

Thermodynamics, fluids & thermal control

Move heat and fluid before temperatures run away

Starting question — Why can a spacecraft be cold outside yet overheat inside?

Intuition. Heat must travel through real paths. Power dissipation, fluid transport, conduction, radiation and thermal inertia determine whether equipment stays inside its operating envelope.

- Explain the governing idea before calculating.
- Name the units, evidence source and operational boundary of every key quantity.
- Check the result with an inverse, bound, refinement or independent physical estimate.

In vacuum, heat does not disappear: it must conduct through structures and ultimately radiate to space. In a duct, gas density, pressure and sometimes temperature change as the flow accelerates. A Martian habitat, a cryogenic tank, a rocket engine and onboard electronics therefore pose different but connected problems governed by conservation laws. This module builds those laws from practical balances.

Before you start — Prerequisites: modules 01 to 09 recommended. Every important symbol is defined again at first use.

Mastery objectives

- explain concepts with units and assumptions
- redo a simple calculation by hand before using a tool
- identify at least one failure mode or model limitation
- connect the discipline to a complete Mars architecture

Zero-prerequisite concepts

These four concept cards establish the vocabulary needed before the calculations and mission decisions in this module.

temperature

Definition. Temperature describes thermal state and determines the direction of spontaneous heat transfer between bodies.

Example. A small electronics package can be hotter than a large water tank even though the tank contains more total thermal energy.

Pitfall. Temperature is not the same quantity as heat or stored energy.

Mental check. Ask which object is hotter and which one contains or releases more energy; those answers need not match.

Guided exercise — temperature

In a Mars mission scenario, identify one situation in which “temperature” changes an engineering or operational decision. State the evidence you would inspect, the mistake you must avoid, and one independent check you would perform before accepting the decision.

Detailed correction — temperature

Core meaning. Temperature describes thermal state and determines the direction of spontaneous heat transfer between bodies.

Mission example. A small electronics package can be hotter than a large water tank even though the tank contains more total thermal energy.

Error to reject. Temperature is not the same quantity as heat or stored energy.

Independent check. Ask which object is hotter and which one contains or releases more energy; those answers need not match.

Quantification

Use the physical unit that belongs to temperature when it is quantitative; if it is qualitative, do not invent a numerical unit.

Verification

Compare the conclusion with the mission example, the stated pitfall and the mental check before using temperature operationally.

thermal power

Definition. Thermal power is the rate at which heat is generated, moved or rejected, measured in watts.

Example. A 500 W computer ultimately adds roughly 500 W of heat to its environment unless useful energy leaves in another form.

Pitfall. Watts are not joules; time is needed to convert a power rate into accumulated energy.

Mental check. Multiply by duration to estimate energy, or divide energy by time to recover average power.

Guided exercise — thermal power

In a Mars mission scenario, identify one situation in which “thermal power” changes an engineering or operational decision. State the evidence you would inspect, the mistake you must avoid, and one independent check you would perform before accepting the decision.

Detailed correction — thermal power

Core meaning. Thermal power is the rate at which heat is generated, moved or rejected, measured in watts.

Mission example. A 500 W computer ultimately adds roughly 500 W of heat to its environment unless useful energy leaves in another form.

Error to reject. Watts are not joules; time is needed to convert a power rate into accumulated energy.

Independent check. Multiply by duration to estimate energy, or divide energy by time to recover average power.

Quantification

Use the physical unit that belongs to thermal power when it is quantitative; if it is qualitative, do not invent a numerical unit.

Verification

Compare the conclusion with the mission example, the stated pitfall and the mental check before using thermal power operationally.

mass flow rate

Definition. Mass flow rate is the mass of fluid crossing a boundary per unit time, commonly kg/s.

Example. A coolant loop moving 0.2 kg of water each second can transport substantial heat with only a modest temperature rise.

Pitfall. Volumetric flow alone is insufficient when density can change.

Mental check. Check that density times velocity times flow area produces kg/s.

Guided exercise — mass flow rate

In a Mars mission scenario, identify one situation in which “mass flow rate” changes an engineering or operational decision. State the evidence you would inspect, the mistake you must avoid, and one independent check you would perform before accepting the decision.

Detailed correction — mass flow rate

Core meaning. Mass flow rate is the mass of fluid crossing a boundary per unit time, commonly kg/s.

Mission example. A coolant loop moving 0.2 kg of water each second can transport substantial heat with only a modest temperature rise.

Error to reject. Volumetric flow alone is insufficient when density can change.

Independent check. Check that density times velocity times flow area produces kg/s.

Quantification

Use the physical unit that belongs to mass flow rate when it is quantitative; if it is qualitative, do not invent a numerical unit.

Verification

Compare the conclusion with the mission example, the stated pitfall and the mental check before using mass flow rate operationally.

radiator

Definition. A radiator rejects thermal energy primarily by electromagnetic radiation to its surroundings.

Example. A spacecraft radiator must see a sufficiently cold part of space and avoid excessive absorbed sunlight or planetary infrared.

Pitfall. A radiator is not simply a cold metal panel; view factor, emissivity and temperature control its performance.

Mental check. For the same area and emissivity, a hotter radiator can reject much more power because radiation rises strongly with absolute temperature.

Guided exercise — radiator

In a Mars mission scenario, identify one situation in which “radiator” changes an engineering or operational decision. State the evidence you would inspect, the mistake you must avoid, and one independent check you would perform before accepting the decision.

Detailed correction — radiator

Core meaning. A radiator rejects thermal energy primarily by electromagnetic radiation to its surroundings.

