 0.892 = 241.8.
2. h = 241.8 × 0.026/0.5.

Answer: 12.6 W/(m²·K).

Example 5.3 Heat from a 0.5 × 1 m plate 30 K above the air?

1. q = 12.58 × 0.5 × 30.

Answer: 189 W.

Practice problems

Work each on paper first, then check.

1. Repeat h at 10 m/s.

   Re = 333,333, h = 17.8 W/(m²·K) (√2 times higher).

2. Re at 1 m/s?

   33,333.

3. Name the dimensionless h.

   Nusselt number.

4. Why does turbulence raise h?

   Mixing thins the slow near-wall layer.

Common misconceptions

Myth: Nu uses the solid’s k.

Actually: It uses the fluid’s k.

Myth: One correlation fits all flows.

Actually: Check range and geometry.

Myth: h is constant along a plate.

Actually: Local h falls as the layer grows.

Flashcards

Reynolds number

Inertia over viscosity.

Prandtl number

ν/α.

Nusselt number

hL/k.

Boundary layer

Thin near-wall region.

Correlation

Fit to experiments.

Transition

Laminar to turbulent.

Self-check quiz

1. Re at 5 m/s...

166,667

16,667

1.67×10^6

6000

166,667. VL/ν.

2. Average h…

12.6 W/(m²·K)

126

1.26

242

12.6 W/(m²·K). Nu k/L.

3. Heat rate…

189 W

18.9 W

377 W

63 W

189 W. hAΔT.

4. Transition near…

5×10^5

2300

10^3

10^9

5×10^5. Flat plate.

Try this quiz again

How this helps save the planet

NASA's Earth Observatory says convection carries about 5% of incoming solar energy from the surface into the atmosphere, while evaporation carries about 25%.

Wind speed sets h over oceans and land just as velocity sets h on this unit's plate, which is why winds shape how fast the surface sheds heat.

On Saving Planets: Fluid Mechanics · Oceans

Sources: NASA Earth Observatory: Climate and Earth's Energy Budget (https://earthobservatory.nasa.gov/features/EnergyBalance)

Free learning resources

- J. H. Lienhard IV and J. H. Lienhard V, A Heat Transfer Textbook (free online edition) (https://ahtt.mit.edu/): Free textbook, Chapters 6–7.
- MIT OpenCourseWare 2.51 Intermediate Heat and Mass Transfer (Fall 2008) (https://ocw.mit.edu/courses/2-51-intermediate-heat-and-mass-transfer-fall-2008/): Free MIT lectures.

☐ **I finished this unit**

Internal Flow and Heat Exchangers

Pipe-flow convection, mean temperature, the Dittus–Boelter correlation, heat exchanger types, LMTD and effectiveness–NTU.

Learning objectives

By the end of this unit you can:

- Use laminar and turbulent pipe correlations.
- Compute a log-mean temperature difference.
- Size a heat exchanger with UA and LMTD.
- Use effectiveness–NTU.

Key concepts

- In a pipe, the bulk (mean) temperature changes along the length as heat enters or leaves.
- Fully developed laminar flow with constant wall temperature has Nu = 3.66; turbulent flow uses Dittus–Boelter (textbook correlations).
- Counterflow exchangers beat parallel flow because the temperature difference stays more even.
- The LMTD method suits sizing when all four temperatures are known.
- The ε-NTU method suits rating when outlet temperatures are unknown.

Key equations

$$Nu_D = 0.023 Re_D^{4/5} Pr^{0.4}$$

```
Nu_D=0.023Re_D^4/5Pr^0.4
```

Dittus–Boelter (heating)

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

```
Δ T_lm=(Δ T_1-Δ T_2)/((Δ T_1/Δ T_2))
```

Log-mean temperature difference

$$q = U A \Delta T_{lm}$$

```
q=UAΔ T_lm
```

Exchanger heat rate

$$\varepsilon = 1 - e^{-NTU} \ (C_r = 0)$$

`=1-e^-NTU\ (C_r=0)`

Effectiveness, condenser or evaporator

Worked examples, step by step

Example 6.1 Water (k = 0.6, Pr = 7, textbook values) flows at Re = 20,000 in a 20 mm tube. Find h.

1. Nu = 0.023 × 20,000^0.8 × 7^0.4 = 138.2.
2. h = 138.2 × 0.6/0.02.

Answer: About 4150 W/(m²·K).

Example 6.2 Counterflow: hot 90 → 50 °C, cold 20 → 40 °C. Find the LMTD.

1. ΔT_1 = 90 − 40 = 50 K; ΔT_2 = 50 − 20 = 30 K.
2. LMTD = 20/ln(50/30).

Answer: 39.15 K.

Example 6.3 With U = 500 W/(m²·K) and A = 2 m², find q.

1. q = 500 × 2 × 39.15.

Answer: 39.2 kW.

Practice problems

Work each on paper first, then check.

1. ε for NTU = 2 when one stream condenses (C_r = 0)?

   $1 - e^{-2} = 0.865$.

2. Laminar Nu for constant wall temperature?

   3.66.

3. Why prefer counterflow?

   More even ΔT, more heat per area.

4. Dittus–Boelter Nu for Pr = 0.7, Re = 20,000?

55.0.

