Chapter 7
ENTROPY

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Objectives

- Apply the second law of thermodynamics to processes.
- Define a new property called *entropy* to quantify the second-law effects.
- Establish the *increase of entropy principle*.
- Calculate the entropy changes that take place during processes for pure substances, incompressible substances, and ideal gases.
- Examine a special class of idealized processes, called *isentropic processes*, and develop the property relations for these processes.
- Derive the reversible steady-flow work relations.
- Develop the isentropic efficiencies for various steady-flow devices.
- Introduce and apply the entropy balance to various systems.
The system considered in the development of the Clausius inequality.

The equality in the Clausius inequality holds for totally or just internally reversible cycles and the inequality for the irreversible ones.

Formal definition of entropy

\[ dS = \left( \frac{\delta Q}{T} \right)_{\text{int rev}} \quad (\text{kJ/K}) \]

\[ \Delta S = S_2 - S_1 = \int_{1}^{2} \left( \frac{\delta Q}{T} \right)_{\text{int rev}} \]

\[ \oint \frac{\delta Q}{T} \leq 0 \quad \delta W_C = \delta Q_R - dE_C \]

\[ \frac{\delta Q_R}{T_R} = \frac{\delta Q}{T} \quad \delta W_C = T_R \frac{\delta Q}{T} - dE_C \]

Clausius inequality
Entropy is an extensive property of a system. The net change in volume (a property like volume) during a cycle is always zero.

A quantity whose cyclic integral is zero (i.e., a property like volume)

Entropy is an extensive property of a system.

The entropy change between two specified states is the same whether the process is reversible or irreversible.

A Special Case: Internally Reversible Isothermal Heat Transfer Processes

\[ \Delta S = \int_{1}^{2} \left( \frac{\delta Q}{T} \right)_{\text{int rev}} = \int_{1}^{2} \left( \frac{\delta Q}{T_0} \right)_{\text{int rev}} = \frac{1}{T_0} \int_{1}^{2} (\delta Q)_{\text{int rev}} \]

This equation is particularly useful for determining the entropy changes of thermal energy reservoirs.
THE INCREASE OF ENTROPY PRINCIPLE

A cycle composed of a reversible and an irreversible process.

\[ \int_1^2 \frac{\delta Q}{T} \leq 0 \quad \int_1^2 \frac{\delta Q}{T} + \left( \int_2^1 \frac{\delta Q}{T} \right)_{\text{int rev}} \leq 0 \]

\[ \int_1^2 \frac{\delta Q}{T} + S_1 - S_2 \leq 0 \quad S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T} \]

The equality holds for an internally reversible process and the inequality for an irreversible process.

\[ dS \geq \frac{\delta Q}{T} \]

Some entropy is *generated* or *created* during an irreversible process, and this generation is due entirely to the presence of irreversibilities.

\[ \Delta S_{\text{sys}} = S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{\text{gen}} \]

\[ S_{\text{gen}} = \Delta S_{\text{total}} = \Delta S_{\text{sys}} + \Delta S_{\text{surr}} \geq 0 \]

The entropy generation \( S_{\text{gen}} \) is always a *positive* quantity or zero.

Can the entropy of a system during a process decrease?
The entropy change of an isolated system is the sum of the entropy changes of its components, and is never less than zero.

\[ \Delta S_{\text{isolated}} \geq 0 \]

\[ S_{\text{gen}} = \Delta S_{\text{total}} = \Delta S_{\text{sys}} + \Delta S_{\text{surr}} \geq 0 \]

\[ S_{\text{gen}} \begin{cases} > 0 & \text{Irreversible process} \\ = 0 & \text{Reversible process} \\ < 0 & \text{Impossible process} \end{cases} \]

A system and its surroundings form an isolated system.

The increase of entropy principle
Some Remarks about Entropy

1. Processes can occur in a certain direction only, not in any direction. A process must proceed in the direction that complies with the increase of entropy principle, that is, \( S_{\text{gen}} \geq 0 \). A process that violates this principle is impossible.

2. Entropy is a nonconserved property, and there is no such thing as the conservation of entropy principle. Entropy is conserved during the idealized reversible processes only and increases during all actual processes.

3. The performance of engineering systems is degraded by the presence of irreversibilities, and entropy generation is a measure of the magnitudes of the irreversibilities during that process. It is also used to establish criteria for the performance of engineering devices.
Example 7-2

Entropy Generation during Heat Transfer Processes

*FIGURE 7–9*
Schematic for Example 7–2.
Entropy is a property, and thus the value of entropy of a system is fixed once the state of the system is fixed.