Mission example. A spacecraft radiator must see a sufficiently cold part of space and avoid excessive absorbed sunlight or planetary infrared.

Error to reject. A radiator is not simply a cold metal panel; view factor, emissivity and temperature control its performance.

Independent check. For the same area and emissivity, a hotter radiator can reject much more power because radiation rises strongly with absolute temperature.

Quantification

Use the physical unit that belongs to radiator when it is quantitative; if it is qualitative, do not invent a numerical unit.

Verification

Compare the conclusion with the mission example, the stated pitfall and the mental check before using radiator operationally.

Calculation laboratory — formula, units, inverse check and limits

Each relation is taught from zero prerequisites: what it asks, what every symbol means, why the operation is valid, how to calculate it and how to catch a wrong result independently.

Canonical quantitative mini-lessons

This block is the module quantitative reference; exercise values are pedagogical and must not be confused with mission data.

Sensible heat for a temperature change

$$Q = m \times c_p \times \Delta T$$

1 — Concrete question

What does “ $Q = m \times c_p \times \Delta T$ ” compute in “Sensible heat for a temperature change”?

2 — Intuition without symbols

Heating a mass requires energy proportional to mass, heat capacity and temperature change.

3 — Quantities

Q : thermal energy; m : mass; c_p : specific heat capacity; ΔT : temperature change

4 — Formula

$$Q = m \times c_p \times \Delta T$$

5 — Read aloud

Read “ $Q = m \times c_p \times \Delta T$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

Q : thermal energy; m : mass; c_p : specific heat capacity; ΔT : temperature change

7 — Pronunciation

Say subscripts, powers, Greek letters and parentheses explicitly so the relation can be reconstructed without seeing the page.

8 — Units

Q in J; m in kg; c_p in J/(kg·K); ΔT in K

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Multiplication converts a rate or specific quantity into a total over the chosen interval or population.

11 — Assumptions

Factors must describe the same scenario and their units must be compatible.

12 — Unit check

Q in J; m in kg; c_p in J/(kg·K); ΔT in K. Verify that dimensional reduction reaches the unit of the requested output.

13 — Numerical case

For $m=10$ kg, $c_p=900$ J/(kg·K) and $\Delta T=20$ K, $Q=180,000$ J = 180 kJ.

14 — Why the calculation works

Multiplication converts a rate or specific quantity into a total over the chosen interval or population.

15 — Independent check

Dividing the result by any non-zero factor must recover the other factor.

16 — Mental estimate

Estimating each factor separately predicts the order of magnitude of the product.

17 — Interpretation

The relation assumes a representative heat capacity across the temperature range.

18 — What the result does not prove

The calculation proves neither that the inputs are correct nor that the model remains valid outside the declared scenario; those questions require separate evidence.

19 — Sensitivity

With independent factors, a relative change in one factor transfers directly to the product.

20 — Guided and autonomous exercises

Guided exercise. $m=5$ kg, $c_p=1000$ J/(kg·K), $\Delta T=15$ K.

Detailed guided correction — open after trying

$m=5$ kg, $c_p=1000$ J/(kg·K), $\Delta T=15$ K. $Q=75,000$ J = 75 kJ.

Autonomous exercise. $m=20$ kg, $c_p=500$ J/(kg·K), $\Delta T=8$ K.

Autonomous correction — open after trying

$m=20\text{ kg}$, $c_p=500\text{ J/(kg}\cdot\text{K)}$, $\Delta T=8\text{ K}$. $Q=80,000\text{ J} = 80\text{ kJ}$.

21 — Mission decision

Size the thermal source or sink using both total energy and available power.

First law for a closed system

$$\Delta U = Q_{\text{in}} - W_{\text{out}}$$

1 — Concrete question

What does “ $\Delta U = Q_{\text{in}} - W_{\text{out}}$ ” compute in “First law for a closed system”?

2 — Intuition without symbols

Internal energy changes according to heat entering and work leaving.

3 — Quantities

ΔU : internal-energy change; Q_{in} : net heat received; W_{out} : net work delivered by the system

4 — Formula

$$\Delta U = Q_{\text{in}} - W_{\text{out}}$$

5 — Read aloud

Read “ $\Delta U = Q_{\text{in}} - W_{\text{out}}$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

ΔU : internal-energy change; Q_{in} : net heat received; W_{out} : net work delivered by the system

7 — Pronunciation

Say subscripts, powers, Greek letters and parentheses explicitly so the relation can be reconstructed without seeing the page.

8 — Units

all terms in J

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Subtraction isolates a margin or change between two quantities expressed on the same basis.

11 — Assumptions

Both terms must use the same frame, unit and system boundary.

12 — Unit check

all terms in J Verify that dimensional reduction reaches the unit of the requested output.

13 — Numerical case

With $Q_{\text{in}}=500\text{ kJ}$ and $W_{\text{out}}=120\text{ kJ}$, $\Delta U=380\text{ kJ}$.

14 — Why the calculation works

Subtraction isolates a margin or change between two quantities expressed on the same basis.

15 — Independent check

Adding the difference back to the subtracted term must recover the initial term.

16 — Mental estimate

Comparing the two terms is enough to predict the sign and scale of the difference.

17 — Interpretation

The sign depends on the adopted heat/work convention and must remain consistent.

18 — What the result does not prove

The calculation proves neither that the inputs are correct nor that the model remains valid outside the declared scenario; those questions require separate evidence.

19 — Sensitivity

Increasing the first term raises the result; increasing the second lowers it with unit slope.