Common misconceptions

Myth: Use the arithmetic mean ΔT.

Actually: Use the log mean.

Myth: ε can exceed 1.

Actually: It cannot.

Myth: Laminar correlations work for turbulent flow.

Actually: Check Re first.

Flashcards

LMTD

Log-mean ΔT.

NTU

UA/C_min.

Effectiveness

Actual over maximum heat.

Counterflow

Opposite stream directions.

Fouling

Deposits that add resistance.

Dittus–Boelter

Turbulent pipe correlation.

Self-check quiz

1. LMTD...

39.15 K

40 K

30 K

50 K

39.15 K. 20/ln(5/3).

2. Exchanger q…

39.2 kW

3.92 kW

20 kW

78 kW

39.2 kW. UA LMTD.

3. ε at NTU 2…

0.865

0.5

0.98

2

0.865. $1 - e^{-2}$.

4. Water h…

≈ 4150 W/(m²·K)

≈ 41

≈ 415,000

≈ 1.4

≈ 4150 W/(m²·K). Nu k/D.

Try this quiz again

How this helps save the planet

ENERGY STAR explains that an air-source heat pump moves heat between indoor and outdoor air instead of making it from fuel, using heat exchangers (coils) on both sides.

Better exchangers need a smaller temperature difference to move the same heat, which is one reason modern heat pumps deliver more heat per unit of electricity.

On Saving Planets: Solutions · Thermodynamics

Sources: ENERGY STAR: Air-Source Heat Pumps (https://www.energystar.gov/products/air_source_heat_pumps)

Free learning resources

- J. H. Lienhard IV and J. H. Lienhard V, A Heat Transfer Textbook (free online edition) (https://ahtt.mit.edu/): Free textbook, Chapters 3 and 7.
- MIT OpenCourseWare 2.51 Intermediate Heat and Mass Transfer (Fall 2008) (https://ocw.mit.edu/courses/2-51-intermediate-heat-and-mass-transfer-fall-2008/): Free MIT lectures.

☐ **I finished this unit**

Natural Convection and Boiling

Buoyancy-driven flow, Grashof and Rayleigh numbers, vertical-plate correlations, and an introduction to boiling and condensation.

Learning objectives

By the end of this unit you can:

- Compute the Rayleigh number.
- Use a vertical-plate correlation.
- Compare natural and forced h.
- Describe the boiling curve.

Key concepts

- Warm fluid is lighter and rises; buoyancy, not a fan, drives the flow.
- The Rayleigh number Ra = gβΔTL³/(να) plays the role Re plays in forced flow.
- On a vertical plate, flow is laminar below about Ra = 10⁹ (textbook value).
- Natural-convection h in air is only a few W/(m²·K), so radiation is often comparable.
- Boiling and condensation move large heat at small ΔT because of latent heat.

Key equations

$$Ra_L = \frac{g\beta \Delta T L^3}{\nu \alpha}$$

`Ra_L=(gβΔ TL^3)/(να)`

Rayleigh number

$$\overline{Nu}_L = 0.59 Ra_L^{1/4}$$

`_L=0.59Ra_L^1/4`

Laminar vertical plate

$$\beta = 1/T$$

Ideal-gas expansion coefficient

$$Gr = Ra/Pr$$

`Gr=Ra/Pr`

Worked examples, step by step

Example 7.1 A 0.3 m vertical plate is 30 K above air ($\beta = 1/300$ K^{-1}, $\nu = 1.6 \times 10^{-5}$, $\alpha = 2.2 \times 10^{-5}$, sample values). Find Ra.

1. $Ra = 9.80665 \times (1/300) \times 30 \times 0.3^3/(1.6 \times 10^{-5} \times 2.2 \times 10^{-5})$.

Answer: 7.52×10^7, laminar.

Example 7.2 Find Nu and h with k = 0.026.

1. $Nu = 0.59 \times (7.52 \times 10^7)\text{^}¼ = 54.9$.
2. $h = 54.9 \times 0.026/0.3$.

Answer: 4.76 W/(m²·K).

Example 7.3 Heat from a 0.3 × 1 m plate?

1. $q = 4.76 \times 0.3 \times 30$.

Answer: 42.9 W.

Practice problems

Work each on paper first, then check.

1. Compare with Unit 5's forced h of 12.6.

   Forced is about 2.64 times higher.

2. Laminar limit on Ra?

   About 10^9.

3. Why is boiling so effective?

   Latent heat moves energy at small ΔT.

4. β for an ideal gas at 300 K?

   1/300 K^{-1} = 3.33×10^{-3}.

Common misconceptions

Myth: Natural convection is negligible.

Actually: It often matches radiation.

Myth: Ra uses velocity.

Actually: It uses buoyancy.

Myth: Boiling h is low.

Actually: It is among the highest.

Flashcards

Rayleigh number

Buoyancy strength.

Grashof number

Buoyancy over viscosity.

β

Expansion coefficient.

Boiling curve

Heat flux vs wall superheat.

Critical heat flux

Peak nucleate boiling flux.

Condensation

Vapor to liquid on a cold wall.