The entropy of a pure substance is determined from the tables (like other properties).

Schematic of the $T$-$s$ diagram for water.

Entropy change

$$\Delta S = m \Delta s = m(s_2 - s_1) \quad \text{(kJ/K)}$$
Example 7-3

Entropy Change of a Substance in a Tank

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**Figure 7-12**
Schematic and T-s diagram for Example 7-3.

- $m = 5 \text{ kg}$
- Refrigerant-134a
- $T_1 = 20^\circ \text{C}$
- $P_1 = 140 \text{ kPa}$
- $\Delta S = ?$

- Heat flow indicated

- $\nu = \text{ constant}$

- $s_1$ and $s_2$ marked

---
Example 7-4

Entropy Change during a constant-pressure process

**FIGURE 7–13**
Schematic and T-s diagram for Example 7–4.
A process during which the entropy remains constant is called an **isentropic process**.

During an internally reversible, adiabatic (isentropic) process, the entropy remains constant.

\[ \Delta s = 0 \quad \text{or} \quad s_2 = s_1 \quad (\text{kJ/kg} \cdot \text{K}) \]

The isentropic process appears as a **vertical** line segment on a $T$-$s$ diagram.
Example 7-5

Isentropic expansion of steam in a Turbine

$P_1 = 5 \text{ MPa}$
$T_1 = 450^\circ\text{C}$

$P_2 = 1.4 \text{ MPa}$
$s_2 = s_1$

$w_{\text{out}} = ?$

**FIGURE 7-15**

$1.4 \text{ MPa}$

$5 \text{ MPa}$

Isentropic expansion

$s_2 = s_1$
PROPERTY DIAGRAMS INVOLVING ENTROPY

On a $T$-$S$ diagram, the area under the process curve represents the heat transfer for internally reversible processes.

$$\delta Q_{\text{int rev}} = T \, dS$$
$$Q_{\text{int rev}} = \int_1^2 T \, dS$$

$$\delta q_{\text{int rev}} = T \, ds$$
$$q_{\text{int rev}} = \int_1^2 T \, ds$$

$$Q_{\text{int rev}} = T_0 \, \Delta S$$
$$q_{\text{int rev}} = T_0 \, \Delta s$$

For adiabatic steady-flow devices, the vertical distance $\Delta h$ on an $h$-$s$ diagram is a measure of work, and the horizontal distance $\Delta s$ is a measure of irreversibilities.

Mollier diagram: The $h$-$s$ diagram
Example 7-6

The T-S diagram of the Carnot cycle

\[ W_{\text{net}} \]

FIGURE 7–19

The T-S diagram of a Carnot cycle
(Example 7–6)
WHAT IS ENTROPY?

The level of molecular disorder (entropy) of a substance increases as it melts or evaporates.

A pure crystalline substance at absolute zero temperature is in perfect order, and its entropy is zero (the third law of thermodynamics).

Disorganized energy does not create much useful effect, no matter how large it is.
In the absence of friction, raising a weight by a rotating shaft does not create any disorder (entropy), and thus energy is not degraded during this process.

**FIGURE 7-26**
The use of entropy (disorganization, uncertainty) is not limited to thermodynamics.

During a heat transfer process, the net entropy increases. (The increase in the entropy of the cold body more than offsets the decrease in the entropy of the hot body.)
FIGURE 7–27

As in mechanical systems, friction in the workplace is bound to generate entropy and reduce performance.
The \( T ds \) relations are valid for both reversible and irreversible processes and for both closed and open systems.

\[
\delta Q_{\text{int,rev}} - \delta W_{\text{int,rev,out}} = dU
\]

\[
\delta Q_{\text{int,rev}} = T \, ds
\]

\[
\delta W_{\text{int,rev,out}} = P \, d\nu
\]

\[
T \, ds = dU + P \, d\nu \quad \text{(kJ)}
\]

\[
T \, ds = du + P \, d\nu \quad \text{(kJ/kg)}
\]

the first \( T ds \), or Gibbs equation

\[
h = u + P \nu
\]

\[
\begin{aligned}
\delta h &= \delta u + P \, d\nu + \nu \, dP \\
T \, ds &= dh - \nu \, dP
\end{aligned}
\]

the second \( T ds \) equation

\[
ds = \frac{du}{T} + \frac{P \, d\nu}{T}
\]

\[
ds = \frac{dh}{T} - \frac{\nu \, dP}{T}
\]