20 — Guided and autonomous exercises

Guided exercise. $Q_{\text{in}}=300\text{ kJ}$, $W_{\text{out}}=80\text{ kJ}$.

Detailed guided correction — open after trying

$Q_{\text{in}}=300 \text{ kJ}$, $W_{\text{out}}=80 \text{ kJ}$. $\Delta U=220 \text{ kJ}$.

Autonomous exercise. $Q_{\text{in}}=100 \text{ kJ}$, $W_{\text{out}}=160 \text{ kJ}$.

Autonomous correction — open after trying

$Q_{\text{in}}=100 \text{ kJ}$, $W_{\text{out}}=160 \text{ kJ}$. $\Delta U=-60 \text{ kJ}$.

21 — Mission decision

Close the energy balance before inferring temperature or thermodynamic state.

Ideal-gas pressure

$$p = n \times R_{\text{gas}} \times T / V$$

1 — Concrete question

What does “ $p = n \times R_{\text{gas}} \times T / V$ ” compute in “Ideal-gas pressure”?

2 — Intuition without symbols

For a sufficiently dilute gas, pressure, amount, temperature and volume follow a simple relationship.

3 — Quantities

p : pressure; n : amount of substance; R_{gas} : gas constant; T : absolute temperature; V : volume

4 — Formula

$$p = n \times R_{\text{gas}} \times T / V$$

5 — Read aloud

Read “ $p = n \times R_{\text{gas}} \times T / V$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

p : pressure; n : amount of substance; R_{gas} : gas constant; T : absolute temperature; V : volume

7 — Pronunciation

Say subscripts, powers, Greek letters and parentheses explicitly so the relation can be reconstructed without seeing the page.

8 — Units

p in Pa; n in mol; R_{gas} in J/(mol·K); T in K; V in m³

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

The relation turns the mini-lesson mechanism into a quantitative statement that can be checked by numerical substitution.

11 — Assumptions

Inputs must come from the same scenario with units, signs and conventions explicitly aligned.

12 — Unit check

p in Pa; n in mol; R_{gas} in J/(mol·K); T in K; V in m³ Verify that dimensional reduction reaches the unit of the requested output.

13 — Numerical case

With $n=100 \text{ mol}$, $R_{\text{gas}}=8.314 \text{ J/(mol·K)}$, $T=300 \text{ K}$ and $V=2 \text{ m}^3$, $p \approx 124,710 \text{ Pa}$.

14 — Why the calculation works

The relation turns the mini-lesson mechanism into a quantitative statement that can be checked by numerical substitution.

15 — Independent check

Recomputing with the inverse relation or a second method should recover the same order of magnitude.

16 — Mental estimate

Estimating the scale before using a calculator helps catch factor, sign or unit errors.

17 — Interpretation

The model becomes less accurate at high pressure or near phase change.

18 — What the result does not prove

The calculation proves neither that the inputs are correct nor that the model remains valid outside the declared scenario; those questions require separate evidence.

19 — Sensitivity

Varying one input at a time reveals which variable drives the decision most strongly.

20 — Guided and autonomous exercises

Guided exercise. $n=50$ mol, $T=290$ K, $V=1$ m³.

Detailed guided correction — open after trying

$n=50$ mol, $T=290$ K, $V=1$ m³. $p=50 \times 8.314 \times 290 \approx 120,553$ Pa.

Autonomous exercise. $n=200$ mol, $T=250$ K, $V=4$ m³.

Autonomous correction — open after trying

$n=200$ mol, $T=250$ K, $V=4$ m³. $p \approx 103,925$ Pa.

21 — Mission decision

Use a qualified equation of state when conditions leave the ideal-gas regime.

Mass flow through a section

$$\dot{m} = \rho \times A \times v$$

1 — Concrete question

What does “ $\dot{m} = \rho \times A \times v$ ” compute in “Mass flow through a section”?

2 — Intuition without symbols

Mass flow is the volume crossing the section each second multiplied by fluid density.

3 — Quantities

$\dot{m}$: mass flow; ρ : density; A : flow area; v : mean speed

4 — Formula

$$\dot{m} = \rho \times A \times v$$

5 — Read aloud

Read “ $\dot{m} = \rho \times A \times v$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

$\dot{m}$: mass flow; ρ : density; A : flow area; v : mean speed

7 — Pronunciation

Say subscripts, powers, Greek letters and parentheses explicitly so the relation can be reconstructed without seeing the page.

8 — Units

$\dot{m}$ in kg/s; ρ in kg/m³; A in m²; v in m/s

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Multiplication converts a rate or specific quantity into a total over the chosen interval or population.

11 — Assumptions

Factors must describe the same scenario and their units must be compatible.

12 — Unit check

$\dot{m}$ in kg/s; ρ in kg/m³; A in m²; v in m/s Verify that dimensional reduction reaches the unit of the requested output.

13 — Numerical case

With $\rho=995$ kg/m³, $A=1.13 \times 10^{-4}$ m² and $v=0.80$ m/s, $\dot{m} \approx 0.0900$ kg/s.

14 — Why the calculation works

Multiplication converts a rate or specific quantity into a total over the chosen interval or population.

15 — Independent check

Dividing the result by any non-zero factor must recover the other factor.

16 — Mental estimate

Estimating each factor separately predicts the order of magnitude of the product.

17 — Interpretation

The relation uses section-average values and assumes density and velocity are defined consistently.

18 — What the result does not prove

The calculation proves neither that the inputs are correct nor that the model remains valid outside the declared scenario; those questions require separate evidence.

19 — Sensitivity

With independent factors, a relative change in one factor transfers directly to the product.