Self-check quiz

1. Ra...

7.52×10^{7}

7.52×10^{9}

752

5×10^{5}

7.52×10^{7}. $g\beta\Delta TL^{3}/(\nu\alpha)$.

2. h…

4.76 W/(m²·K)

47.6

0.476

12.6

4.76 W/(m²·K). Nu k/L.

3. Heat…

42.9 W

429 W

4.29 W

189 W

42.9 W. hAΔT.

4. Driver of natural convection…

buoyancy

a pump

radiation

pressure drop

buoyancy. Density difference.

Try this quiz again

How this helps save the planet

NASA's Earth Observatory says evaporation removes about 25% of incoming solar energy from the surface and convection about 5%; the latent heat is released when water vapor condenses into

clouds.

At 340 W/m² average sunlight, those shares are about 85 and 17 W/m², the same phase-change and buoyancy processes this unit treats.

On Saving Planets: Oceans · Earth Observation

Sources: NASA Earth Observatory: Climate and Earth's Energy Budget (https://earthobservatory.nasa.gov/features/EnergyBalance)

Free learning resources

- J. H. Lienhard IV and J. H. Lienhard V, A Heat Transfer Textbook (free online edition) (https://ahtt.mit.edu/): Free textbook, Chapters 8–9.
- MIT OpenCourseWare 2.51 Intermediate Heat and Mass Transfer (Fall 2008) (https://ocw.mit.edu/courses/2-51-intermediate-heat-and-mass-transfer-fall-2008/): Free MIT lectures.

☐ **I finished this unit**

Radiation Fundamentals

Blackbodies, Planck's law, Wien's law, the Stefan–Boltzmann law, emissivity, absorptivity and Kirchhoff's law.

Learning objectives

By the end of this unit you can:

- Find a blackbody's peak wavelength.
- Compute emissive power.
- Use emissivity and absorptivity.
- Find a planet's effective temperature.

Key concepts

- A blackbody absorbs all radiation and emits the most possible at each temperature and wavelength.
- Wien's law: peak wavelength is inversely proportional to absolute temperature.
- Total emissive power grows as σT^4, so doubling temperature multiplies emission by 16.
- Real surfaces emit a fraction ε of blackbody power; for a gray surface $\alpha = \varepsilon$ (Kirchhoff).
- Solar radiation is short-wave; Earth's emission is long-wave infrared, which is why gases like CO_2 and water vapor matter.

Key equations

$$\lambda_{max} T = 2898\ \mu m \cdot K$$

_maxT=2898\ μ m· K

Wien's displacement law

$$E_b = \sigma T^4$$

E_b=σ T^4

Stefan–Boltzmann

$$E = \varepsilon \sigma T^4$$

E=σ T^4

Real surface

$$T_e = \left(\frac{\bar{S}(1-a)}{\sigma} \right)^{1/4}$$

`T_e=(( S(1-a))/(σ))^1/4`

Effective temperature

Worked examples, step by step

Example 8.1 NASA gives the Sun about 5,800 K. Find its peak wavelength.

1. 2898/5800.

Answer: 0.500 µm, visible light.

Example 8.2 Earth absorbs about 240 W/m² (NASA). Find its effective temperature.

1. T = (240/5.670374419 × 10⁻⁸)^¼.

Answer: 255.1 K, about −18 °C (NASA rounds to about −20 °C).

Example 8.3 Blackbody emission from a 288 K surface?

1. σ × 288⁴.

Answer: 390 W/m².

Practice problems

Work each on paper first, then check.

1. Peak wavelength at 288 K?

   10.06 µm, thermal infrared.

2. Emission ratio when T doubles?

   $2^4 = 16$.

3. Peak for a 3000 K lamp filament?

   0.966 µm, near infrared.

4. Gray surface with ε = 0.8: α?

   0.8.

Common misconceptions

Myth: Hot means visible.

Actually: Room-temperature objects glow in infrared.

Myth: Use °C in σT^4.

Actually: Use kelvin.

Myth: Shiny means cold.

Actually: Low ε means it emits and absorbs little.

Flashcards

Blackbody

Perfect absorber and emitter.

Wien’s law

λ_max T = 2898 μm·K.

Emissivity

Emission relative to blackbody.

Kirchhoff’s law

α = ε for gray surfaces.

Planck’s law

Spectral blackbody emission.

Effective temperature

Blackbody-equivalent T.

Self-check quiz

1. Sun peak...

0.500 μm

10 μm

5 μm

0.05 μm

0.500 μm. 2898/5800.

2. Earth effective temperature...

255 K

288 K

300 K

5800 K

255 K. (240/σ)^¼.

3. Double T, emission...

×16

×2

×4

×8

×16. T^4.

4. 288 K blackbody...

390 W/m²

240 W/m²

1360 W/m²

39 W/m²

390 W/m². σT^4.

Try this quiz again

How this helps save the planet

NASA's Earth Observatory says the Sun's surface is about 5,800 K, Earth's effective radiating temperature is about −20 °C, and doubling an object's temperature multiplies its radiated energy by 16.

NASA also notes that water vapor lets most infrared escape between 8 and 14 μm, while carbon dioxide absorbs at wavelengths beyond about 12–13 μm, near the edge of that window.