Differential changes in entropy in terms of other properties
ds = \frac{du}{T} + \frac{P}{T} \frac{dV}{T}

Since \( dV \approx 0 \) for liquids and solids

\[ ds = \frac{du}{T} = \frac{c}{T} \, dT \]

since \( c_p = c_v = c \) and \( du = c \, dT \)

**Liquids, solids:** \[ s_2 - s_1 = \int_1^2 c(T) \frac{dT}{T} \approx c_{\text{avg}} \ln \frac{T_2}{T_1} \quad (\text{kJ/kg} \cdot \text{K}) \]

For an isentropic process of an incompressible substance

**Isentropic:** \[ s_2 - s_1 = c_{\text{avg}} \ln \frac{T_2}{T_1} = 0 \quad \rightarrow \quad T_2 = T_1 \]
**THE ENTROPY CHANGE OF IDEAL GASES**

**From the first $T\,ds$ relation**

\[
ds = \frac{du}{T} + \frac{P}{T} \, d\nu
\]

\[
du = c_{v} \, dT
\]

\[
P = \frac{RT}{\nu}
\]

\[
ds = c_{v} \frac{dT}{T} + R \frac{d\nu}{\nu}
\]

\[
s_{2} - s_{1} = \int_{1}^{2} c_{v}(T) \frac{dT}{T} + R \ln \frac{\nu_{2}}{\nu_{1}}
\]

**From the second $T\,ds$ relation**

\[
ds = \frac{dh}{T} - \frac{\nu}{T} \, dP
\]

\[
dh = c_{p} \, dT \quad \nu = \frac{RT}{P}
\]

\[
ds = \int_{1}^{2} c_{p}(T) \frac{dT}{T} - R \ln \frac{P_{2}}{P_{1}}
\]

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$P\nu = RT$

$du = C_{v} \, dT$

$dh = C_{p} \, dT$

A broadcast from channel IG.
Constant Specific Heats (Approximate Analysis)

Under the constant-specific-heat assumption, the specific heat is assumed to be constant at some average value.

Entropy change of an ideal gas on a unit–mole basis:

\[
\bar{s}_2 - \bar{s}_1 = \bar{c}_{\text{v,avg}} \ln \frac{T_2}{T_1} + R \ln \frac{\nu_2}{\nu_1}
\]

\[
\bar{s}_2 - \bar{s}_1 = \bar{c}_{p,\text{avg}} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}
\](kJ/kg · K)

Under the constant-specific-heat assumption, the specific heat is assumed to be constant at some average value.
Isentropic Processes of Ideal Gases

Constant Specific Heats (Approximate Analysis)

\[ s_2 - s_1 = c_{v,\text{avg}} \ln \frac{T_2}{T_1} + R \ln \frac{\nu_2}{\nu_1} \]

Setting this eq. equal to zero, we get

\[ \ln \frac{T_2}{T_1} = -\frac{R}{c_v} \ln \frac{\nu_2}{\nu_1} \]

\[ \ln \frac{T_2}{T_1} = \ln \left( \frac{\nu_1}{\nu_2} \right)^{R/c_v} \]

\[ R = c_p - c_v, \quad k = \frac{c_p}{c_v} \]

and thus \(\frac{R}{c_v} = k - 1\)

\[ \left( \frac{T_2}{T_1} \right)_{s=\text{const.}} = \left( \frac{\nu_1}{\nu_2} \right)^{k-1} \]

\[ \left( \frac{T_2}{T_1} \right)_{s=\text{const.}} = \left( \frac{P_2}{P_1} \right)^{(k-1)/k} \]

\[ \left( \frac{P_2}{P_1} \right)_{s=\text{const.}} = \left( \frac{\nu_1}{\nu_2} \right)^k \]

The isentropic relations of ideal gases are valid for the isentropic processes of ideal gases only.

\[ T\nu^{k-1} = \text{constant} \]

\[ TP^{(1-k)/k} = \text{constant} \]

\[ P\nu^k = \text{constant} \]
End
Final examination
[on October 4, 2013 9:00-1200]