20 — Guided and autonomous exercises

Guided exercise. $\rho=1000 \text{ kg/m}^3$, $A=0.002 \text{ m}^2$, $v=1.5 \text{ m/s}$.

Detailed guided correction — open after trying

$\rho=1000 \text{ kg/m}^3$, $A=0.002 \text{ m}^2$, $v=1.5 \text{ m/s}$. $\dot{m}=3.0 \text{ kg/s}$.

Autonomous exercise. $\rho=1.2 \text{ kg/m}^3$, $A=0.5 \text{ m}^2$, $v=10 \text{ m/s}$.

Autonomous correction — open after trying

$\rho=1.2 \text{ kg/m}^3$, $A=0.5 \text{ m}^2$, $v=10 \text{ m/s}$. $\dot{m}=6.0 \text{ kg/s}$.

21 — Mission decision

Check compressibility and flow profile before using it for detailed sizing.

Mach number

$\text{Mach} = v / a_{\text{sound}}$

1 — Concrete question

What does “ $\text{Mach} = v / a_{\text{sound}}$ ” compute in “Mach number”?

2 — Intuition without symbols

Mach number compares flow speed with the local speed of sound.

3 — Quantities

Mach: Mach number; v : flow speed; a_{sound} : local speed of sound

4 — Formula

$\text{Mach} = v / a_{\text{sound}}$

5 — Read aloud

Read “ $\text{Mach} = v / a_{\text{sound}}$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

Mach: Mach number; v : flow speed; a_{sound} : local speed of sound

7 — Pronunciation

Say subscripts, powers, Greek letters and parentheses explicitly so the relation can be reconstructed without seeing the page.

8 — Units

Mach dimensionless; v and a_{sound} in the same speed unit

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Division compares one quantity with a homogeneous reference and produces a proportion indicator.

11 — Assumptions

Both quantities must belong to the same scope and time period.

12 — Unit check

Mach dimensionless; v and a_{sound} in the same speed unit Verify that dimensional reduction reaches the unit of the requested output.

13 — Numerical case

With $v=680$ m/s and $a_{\text{sound}}=340$ m/s, $\text{Mach}=2.0$.

14 — Why the calculation works

Division compares one quantity with a homogeneous reference and produces a proportion indicator.

15 — Independent check

Multiplying the result by the denominator must recover the numerator.

16 — Mental estimate

Before calculating, compare numerator and denominator mentally to predict whether the result should be below, near or above one.

17 — Interpretation

Sound speed depends on gas composition and temperature; it is not universal.

18 — What the result does not prove

The calculation proves neither that the inputs are correct nor that the model remains valid outside the declared scenario; those questions require separate evidence.

19 — Sensitivity

The result rises with the numerator and falls with the denominator, all else equal.

20 — Guided and autonomous exercises

Guided exercise. $v=255$ m/s, $a_{\text{sound}}=340$ m/s.

Detailed guided correction — open after trying

$v=255$ m/s, $a_{\text{sound}}=340$ m/s. $\text{Mach}=0.75$.

Autonomous exercise. $v=1020$ m/s, $a_{\text{sound}}=340$ m/s.

Autonomous correction — open after trying

$v=1020$ m/s, $a_{\text{sound}}=340$ m/s. $\text{Mach}=3.0$.

21 — Mission decision

Use local fluid properties before classifying a regime as subsonic, transonic or supersonic.

Steady thermal conduction

$$Q_{\text{dot_cond}} = k \times A \times \Delta T / L$$

1 — Concrete question

What does “ $Q_{\text{dot_cond}} = k \times A \times \Delta T / L$ ” compute in “Steady thermal conduction”?

2 — Intuition without symbols

Conduction rises with conductivity, area and temperature difference, but falls as the path becomes longer.

3 — Quantities

$Q_{\text{dot_cond}}$: conducted heat rate; k : conductivity; A : conducting area; ΔT : temperature difference; L : thickness

4 — Formula

$$Q_{\text{dot_cond}} = k \times A \times \Delta T / L$$

5 — Read aloud

Read “ $Q_{\text{dot_cond}} = k \times A \times \Delta T / L$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

$Q_{\text{dot_cond}}$: conducted heat rate; k : conductivity; A : conducting area; ΔT : temperature difference; L : thickness

7 — Pronunciation

Say subscripts, powers, Greek letters and parentheses explicitly so the relation can be reconstructed without seeing the page.

8 — Units

$Q_{\text{dot_cond}}$ in W; k in $\text{W}/(\text{m}\cdot\text{K})$; A in m^2 ; ΔT in K; L in m

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

The relation turns the mini-lesson mechanism into a quantitative statement that can be checked by numerical substitution.

11 — Assumptions

Inputs must come from the same scenario with units, signs and conventions explicitly aligned.

12 — Unit check

$Q_{\text{dot_cond}}$ in W; k in $\text{W}/(\text{m}\cdot\text{K})$; A in m^2 ; ΔT in K; L in m Verify that dimensional reduction reaches the unit of the requested output.

13 — Numerical case

With $k=0.04 \text{ W}/(\text{m}\cdot\text{K})$, $A=10 \text{ m}^2$, $\Delta T=40 \text{ K}$ and $L=0.20 \text{ m}$, $Q_{\text{dot_cond}}=80 \text{ W}$.

14 — Why the calculation works

The relation turns the mini-lesson mechanism into a quantitative statement that can be checked by numerical substitution.

15 — Independent check

Recomputing with the inverse relation or a second method should recover the same order of magnitude.