On Saving Planets: Earth Observation · Solutions

Sources: NASA Earth Observatory: Climate and Earth's Energy Budget (https://earthobservatory.nasa.gov/features/EnergyBalance)

Free learning resources

- J. H. Lienhard IV and J. H. Lienhard V, A Heat Transfer Textbook (free online edition) (https://ahtt.mit.edu/): Free textbook, Chapter 10.
- PhET: Blackbody Spectrum (https://phet.colorado.edu/en/simulations/blackbody-spectrum): Free simulation.

☐ **I finished this unit**

Radiation Exchange and Shields

View factors, reciprocity, gray-surface networks, parallel plates, radiation shields and thermal protection in space.

Learning objectives

By the end of this unit you can:

- Use view-factor reciprocity.
- Compute net exchange between parallel plates.
- Show how a shield cuts heat flow.
- Estimate radiation from a hot shield.

Key concepts

- The view factor F_{12} is the fraction of radiation leaving surface 1 that reaches surface 2.
- Reciprocity: $A_1F_{12} = A_2F_{21}$; summation: the view factors from a surface add to 1.
- Gray surfaces exchange heat through surface resistances $(1 - \varepsilon)/(\varepsilon A)$ and space resistances $1/(A_1F_{12})$.
- A thin low-ε shield between two plates adds resistances and cuts exchange sharply; multilayer insulation stacks many.
- A heat shield facing the Sun gets hot, reradiates, and protects what lies in its shadow.

Key equations

$$A_1F_{12} = A_2F_{21}$$

```
A_1F_12=A_2F_21
```

Reciprocity

$$q'' = \frac{\sigma(T_1^4 - T_2^4)}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}$$

```
q^=(σ(T_1^4-T_2^4))/(1/_1+1/_2-1)
```

Parallel plates

$$R_{surf} = \frac{1 - \varepsilon}{\varepsilon A}$$

```
R_surf=(1-)/( A)
```

Surface resistance

$$R_{space} = \frac{1}{A_1 F_{12}}$$

`R_space=1A_1F_12`

Space resistance

Worked examples, step by step

Example 9.1 Large parallel plates at 400 K and 300 K, both ε = 0.8. Net flux?

1. Denominator: 1.25 + 1.25 − 1 = 1.5.
2. q" = σ(400⁴ − 300⁴)/1.5.

Answer: 662 W/m².

Example 9.2 Insert a shield with ε = 0.05 on both sides.

1. Resistance: 2 × (1.25 + 20 − 1) = 40.5.
2. q" = σ × 1.75 × 10¹⁰/40.5.

Answer: 24.5 W/m², 27 times less.

Example 9.3 A small sphere (A_1 = 1 m²) sits inside a shell of area 4 m². Find F_{21}.

1. F_{12} = 1.
2. $F_{21} = A_1F_{12}/A_2$.

Answer: 0.25.

Practice problems

Work each on paper first, then check.

1. Blackbody flux at Parker's 1,377 °C shield limit?

   σ × 1650.15⁴ = 4.20 × 10⁵ W/m².

2. Why does one shield with ε = 0.05 work so well?

   Its two surface resistances add about 39.

3. Sum of view factors from an enclosure surface?

    1.

4. What is MLI?

    Many thin low-ε shields in a stack.

Common misconceptions

Myth: View factors are symmetric.
Actually: Only $A_1F_{12} = A_2F_{21}$.

Myth: Shields must be thick.
Actually: Low ε matters, not thickness.

Myth: Black surfaces make good shields.
Actually: Shields need low ε.

Flashcards

View factor

Fraction of radiation intercepted.

Reciprocity

$A_1F_{12} = A_2F_{21}$.

Radiosity

All radiation leaving a surface.

Radiation shield

Low-ε barrier.

MLI

Multilayer insulation.

Gray surface

ε independent of wavelength.

Self-check quiz

1. Plate flux...

662 W/m²

993 W/m²

24.5 W/m²

1000 W/m²

662 W/m². σΔT⁴/1.5.

2. With shield...

24.5 W/m²

331 W/m²

66 W/m²

2.45 W/m²

24.5 W/m². ÷ 40.5.

3. F_{21}...

0.25

1

4

0.5

0.25. Reciprocity.

4. Good shields have...

low ε

high ε

high k

high h

low ε. Weak emitters.

Try this quiz again

How this helps save the planet

NASA says Parker Solar Probe, launched August 12, 2018, is protected by a 4.5-inch (11.43 cm) carbon-composite shield that withstands nearly 2,500 °F (1,377 °C) as the spacecraft passes about 3.9 million miles (6.2 million km) from the Sun.

In 2021 Parker became the first spacecraft to fly through the Sun's corona; its shield keeps the instruments behind it in shadow, the same idea as this unit's radiation shield.

On Saving Planets: Spacecraft Design · Earth Observation

Sources: NASA Science: Parker Solar Probe (https://science.nasa.gov/mission/parker-solar-probe/)

Free learning resources

- J. H. Lienhard IV and J. H. Lienhard V, A Heat Transfer Textbook (free online edition) (https://ahtt.mit.edu/): Free textbook, Chapter 10.
- NASA Science: Parker Solar Probe (https://science.nasa.gov/mission/parker-solar-probe/): NASA mission page.