1) Closed books and Closed notes
2) 3-hour exam
3) Only provided calculators are allowed
4) 5 problems
   4-1 Definitions and Tables
   4-2 Energy analysis of closed systems [Chapter 4]
   4-3 Mass and energy analysis of CV [Chapter 5, excluding 5-5]
   4-4 The 2nd law of Thermodynamics [Chapter 6, excluding 6-5]
   4-5 Entropy [Chapter 7]
Practice problems (don’t have to submit)

1) 7-20
2) 7-21
3) 7-30
4) 7-60
5) 7-94
Isentropic Processes of Ideal Gases

Variable Specific Heats (Exact Analysis)

\[ 0 = s_2^0 - s_1^0 - R \ln \frac{P_2}{P_1} \rightarrow s_2^0 = s_1^0 + R \ln \frac{P_2}{P_1} \]

Relative Pressure and Relative Specific Volume

\[
\frac{P_2}{P_1} = \exp \frac{s_2^0 - s_1^0}{R} \quad \text{exp}(s^0/R) \text{ is the relative pressure } P_r.
\]

\[
\frac{P_2}{P_1} = \exp \frac{s_2^0}{R} / \exp \frac{s_1^0}{R} \quad \left( \frac{P_2}{P_1} \right)_{s=\text{const.}} = \frac{P_{r_2}}{P_{r_1}}
\]

\[
\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2} \rightarrow \frac{v_2}{v_1} = \frac{T_2}{T_1} \frac{P_1}{P_2} = \frac{T_2}{T_1} \frac{P_{r_1}}{P_{r_2}} = \frac{T_2/P_{r_2}}{T_1/P_{r_1}}
\]

\[
\left( \frac{v_2}{v_1} \right)_{s=\text{const.}} = \frac{v_{r_2}}{v_{r_1}}
\]

\(T/P_r\) is the relative specific volume \(v_r\).
REVERSIBLE STEADY-FLOW WORK

\[ \delta q_{\text{rev}} - \delta w_{\text{rev}} = dh + d\text{ke} + d\text{pe} \]

\[ \delta q_{\text{rev}} = T\,ds \quad (\text{Eq. 7–16}) \]
\[ T\,ds = dh - \nu\,dP \quad (\text{Eq. 7–24}) \]
\[ \delta q_{\text{rev}} = dh - \nu\,dP \]

\[-\delta w_{\text{rev}} = \nu\,dP + d\text{ke} + d\text{pe} \]

\[ w_{\text{rev}} = -\int_{1}^{2} \nu\,dP - \Delta\text{ke} - \Delta\text{pe} \]

\[ w_{\text{rev}} = -\int_{1}^{2} \nu\,dP \]

When kinetic and potential energies are negligible

\[ w_{\text{rev,in}} = \int_{1}^{2} \nu\,dP + \Delta\text{ke} + \Delta\text{pe} \]

\[ w_{\text{rev}} = -\nu(P_{2} - P_{1}) - \Delta\text{ke} - \Delta\text{pe} \]

For the steady flow of a liquid through a device that involves no work interactions (such as a pipe section), the work term is zero (Bernoulli equation):

\[ \nu(P_{2} - P_{1}) + \frac{V_{2}^{2} - V_{1}^{2}}{2} + g(z_{2} - z_{1}) = 0 \]

The larger the specific volume, the greater the work produced (or consumed) by a steady-flow device.

Reversible work relations for steady-flow and closed systems.
Proof that Steady-Flow Devices Deliver the Most and Consume the Least Work when the Process Is Reversible

Taking heat input and work output positive:

\[ \delta q_{\text{act}} - \delta w_{\text{act}} = dh + dke + dpe \]
\[ \delta q_{\text{rev}} - \delta w_{\text{rev}} = dh + dke + dpe \]

\[ \delta q_{\text{act}} - \delta w_{\text{act}} = \delta q_{\text{rev}} - \delta w_{\text{rev}} \]
\[ \delta w_{\text{rev}} - \delta w_{\text{act}} = \delta q_{\text{rev}} - \delta q_{\text{act}} \]

\[ \delta q_{\text{rev}} = T \, ds \]
\[ ds \geq \frac{\delta q_{\text{act}}}{T} \]

\[ \frac{\delta w_{\text{rev}} - \delta w_{\text{act}}}{T} = ds - \frac{\delta q_{\text{act}}}{T} \geq 0 \]

\[ \delta w_{\text{rev}} \geq \delta w_{\text{act}} \]

\[ w_{\text{rev}} \geq w_{\text{act}} \]

A reversible turbine delivers more work than an irreversible one if both operate between the same end states.