16 — Mental estimate

Estimating the scale before using a calculator helps catch factor, sign or unit errors.

17 — Interpretation

The model assumes an approximately one-dimensional gradient and steady conditions.

18 — What the result does not prove

The calculation proves neither that the inputs are correct nor that the model remains valid outside the declared scenario; those questions require separate evidence.

19 — Sensitivity

Varying one input at a time reveals which variable drives the decision most strongly.

20 — Guided and autonomous exercises

Guided exercise. $k=0.1$, $A=2$, $\Delta T=30$, $L=0.05$.

Detailed guided correction — open after trying

$k=0.1$, $A=2$, $\Delta T=30$, $L=0.05$. $Q_{\text{dot_cond}}=120 \text{ W}$.

Autonomous exercise. $k=0.02$, $A=5$, $\Delta T=50$, $L=0.10$.

Autonomous correction — open after trying

$k=0.02$, $A=5$, $\Delta T=50$, $L=0.10$. $Q_{\text{dot_cond}}=50 \text{ W}$.

21 — Mission decision

Add thermal bridges and real geometry before freezing insulation design.

Net radiative heat transfer between two temperatures

$$Q_{\text{dot_rad}} = \epsilon \times \sigma \times A \times (T_{\text{hot}}^4 - T_{\text{cold}}^4)$$

1 — Concrete question

What does “ $Q_{\text{dot_rad}} = \epsilon \times \sigma \times A \times (T_{\text{hot}}^4 - T_{\text{cold}}^4)$ ” compute in “Net radiative heat transfer between two temperatures”?

2 — Intuition without symbols

Radiation depends very strongly on absolute temperature because power scales with the fourth power.

3 — Quantities

$Q_{\text{dot_rad}}$: net radiative heat rate; ϵ : effective emissivity; σ : Stefan-Boltzmann constant; A : area;
 T_{hot} : hot absolute temperature; T_{cold} : cold absolute temperature

4 — Formula

$$Q_{\text{dot_rad}} = \epsilon \times \sigma \times A \times (T_{\text{hot}}^4 - T_{\text{cold}}^4)$$

5 — Read aloud

Read " $Q_{\text{dot_rad}} = \epsilon \times \sigma \times A \times (T_{\text{hot}}^4 - T_{\text{cold}}^4)$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

$Q_{\text{dot_rad}}$: net radiative heat rate; ϵ : effective emissivity; σ : Stefan-Boltzmann constant; A : area;
 T_{hot} : hot absolute temperature; T_{cold} : cold absolute temperature

7 — Pronunciation

Say subscripts, powers, Greek letters and parentheses explicitly so the relation can be reconstructed without seeing the page.

8 — Units

$Q_{\text{dot_rad}}$ in W; ϵ dimensionless; σ in $\text{W}/(\text{m}^2 \cdot \text{K}^4)$; A in m^2 ; temperatures in K

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

The power-law relation is nonlinear: a small change in a powered variable can strongly move the result.

11 — Assumptions

Parameters and temperatures must use the absolute units required by the model.

12 — Unit check

$Q_{\text{dot_rad}}$ in W; ϵ dimensionless; σ in $\text{W}/(\text{m}^2 \cdot \text{K}^4)$; A in m^2 ; temperatures in K Verify that dimensional reduction reaches the unit of the requested output.

13 — Numerical case

With $\epsilon=0.9$, $A=2 \text{ m}^2$, $T_{\text{hot}}=300 \text{ K}$, $T_{\text{cold}}=200 \text{ K}$ and $\sigma=5.670\text{e-}8$, $Q_{\text{dot_rad}} \approx 663.4 \text{ W}$.

14 — Why the calculation works

The power-law relation is nonlinear: a small change in a powered variable can strongly move the result.

15 — Independent check

Recomputing each powered term separately and then the difference provides an independent check.

16 — Mental estimate

Comparing the powered terms before coefficients quickly exposes an impossible order of magnitude.

17 — Interpretation

Real geometry also requires view factors and sometimes multiple radiating surfaces.

18 — What the result does not prove

The calculation proves neither that the inputs are correct nor that the model remains valid outside the declared scenario; those questions require separate evidence.

19 — Sensitivity

Sensitivity is dominated by the variable raised to the highest power.

20 — Guided and autonomous exercises

Guided exercise. $\epsilon=0.8$, $A=1 \text{ m}^2$, $T_{\text{hot}}=320 \text{ K}$, $T_{\text{cold}}=250 \text{ K}$.

Detailed guided correction — open after trying

$\epsilon=0.8$, $A=1 \text{ m}^2$, $T_{\text{hot}}=320 \text{ K}$, $T_{\text{cold}}=250 \text{ K}$. $Q_{\text{dot_rad}} \approx 298.4 \text{ W}$.

Autonomous exercise. $\epsilon=0.9$, $A=3 \text{ m}^2$, $T_{\text{hot}}=280 \text{ K}$, $T_{\text{cold}}=220 \text{ K}$.

Autonomous correction — open after trying

$\epsilon=0.9$, $A=3 \text{ m}^2$, $T_{\text{hot}}=280 \text{ K}$, $T_{\text{cold}}=220 \text{ K}$. $Q_{\text{dot_rad}} \approx 582.4 \text{ W}$.

21 — Mission decision

Size a radiator using qualified absolute temperatures, optical properties and view factors.

1. Temperature, heat and internal energy

Temperature describes thermal state; heat is energy transferred because of a temperature difference. Confusing the two produces bad reasoning. An object can store substantial energy without extreme temperature if its heat capacity is large. Spacecraft analysis therefore tracks energy entering, leaving and accumulating in a component or volume.