☐ **I finished this unit**

Heat Pumps, Buildings and Earth’s Energy Balance

Heat-pump COP, Carnot limits, whole-building heat loss, and the planetary energy imbalance measured from space.

Learning objectives

By the end of this unit you can:

- Compute heat-pump COP and its Carnot limit.
- Size electricity for a heating load.
- Convert a flux imbalance to total power.
- Connect all three modes in one system.

Key concepts

- A heat pump moves heat from cold to hot using work; its heating COP is heat delivered divided by work.
- The Carnot COP, T_h/(T_h − T_c), is an upper limit that falls as the outdoor temperature drops.
- A building’s heat loss is its UA times the indoor–outdoor difference; insulation lowers UA before you buy equipment.
- Earth’s energy imbalance is a small difference between two large flows, measured by satellites such as NASA’s CERES instruments.
- Every system in this course combines conduction, convection and radiation in a resistance network.

Key equations

$$COP_h = \frac{Q_h}{W}$$

```
COP_h=(Q_h)/(W)
```

Heating COP

$$COP_{Carnot} = \frac{T_h}{T_h - T_c}$$

```
COP_Carnot=(T_h)/(T_h-T_c)
```

Carnot limit

$$Q = UA\Delta T$$

```
Q=UAΔ T
```

Building heat loss

$$P = \Delta F \cdot A_E$$

P=Δ F· A_E

Planetary imbalance power

Worked examples, step by step

Example 10.1 ENERGY STAR says a heat pump can deliver up to three times more heat than the electricity it uses. Electricity for 9 kW of heat?

1. W = 9/3.

Answer: 3 kW.

Example 10.2 Carnot heating COP with 35 °C (308 K) delivery and 0 °C (273 K) outdoors?

1. 308/(308 − 273).

Answer: 8.8; real units reach about a third of that.

Example 10.3 NASA says the imbalance is a little over 0.8 W/m². With Earth's area 5.1 × 10¹⁴ m² (textbook value), total power?

1. 0.8 × 5.1 × 10¹⁴.

Answer: About 4.1 × 10¹⁴ W.

Practice problems

Work each on paper first, then check.

1. Half of a $1,900 yearly energy bill?

   About $950 for heating and cooling.

2. Carnot COP at −10 °C (263 K) outdoors, 308 K delivery?

   6.84.

3. Why insulate before buying a heat pump?

   Lower UA means a smaller, cheaper unit.

4. What does CERES measure?

   Earth's radiant energy from space.

Common misconceptions

Myth: COP above 1 breaks energy conservation.
Actually: Heat is moved, not created.

Myth: Turn heat pumps way down at night.
Actually: ENERGY STAR advises a steady setting.

Myth: 0.8 W/m² is negligible.
Actually: Over Earth it is about 4×10^{14} W.

Flashcards

COP

Heat delivered per unit work.

Carnot COP

Ideal limit.

UA

Overall conductance.

Energy imbalance

Absorbed minus emitted.

CERES

NASA radiation-budget instruments.

Heat pump

Moves heat with work.

Self-check quiz

1. Electricity for 9 kW at COP 3...

3 kW

27 kW

9 kW

1 kW

3 kW. 9/3.

2. Carnot COP…

8.8

3

1.13

35

8.8. 308/35.

3. Imbalance power…

≈ 4.1×10^{14} W

≈ 4×10^{9} W

≈ 0.8 W

≈ 10^{20} W

≈ 4.1×10^{14} W. $0.8 \times 5.1 \times 10^{14}$.

4. Lower UA by…

insulating

raising COP

adding fins

painting black

insulating. Resistance.

Try this quiz again

How this helps save the planet

ENERGY STAR says an air-source heat pump can deliver up to three times more heat energy than the electrical energy it uses, because it moves heat instead of making it.

NASA's Earth Observatory says Earth is absorbing a little more than 0.8 W/m² more than it emits; NASA's CERES instruments measure the radiation budget from orbit.

On Saving Planets: Solutions · Earth Observation

Sources: ENERGY STAR: Air-Source Heat Pumps (https://www.energystar.gov/products/air_source_heat_pumps) · NASA Earth Observatory: Climate and Earth's Energy Budget (https://earthobservatory.nasa.gov/features/EnergyBalance) · NASA Langley: CERES (Clouds and the Earth's Radiant Energy System) (https://ceres.larc.nasa.gov/)

Free learning resources

- ENERGY STAR: Air-Source Heat Pumps (https://www.energystar.gov/products/air_source_heat_pumps): ENERGY STAR guide.
- NASA Langley: CERES (Clouds and the Earth's Radiant Energy System) (https://ceres.larc.nasa.gov/): NASA CERES.

☐ **I finished this unit**

Problem Sets

These practice problems live inside each unit. Work on paper first, then open the answer.

1. Modes of Heat Transfer and Energy Balances
   4 problems
2. Steady Conduction and Thermal Resistance
   4 problems
3. Cylinders, Spheres and Fins
   4 problems
4. Transient Conduction
   4 problems
5. External Forced Convection
   4 problems
6. Internal Flow and Heat Exchangers
   4 problems
7. Natural Convection and Boiling
   4 problems
8. Radiation Fundamentals
   4 problems
9. Radiation Exchange and Shields
   4 problems
10. Heat Pumps, Buildings and Earth's Energy Balance

4 problems

The lab (Heat transfer lab)

The lab is the hands-on part of the course. Here it is free and for practice only, with no credit.