Work-producing devices such as turbines deliver more work, and work-consuming devices such as pumps and compressors require less work when they operate reversibly.
MINIMIZING THE COMPRESSOR WORK

\[ w_{\text{rev.in}} = \int_{1}^{2} \sqrt{v} \, dP \]

When kinetic and potential energies are negligible

Isentropic \((Pv^k = \text{constant})\):

\[ w_{\text{comp.in}} = \frac{kR(T_2 - T_1)}{k - 1} = \frac{kRT_1}{k - 1} \left[ \left( \frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right] \]

Polytropic \((Pv^n = \text{constant})\):

\[ w_{\text{comp.in}} = \frac{nR(T_2 - T_1)}{n - 1} = \frac{nRT_1}{n - 1} \left[ \left( \frac{P_2}{P_1} \right)^{(n-1)/n} - 1 \right] \]

Isothermal \((Pv = \text{constant})\):

\[ w_{\text{comp.in}} = RT \ln \frac{P_2}{P_1} \]

The adiabatic compression \((Pv^\kappa = \text{constant})\) requires the maximum work and the isothermal compression \((T = \text{constant})\) requires the minimum. Why?
Multistage Compression with Intercooling

The gas is compressed in stages and cooled between each stage by passing it through a heat exchanger called an *intercooler*.

$P$-$v$ and $T$-$s$ diagrams for a two-stage steady-flow compression process.

$$w_{\text{comp, in}} = w_{\text{comp I,in}} + w_{\text{comp II,in}}$$

$$= \frac{nRT_1}{n-1} \left[ \left( \frac{P_x}{P_1} \right)^{(n-1)/n} - 1 \right] + \frac{nRT_1}{n-1} \left[ \left( \frac{P_2}{P_x} \right)^{(n-1)/n} - 1 \right]$$

$$P_x = (P_1P_2)^{1/2} \quad \text{or} \quad \frac{P_x}{P_1} = \frac{P_2}{P_x}$$

To minimize compression work during two-stage compression, the pressure ratio across each stage of the compressor must be the same.
The isentropic process involves no irreversibilities and serves as the ideal process for **adiabatic devices**.

**Isentropic Efficiency of Turbines**

\[
\eta_T = \frac{\text{Actual turbine work}}{\text{Isentropic turbine work}} = \frac{w_a}{w_s}
\]

\[
\eta_T \approx \frac{h_1 - h_{2a}}{h_1 - h_{2s}}
\]

The \( h-s \) diagram for the actual and isentropic processes of an adiabatic turbine.
Isentropic Efficiencies of Compressors and Pumps

\[ \eta_c = \frac{\text{Isentropic compressor work}}{\text{Actual compressor work}} = \frac{w_s}{w_a} \]

\[ \eta_c \approx \frac{h_{2s} - h_1}{h_{2a} - h_1} \]

When kinetic and potential energies are negligible

\[ \eta_p = \frac{w_s}{w_a} = \frac{\sqrt{(P_2 - P_1)}}{h_{2a} - h_1} \]

For a pump

The \( h-s \) diagram of the actual and isentropic processes of an adiabatic compressor.

Compressors are sometimes intentionally cooled to minimize the work input.

Can you use isentropic efficiency for a non-adiabatic compressor?

Can you use isothermal efficiency for an adiabatic compressor?
Isentropic Efficiency of Nozzles

\[ \eta_N = \frac{\text{Actual KE at nozzle exit}}{\text{Isentropic KE at nozzle exit}} = \frac{V_{2a}^2}{V_{2s}^2} \]

If the inlet velocity of the fluid is small relative to the exit velocity, the energy balance is

\[ h_1 = h_{2a} + \frac{V_{2a}^2}{2} \]

Then,

\[ \eta_N \approx \frac{h_1 - h_{2a}}{h_1 - h_{2s}} \]

A substance leaves actual nozzles at a higher temperature (thus a lower velocity) as a result of friction.
ENTROPY BALANCE

\[
\begin{align*}
\text{Total entropy entering} & - \text{Total entropy leaving} + \text{Total entropy generated} = \text{Change in the total entropy of the system} \\
S_{\text{in}} - S_{\text{out}} + S_{\text{gen}} & = \Delta S_{\text{system}}
\end{align*}
\]

Entropy Change of a System, \( \Delta S_{\text{system}} \)

\[\Delta S_{\text{system}} = S_{\text{final}} - S_{\text{initial}} = S_2 - S_1\]