Engineering habit. For “temperature, heat and internal energy”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

2. First law: close the energy balance

Over a chosen time interval, change in stored energy equals inputs minus losses plus work received. The principle applies to batteries, habitats and fluids. The most important choice is the system boundary. A poorly defined boundary creates double counting, for example when electrical power that later appears as heat is counted twice.

Engineering habit. For “first law: close the energy balance”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

Approfondissement — Entropy and irreversibility: why no thermal machine reaches 100 percent

The first law of thermodynamics conserves energy; the second says that real conversions are not perfectly reversible. Entropy S is a state quantity associated with energy dispersal and irreversibility. In a real isolated system, total entropy does not decrease. That is why pumps, compressors, heat exchangers and turbines always convert some available energy into less-useful heat.

For a Mars base, this prevents fantasy energy budgets. A compressor that raises carbon-dioxide pressure consumes electrical energy and heats the gas; that heat must later be rejected. A component efficiency η , the Greek letter eta, is useful output energy divided by input energy. If $\eta = 0.78$, then 78% of the input becomes the defined useful effect and 22% appears elsewhere, often as heat. Thermal rejection has to be sized for those losses, not merely for the nameplate power of the headline machine.

3. Ideal gases and the equation of state

For many preliminary calculations, $pV=nRT$ or $p=\rho RT$ connects pressure, volume, amount of gas, density and temperature. It can estimate the gas mass in a habitat or pressure change after a leak. It is still an approximation: high pressure, very low temperature or phase changes require a validity check.

Engineering habit. For “ideal gases and the equation of state”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

4. Continuity and mass flow rate

Mass conservation gives $\dot{m}=\rho VA$ across a flow section: mass flow $\dot{m}$ in kilograms per second, density ρ in kilograms per cubic metre, speed V in metres per second and area A in square metres. Density and speed may both change. In compressible gas flow, speed cannot be increased indefinitely while assuming density remains fixed.

Engineering habit. For “continuity and mass flow rate”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

Approfondissement — Fluid networks: available pressure, pressure losses and pump margin

Fluid does not automatically move through ten meters of pipe, three filters and four valves at the desired flow rate. A pressure gradient is required. Pressure loss Δp , where Δ means change and p denotes pressure, is consumed by friction, fittings, filters and process equipment. A pump or compressor has to provide that loss plus the required process pressure and margin. As a filter loads with contamination, Δp rises and the operating point moves.

Suppose a pump can produce a 220 kPa pressure rise at the intended flow. Clean piping consumes 140 kPa and the process requires 50 kPa, leaving 30 kPa of margin. If a filter gradually adds 25 kPa, only 5 kPa remains; a small viscosity change may then collapse flow. Water, oxygen, methane and thermal loops on Mars therefore need differential-pressure instrumentation. Trending Δp allows maintenance to replace a filter before the critical flow disappears.

5. Mach number and choking

Mach number is flow speed divided by the local speed of sound. When compressible flow reaches Mach 1 at a minimum area, the mass flow may become choked: for fixed upstream conditions, more mass flow requires changes in pressure, temperature or area rather than simply demanding greater velocity. This is central to nozzles and pressurized gas systems.

Engineering habit. For “mach number and choking”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

6. Conduction, convection and radiation

Conduction transfers energy through material; convection exchanges it between a surface and a fluid; radiation transports electromagnetic energy and works in vacuum. On a spacecraft, radiation is the final path to reject heat to space. On Mars, the thin atmosphere adds convection, but in a regime very different from terrestrial environments.

Engineering habit. For “conduction, convection and radiation”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

7. Radiators, insulation and thermal loops

A radiator is a surface designed to reject heat. Multi-layer insulation reduces some radiative exchange; heat pipes and fluid loops transport energy toward rejection areas. Thermal design must handle both hot and cold extremes: a solution that works in sunlight may fail during a long cold phase or after a neighbouring subsystem shuts down.

Engineering habit. For “radiators, insulation and thermal loops”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

8. Transients and thermal inertia

An equilibrium temperature does not describe the first minutes after a failure. Thermal inertia depends on mass and heat capacity. A large habitat can provide time before a limit is crossed, while a small electronic component can overheat quickly. Engineers therefore calculate both steady states and transients.

Engineering habit. For “transients and thermal inertia”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

Approfondissement — Transients: startup, shutdown and faults can be harder than steady operation

Textbooks often describe a system after it has stabilized, but many failures occur during transitions. At thermal-loop startup, metal masses may be cold, valves are changing position, flow is uneven and sensors respond at different rates. The time constant τ , the Greek letter tau, gives an order of magnitude for how quickly a variable approaches a new equilibrium. If a temperature has $\tau = 12$ min, commanding the process as if it settles in thirty seconds can create oscillation or local overheating.

A crewed system therefore has to simulate normal startup, normal shutdown, loss of power and cold restart. After a long blackout on Mars, water may freeze, seals contract and tank pressures change. Recovery needs an order: warm critical components, establish minimum flow, verify sensors, pressurize, then increase load. Engineering a habitat is not only about maximum efficiency at steady state; it is about proving that the system can enter and leave that state without damaging itself.

Worked example step by step

The work method is always the same: state what every symbol represents, convert all units into a coherent system, perform the operation, then translate the result into a sentence. Finally perform an order-of-magnitude check. If the answer changes by a factor of one thousand because millimetres were treated as metres, the conversion must be visible in the calculation.