Every lab runs in a free simulation or a spreadsheet, so there are no burn or electrical hazards. Do not heat, boil or ignite anything for this course. Take screen breaks, sit with good posture, and keep cables out of walkways.

Safety reference: OSHA: Walking-working surfaces (slip, trip and fall hazards) (https://www.osha.gov/walking-working-surfaces)

Lab A: Heat flow and a wall-insulation calculator

WEEK 2

Goal: Watch heat flow between objects in PhET Energy Forms and Changes, then compute wall heat flux for several insulation thicknesses.

$$q'' = \Delta T / R''$$

q^=Δ T/R^

Series wall

Procedure

1. In PhET Energy Forms and Changes, heat a block and watch energy flow to its neighbor and the air.
2. In a spreadsheet, enter Unit 2's wall without insulation: R" = 0.3079 m²·K/W.
3. Add insulation layers of 0.05, 0.1 and 0.2 m (k = 0.04) and compute q" for ΔT = 20 K.
4. Plot q" against thickness and note the diminishing returns.

Data table

Insulation (m)	R" (m²·K/W)	q" (W/m²)
0	0.3079	64.96
0.05	1.558	12.84
0.1	2.808	7.12
0.2	5.308	3.77

Computed sample values.

Sample calculation

1. R"(0.05) = 0.3079 + 0.05/0.04 = 1.558.
2. q" = 20/1.558 = 12.84 W/m².

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

PhET: Energy Forms and Changes (https://phet.colorado.edu/en/simulations/energy-forms-and-changes)

Planet link: ENERGY STAR: almost half of a typical $1,900 household energy bill goes to heating and cooling. ENERGY STAR: Air-Source Heat Pumps (https://www.energystar.gov/products/air_source_heat_pumps)

- [ ] **I completed this lab (wet or virtual)**

Lab B: Fin efficiency explorer

WEEK 4

Goal: Compute pin-fin efficiency for several lengths and see where adding length stops paying off.

$$\eta_f = \tanh(mL)/(mL)$$

`_f=mL/mL`

Fin efficiency

Procedure

1. Enter Unit 3's fin: k = 200, D = 5 mm, h = 50, so m = 14.14 m^{-1}.
2. Compute η for L = 10, 20 and 40 mm.
3. Compute fin heat for a 50 K base excess.
4. Change h to 200 and repeat.

Data table

L (mm)	mL	η
10	0.1414	0.993
20	0.2828	0.974
40	0.5657	0.905

Computed sample values.

Sample calculation

1. m = √(4 × 50/(200 × 0.005)) = 14.14 m^{-1}.
2. η(40 mm) = tanh(0.5657)/0.5657 = 0.905.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

J. H. Lienhard IV and J. H. Lienhard V, A Heat Transfer Textbook (free online edition) (https://ahtt.mit.edu/)

Planet link: Efficient fins and exchangers let heat pumps move more heat per unit of electricity (ENERGY STAR). ENERGY STAR: Air-Source Heat Pumps (https://www.energystar.gov/products/air_source_heat_pumps)

- [ ] **I completed this lab (wet or virtual)**

Lab C: Lumped cooling curve

WEEK 5

Goal: Model Unit 4's aluminum sphere cooling in a spreadsheet and compare an exact curve with a step-by-step (Euler) solution.

$$T = T_\infty + (T_i - T_\infty)e^{-t/\tau}$$

`T=T_∞+(T_i-T_∞)e^-t/τ`

Lumped response

Procedure

1. Enter T_i = 300 °C, T∞ = 20 °C, τ = 81 s.
2. Compute T every τ out to 3τ.
3. Add an Euler column with a 5 s step and compare.
4. Double h and repeat.

Data table

t (s)	T (°C)
0	300
81	123.0
162	57.9
243	33.9

Computed sample values.

Sample calculation

1. $T(81) = 20 + 280e^{-1} = 123.0$ °C.
2. $T(243) = 20 + 280e^{-3} = 33.9$ °C.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

PhET: Energy Forms and Changes (https://phet.colorado.edu/en/simulations/energy-forms-and-changes)

Planet link: NASA: Earth's surface averages about 15 °C, more than 30 °C warmer than with no atmosphere. NASA Earth Observatory: Climate and Earth's Energy Budget (https://earthobservatory.nasa.gov/features/EnergyBalance)

- [ ] **I completed this lab (wet or virtual)**

Lab D: Flat-plate convection calculator

WEEK 7

Goal: Compute Re and average h for air over a 0.5 m plate at several speeds.

$$\bar{h} = 0.664 \frac{k}{L} Re_L^{1/2} Pr^{1/3}$$

```
h=0.664k/LRe_L^1/2Pr^1/3
```

Laminar plate

Procedure

1. Enter air properties: ν = 1.5 × 10⁻⁵, k = 0.026, Pr = 0.71.
2. Compute Re and h at 1, 5 and 10 m/s.
3. Check each Re is below 5 × 10⁵.
4. Plot h against √V.