Progressive exercise

1. Choose a simple case and list every input with units.
2. Compute the nominal result without margin.
3. Vary the most uncertain parameter by $\pm 20\%$ and compare.
4. Inject one credible failure and explain which indicator detects it.
5. Decide whether the system continues, degrades or stops.

Reasoned solution

A good solution is not only the final number. It shows conversions, why the equation applies, sensitivity and the resulting decision. If different plausible assumptions lead to the same operational decision, the design is relatively robust to that uncertainty. If a small variation reverses the decision, the parameter becomes a priority for measurement or margin.

Validation mini-project

Build a two-to-four-page engineering note applying this course to one Mars subsystem. Include need, assumptions, functional sketch, hand calculation, second calculation or simulation, uncertainties, injected failure, decision criteria and three primary references. The goal is a chain of evidence that another reader can reproduce.

Common errors to detect

- mixing units or frames without explicit conversion;
- presenting calculated values as measured data;
- ignoring a model's validity range;
- confusing numerical precision with physical accuracy;
- sizing only the nominal case with no margin or degraded mode.

Mission reasoning laboratory — connect the calculation to a real decision

The purpose of this laboratory is not to memorise isolated definitions. It links the module to a Mars mission decision, identifies evidence, tests boundary cases and preserves an explicit recovery path.

Close the energy balance

Thermal reasoning begins with conservation of energy. Heat generated by electronics, absorbed sunlight, chemical processes and crew metabolism must either raise stored internal energy or leave through conduction, convection, fluid transport or radiation. If a model predicts a steady temperature while input power exceeds all rejection paths, the model is incomplete. Draw a control volume and list every significant energy flow with sign and unit. That simple balance catches many errors before any detailed thermal software is used.

Distinguish temperature from stored energy

A lightweight metal panel at 350 K can be hotter than a massive water tank at 300 K but contain far less total thermal energy. Temperature controls heat-flow direction; heat capacity and mass control how quickly temperature changes for a given net heat flow. This distinction matters during transients. A small electronics box can overheat quickly after cooling stops, while a large habitat wall changes temperature slowly. Thermal inertia buys time but does not remove the need for a long-term rejection path.

Use fluid flow to transport heat

A coolant loop moves energy by carrying warm fluid away from a source and returning cooler fluid. Mass flow rate is central because heat transport by a single-phase liquid is often estimated as $\dot{Q} = \dot{m}c_p\Delta T$. Increasing flow can reduce the required temperature rise, but pump power, pressure drop, cavitation and component limits constrain that choice. A Mars habitat also has to consider leak isolation and maintainability: a highly efficient loop is not resilient if one inaccessible fitting can drain the entire coolant inventory.

Understand radiation as the final space sink

In vacuum, a spacecraft ultimately rejects much of its waste heat by thermal radiation. Radiator performance depends strongly on absolute temperature and surface emissivity, while view to the Sun, Mars or warm spacecraft surfaces can add absorbed heat. A radiator that works in cruise may perform differently on the surface or inside a dust-contaminated environment. Orientation, coating degradation and seasonal conditions therefore belong in the heat-rejection budget, not only the nominal Stefan–Boltzmann calculation.

Treat insulation as a controlled resistance

Insulation reduces heat transfer; it does not make heat disappear. Multilayer insulation can reduce radiative coupling in vacuum, while foams or structural isolators reduce conductive paths. The correct design keeps wanted heat in or unwanted heat out while still allowing necessary equipment heat to escape. Over-insulating electronics can worsen overheating. Thermal design is therefore a network of intentional resistances and conductances, with heaters and control loops used to keep sensitive hardware inside its qualified band.

Plan for transients and failures

Steady-state analysis misses the period immediately after a heater failure, eclipse entry, pump shutdown or hatch opening. Thermal capacitance determines how quickly temperatures move, creating either valuable response time or hidden delayed hazards. Simulate credible transients long enough to see whether limits are crossed before recovery. Also identify which sensors remain valid during the event; a failed circulation fan can create local hot spots that one remotely located temperature sensor may not detect quickly.

Verify with independent heat paths

Thermal models are often complex networks, so simple independent checks remain valuable. Compare total internal electrical dissipation with expected radiator rejection, estimate time-to-limit from stored heat capacity, and check whether measured coolant temperature rise is consistent with mass flow and transported power. These coarse calculations should

not replace detailed analysis, but they expose order-of-magnitude mistakes, missing watts and unit errors that can otherwise survive inside a sophisticated simulation.

Progressive exercises — solve first, then open the correction

Synthesis exercise — thermal loop

A coolant duct carries water-like fluid with density 995 kg/m^3 through a 12 mm internal-diameter tube at average speed 0.80 m/s. Calculate the flow area and mass flow rate. Then explain why that mass flow rate alone does not determine how many watts the loop can remove.

Detailed correction — Synthesis exercise — thermal loop

Area. Radius = 0.006 m, so $A = \pi r^2 \approx 1.13 \times 10^{-4} \text{ m}^2$.

Mass flow. $\dot{m} = 995 \times 0.80 \times 1.13 \times 10^{-4} \approx 0.090 \text{ kg/s}$.

Thermal capacity. Heat transport also depends on fluid heat capacity and allowable temperature rise, approximately $\dot{Q} = \dot{m} c_p \Delta T$ for a simple sensible-heat estimate.

Beginner vocabulary checkpoint

Focus or tap each highlighted term for its definition. The goal is to remove hidden prerequisites before the learner reaches a safety-significant calculation or procedure.