Data table

V (m/s)	Re	h (W/(m²·K))
1	33,333	5.62
5	166,667	12.58
10	333,333	17.78

Computed sample values.

Sample calculation

1. Re(1) = 1 × 0.5/1.5 × 10⁻⁵ = 33,333.
2. h(10) = 0.664 × 577.4 × 0.892 × 0.052 = 17.78.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

MIT OpenCourseWare 2.51 Intermediate Heat and Mass Transfer (Fall 2008) (https://ocw.mit.edu/courses/2-51-intermediate-heat-and-mass-transfer-fall-2008/)

Planet link: NASA: convection carries about 5% of incoming solar energy from the surface. NASA Earth Observatory: Climate and Earth's Energy Budget (https://earthobservatory.nasa.gov/features/EnergyBalance)

- [ ] **I completed this lab (wet or virtual)**

Lab E: Blackbody spectra

WEEK 11

Goal: Use PhET Blackbody Spectrum to see Wien's law, then check peaks in a spreadsheet.

$$\lambda_{max} = 2898/T$$

_max=2898/T

Wien's law

Procedure

1. In PhET Blackbody Spectrum, set the Sun, a lamp and Earth.
2. Read the peak wavelength from the graph.
3. Compute 2898/T for 288, 3000 and 5800 K.
4. Compute σT⁴ for each.

Data table

T (K)	λ_max (μm)	σT⁴ (W/m²)
288	10.06	390
3000	0.966	4.59 × 10⁶
5800	0.500	6.42 × 10⁷

Computed values.

Sample calculation

1. 2898/288 = 10.06 μm.
2. σ × 5800⁴ = 6.42 × 10⁷ W/m².

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Runs in a browser.

PhET: Blackbody Spectrum (https://phet.colorado.edu/en/simulations/blackbody-spectrum)

Planet link: NASA: the Sun is about 5,800 K. NASA Earth Observatory: Climate and Earth's Energy Budget (https://earthobservatory.nasa.gov/features/EnergyBalance)

- [ ] **I completed this lab (wet or virtual)**

Lab F: Greenhouse effect and energy balance

WEEK 14

Goal: Explore PhET Greenhouse Effect, then compute Earth's effective temperature for several albedos.

$$T_e = \left(\frac{S(1-a)}{4\sigma} \right)^{1/4}$$

`T_e=((S(1-a))/(4σ))^1/4`

Effective temperature

Procedure

1. In PhET Greenhouse Effect, add and remove clouds and greenhouse gases and watch the temperature.
2. In a spreadsheet, use S = 1360 W/m² (NASA).
3. Compute T_e for albedo 0.25, 0.29 and 0.35.
4. Explain why T_e is below NASA's 15 °C surface average.

Data table

Albedo	T_e (K)
0.25	259.0
0.29	255.4
0.35	249.9

Computed values.

Sample calculation

1. (1360 × 0.71/(4σ))^¼ = 255.4 K.
2. 255.4 − 273.15 = −17.7 °C.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Runs in a browser.

PhET: Greenhouse Effect (https://phet.colorado.edu/en/simulations/greenhouse-effect)

Planet link: NASA: about 29% of sunlight is reflected and Earth absorbs about 240 W/m². NASA Earth Observatory: Climate and Earth's Energy Budget (https://earthobservatory.nasa.gov/features/EnergyBalance)

- [ ] **I completed this lab (wet or virtual)**

Exam prep practice sets

Time yourself: about 10 minutes per problem. Then compare with the full solutions.

Midterm practice set (Units 1–5)

1. Convection from 3 m^2 at h = 15 $W/(m^2 \cdot K)$, ΔT = 20 K?

    1. 15 × 3 × 20.

    Answer: 900 W.

2. Heat flux through 0.15 m of insulation (k = 0.04) plus 0.3079 $m^2 \cdot K/W$ of other layers at ΔT = 20 K?

    1. R" = 0.3079 + 3.75 = 4.058.
    2. 20/4.058.

    Answer: 4.93 W/m^2.

3. Critical radius for k = 0.1 and h = 10?

    1. k/h.

    Answer: 10 mm.

4. τ for a 20 mm aluminum sphere, h = 50?

    1. 2700 × 900 × (0.02/6)/50.

    Answer: 162 s.

5. Re for air at 2 m/s over 0.5 m?

    1. $2 \times 0.5/1.5 \times 10^{-5}$.

    Answer: 66,667.

Final practice set (Units 1–10)

1. LMTD for ΔT_1 = 60 K and ΔT_2 = 20 K?

    1. 40/ln 3.

Answer: 36.4 K.

2. ε for NTU = 1, C_r = 0?

    1. 1 − e⁻¹.

    Answer: 0.632.

3. Ra for Unit 7's plate at L = 0.6 m?

    1. 7.52 × 10⁷ × 8.

    Answer: 6.02 × 10⁸.

4. Peak wavelength at 1000 K?

    1. 2898/1000.

    Answer: 2.90 µm.

5. Parallel plates 500 K and 300 K, ε = 0.9 both?

    1. σ(500⁴ − 300⁴)/(2/0.9 − 1).