- internal energy — Microscopic energy stored in a material through molecular motion and interactions.
- heat — Energy transferred because of a temperature difference.
- specific heat capacity — Energy required to raise one kilogram of a material by one kelvin.
- first law of thermodynamics — Energy-conservation statement linking changes in internal energy with heat and work.
- ideal gas law — Approximate relation among pressure, volume, amount of gas and absolute temperature.
- pressure — Normal force per unit area exerted by a fluid or solid surface interaction.
- density — Mass per unit volume.
- volumetric flow rate — Volume of fluid crossing a boundary per unit time.
- continuity — Mass-conservation relation connecting density, velocity and flow area through a flow path.
- Mach number — Flow speed divided by the local speed of sound.
- choked flow — Compressible-flow condition in which a restriction reaches Mach 1 and mass flow no longer increases proportionally with downstream pressure reduction.
- conduction — Heat transfer through a material caused by a temperature gradient.
- convection — Heat transfer between a surface and moving fluid.
- radiation — Electromagnetic heat transfer that does not require a material medium.
- emissivity — Dimensionless measure of how effectively a surface emits thermal radiation compared with an ideal blackbody.
- view factor — Geometric fraction describing how much radiation leaving one surface reaches another surface or environment.
- thermal resistance — Measure of how strongly a heat-transfer path opposes heat flow for a given temperature difference.
- thermal capacitance — Ability of a body to store thermal energy as its temperature changes.
- heat exchanger — Device that transfers heat between fluid streams or between a fluid and a surface.
- coolant — Fluid used to transport heat away from a source.
- pump — Machine that raises fluid pressure or drives flow through a hydraulic loop.
- fan — Machine that moves gas through a ventilation or cooling flow path.
- radiator area — Effective emitting surface available to reject heat by radiation.

- thermal control loop — Connected sensors, actuators, fluid paths and control logic used to keep temperatures within limits.
- thermal inertia — Resistance of temperature to rapid change because of stored thermal energy.
- transient — Time-dependent period before a system reaches a new steady condition.

Decision closeout — evidence before acceptance

Translate equipment power into temperature risk

A power budget becomes a thermal problem when the rejected heat cannot follow a sufficient path to a sink. Imagine a 700 W electronics rack whose liquid loop stops while the hardware still operates. The first question is how much thermal energy accumulates each minute; the second is how much heat capacity exists in the equipment and local structure; the third is whether passive conduction or radiation can slow the temperature rise. This sequence estimates time available for automatic shutdown or crew intervention. A thermal emergency is therefore often a race between stored energy, heat rejection and response time.

Check pressure drop and pump authority together

Increasing coolant flow improves heat transport only if the pump can overcome the resulting pressure losses. Narrow lines, filters, valves and long routing add resistance, and some losses rise approximately with the square of flow speed. A design that assumes more flow without checking pump head can predict cooling that the real loop cannot deliver. For maintenance planning, identify where pressure and temperature measurements allow the crew to distinguish a weak pump from a blocked filter, gas ingestion or a partially closed valve. Diagnostics should be designed into the loop, not improvised after failure.

Control condensation as well as overheating

Habitats and crewed vehicles must manage humidity. If moist air contacts a surface below its dew point, water condenses. Condensation can create corrosion, microbial growth, optical contamination and electrical faults. Thermal control therefore needs both temperature limits and humidity awareness. Cold windows, external-wall interfaces and poorly mixed corners deserve special attention. A surface may be comfortably below an electronics maximum temperature yet still be unacceptable because it crosses the dew point. This is a good example of why one thermal metric rarely protects every system consequence.

Use thermal margins that reflect uncertainty

Radiator performance, contact conductance, dust deposition, internal loads and material properties all carry uncertainty. Rather than applying one arbitrary percentage everywhere, identify which uncertainty actually drives the temperature or power limit. A surface coating with uncertain emissivity may dominate one case; a heater duty cycle may dominate another. Sensitivity runs show where added test, measurement or design margin buys the most confidence. During Mars operations, measured performance should update the model so later decisions use the actual system rather than the launch-day prediction forever.

Plan safe thermal states for loss of circulation

A credible thermal architecture defines what happens after pump or fan loss. Essential electronics may be duty-cycled, batteries may need heaters, crew metabolic heat continues, and some fluid lines can freeze if circulation stops too long. Safe mode must therefore include a thermal configuration, not just a power configuration. State which loads remain on, which valves change position, what temperatures trigger further action and how long passive heat capacity protects the system. That duration is operational time available for diagnosis and repair.

Verify heat rejection after maintenance

After replacing a pump, radiator panel, thermal strap or fan, simply observing that the component runs is insufficient. The restored path should be proven under load. Compare inlet and outlet temperatures, electrical power, flow or fan speed and the trend of the controlled hardware temperature. If the repair changed a contact interface, trapped gas or contamination can leave performance degraded even when no alarm appears. A Mars crew needs acceptance criteria that demonstrate recovered heat-transfer capability before returning to full mission demand.

Primary sources and pathways

- [NASA — Small Spacecraft Thermal Control](#)
- [NASA — Spacecraft Components](#)
- [www1.grc.nasa.gov — institutional documentation](#)
- [www.nasa.gov — institutional documentation](#)
- [Space Academy — full pathway](#)

FR ↔ EN parity matrix

EN	FR
Sensible heat for a temperature change	Énergie sensible pour changer une température
First law for a closed system	Premier principe sur un système fermé
Ideal-gas pressure	Pression d'un gaz parfait
Mass flow through a section	Débit massique dans une section
Mach number	Nombre de Mach
Steady thermal conduction	Conduction thermique stationnaire
Net radiative heat transfer between two temperatures	Rayonnement net entre deux températures