    Answer: 2524 W/m².

6. Carnot heating COP, 318 K delivery, 268 K outdoors?

    1. 318/50.

    Answer: 6.36.

Formula sheet

$$q = kA\Delta T/L,\ q = hA\Delta T,\ q = \varepsilon\sigma A(T_s^4 - T_{sur}^4)$$

$$R = L/(kA),\ R = 1/(hA),\ q = \Delta T/\sum R$$

$$R_{cyl} = \ln(r_2/r_1)/(2\pi kL),\ r_{cr} = k/h$$

$$m = \sqrt{hP/(kA_c)},\ \eta_f = \tanh(mL)/(mL)$$

$$Bi = hL_c/k,\ \tau = \rho cV/(hA),\ \theta/\theta_i = e^{-t/\tau}$$

$$Re = VL/\nu,\ Nu = hL/k,\ Nu = 0.664Re^{1/2}Pr^{1/3}$$

$$Nu = 0.023Re^{0.8}Pr^{0.4},\ \Delta T_{lm} = (\Delta T_1 - \Delta T_2)/\ln($$

$$Ra = g\beta\Delta TL^3/(\nu\alpha),\ Nu = 0.59Ra^{1/4}$$

$$\lambda_{max}T = 2898,\ E_b = \sigma T^4,\ A_1F_{12} = A_2F_{21} \qquad COP = Q_h/W,\ COP_C = T_h/(T_h - T_c),\ P = \Delta F$$

Constants

Constant	Value
Stefan–Boltzmann constant	σ = 5.670374419 × 10⁻⁸ W/(m²·K⁴)
Wien's constant (textbook value)	2898 µm·K
Standard gravity	g = 9.80665 m/s²
Air near 300 K (textbook values)	k = 0.026 W/(m·K), ν = 1.5 × 10⁻⁵ m²/s, Pr = 0.71
Aluminum (textbook values)	k = 237 W/(m·K), ρ = 2700 kg/m³, c = 900 J/(kg·K)
Earth's surface area (textbook value)	5.1 × 10¹⁴ m²

Source: NIST: CODATA value, Stefan–Boltzmann constant (https://physics.nist.gov/cgi-bin/cuu/Value?sigma)

Free texts and simulations

Use these free texts, lectures and simulations alongside the course.

- J. H. Lienhard IV and J. H. Lienhard V, A Heat Transfer Textbook (free online edition) (https://ahtt.mit.edu/): Free complete heat transfer textbook.
- MIT OpenCourseWare 2.51 Intermediate Heat and Mass Transfer (Fall 2008) (https://ocw.mit.edu/courses/2-51-intermediate-heat-and-mass-transfer-fall-2008/): Free MIT lectures and problems.
- NASA Earth Observatory: Climate and Earth's Energy Budget (https://earthobservatory.nasa.gov/features/EnergyBalance): Free NASA explainer.
- PhET: Energy Forms and Changes (https://phet.colorado.edu/en/simulations/energy-forms-and-changes): Heat flow interactively.
- PhET: Blackbody Spectrum (https://phet.colorado.edu/en/simulations/blackbody-spectrum): Thermal radiation.
- PhET: Greenhouse Effect (https://phet.colorado.edu/en/simulations/greenhouse-effect): Radiation balance.

Glossary

Albedo
Fraction of sunlight reflected.

Biot number
Internal over external thermal resistance.

Blackbody
Perfect absorber and emitter.

Boundary layer

Thin near-wall flow region.

COP
Heat moved per unit work.

Critical radius
Radius of maximum heat loss from an insulated cylinder.

Effectiveness
Actual over maximum exchanger heat.

Emissivity
Emission relative to a blackbody.

Energy imbalance
Absorbed minus emitted planetary energy.

Fin efficiency
Actual over ideal fin heat.

Fourier’s law
Conduction rate law.

Heat exchanger
Device moving heat between fluids.

LMTD
Log-mean temperature difference.

Lumped capacitance
Uniform-temperature transient model.

Nusselt number
Dimensionless convection coefficient.

Prandtl number
Momentum over thermal diffusivity.

Radiation shield
Low-emissivity barrier.

Rayleigh number
Buoyancy-flow strength.

Thermal resistance
Temperature difference per heat flow.

View factor
Fraction of radiation one surface intercepts.

Self-assessment rubric

No grade or credit is given. Use this to judge honestly where you are in each unit.

Level	What it looks like
4 · Mastery	Draws the system and resistance network, checks dimensionless numbers before choosing a correlation, uses kelvin for radiation, and explains results in plain words.
3 · Proficient	Solves the practice and exam sets with minor slips and checks units.
2 · Developing	Follows worked examples but mixes up k of the solid and fluid, or uses °C in σT^4.
1 · Beginning	Plugs numbers into formulas without a sketch or energy balance; needs to revisit the unit.

Suggested weighting if you want a score

Part	Weight
Practice problems	20%
Labs	25%
Midterm practice set	25%
Final practice set	30%

Aim for level 3 or better in every unit before moving to the next course.

Related courses

- Spacecraft Design AERO 430
- Avionics & Systems Engineering AERO 450
- Propulsion AERO 410
- All courses