When the properties of the system are not uniform

\[S_{\text{system}} = \int s \, \delta m = \int_V s \rho \, dV\]

Energy and entropy balances for a system.
Mechanisms of Entropy Transfer, $S_{\text{in}}$ and $S_{\text{out}}$

1 Heat Transfer

Entropy transfer by heat transfer:

$$S_{\text{heat}} = \frac{Q}{T} \quad (T = \text{constant})$$

$$S_{\text{heat}} = \int_{1}^{2} \frac{\delta Q}{T} \equiv \sum \frac{Q_k}{T_k}$$

Entropy transfer by work:

$$S_{\text{work}} = 0$$

Heat transfer is always accompanied by entropy transfer in the amount of $Q/T$, where $T$ is the boundary temperature.

No entropy accompanies work as it crosses the system boundary. But entropy may be generated within the system as work is dissipated into a less useful form of energy.
2 Mass Flow

Entropy transfer by mass:

$$S_{\text{mass}} = ms$$

When the properties of the mass change during the process

$$\dot{S}_{\text{mass}} = \int_{A_c} s \rho V_n \, dA_c$$

$$S_{\text{mass}} = \int s \, \delta m = \int_{\Delta t} \dot{S}_{\text{mass}} \, dt$$

Mass contains entropy as well as energy, and thus mass flow into or out of system is always accompanied by energy and entropy transfer.
Entropy Generation, $S_{\text{gen}}$

\[
S_{\text{in}} - S_{\text{out}} + S_{\text{gen}} = \Delta S_{\text{system}} \quad (\text{kJ/K})
\]

Net entropy transfer by heat and mass

\[
\dot{S}_{\text{in}} - \dot{S}_{\text{out}} + \dot{S}_{\text{gen}} = \frac{dS_{\text{system}}}{dt} \quad (\text{kW/K})
\]

Rate of net entropy transfer by heat and mass

\[
(s_{\text{in}} - s_{\text{out}}) + s_{\text{gen}} = \Delta s_{\text{system}} \quad (\text{kJ/kg \cdot K})
\]

Mechanisms of entropy transfer for a general system.

Entropy generation outside system boundaries can be accounted for by writing an entropy balance on an extended system that includes the system and its immediate surroundings.
Closed Systems

Closed system: \[ \sum \frac{Q_k}{T_k} + S_{\text{gen}} = \Delta S_{\text{system}} = S_2 - S_1 \] (kJ/K)

The entropy change of a closed system during a process is equal to the sum of the net entropy transferred through the system boundary by heat transfer and the entropy generated within the system boundaries.

Adiabatic closed system: \[ S_{\text{gen}} = \Delta S_{\text{adiabatic system}} \]

System + Surroundings: \[ S_{\text{gen}} = \sum \Delta S = \Delta S_{\text{system}} + \Delta S_{\text{surroundings}} \]

\[ \Delta S_{\text{system}} = m(s_2 - s_1) \]

\[ \Delta S_{\text{surroundings}} = \frac{Q_{\text{surroundings}}}{T_{\text{surroundings}}} \]
The entropy of a substance always increases (or remains constant in the case of a reversible process) as it flows through a single-stream, adiabatic, steady-flow device.

The entropy of a control volume changes as a result of mass flow as well as heat transfer.
Entropy balance for heat transfer through a wall

\[
\dot{S}_{\text{in}} - \dot{S}_{\text{out}} + \dot{S}_{\text{gen}} = \frac{dS_{\text{system}}}{dt}^{0 \text{ (steady)}}
\]

- Rate of net entropy transfer by heat and mass
- Rate of entropy generation
- Rate of change in entropy

\[
\left( \frac{\dot{Q}}{T} \right)_{\text{in}} - \left( \frac{\dot{Q}}{T} \right)_{\text{out}} + \dot{S}_{\text{gen}} = 0
\]

Entropy balance for a throttling process

\[
\dot{S}_{\text{in}} - \dot{S}_{\text{out}} + \dot{S}_{\text{gen}} = \frac{dS_{\text{system}}}{dt}^{0 \text{ (steady)}}
\]

- Rate of net entropy transfer by heat and mass
- Rate of entropy generation
- Rate of change in entropy

\[
\dot{m} s_1 - \dot{m} s_2 + \dot{S}_{\text{gen}} = 0
\]

\[
\dot{S}_{\text{gen}} = \dot{m} (s_2 - s_1)
\]
Entropy Generated when a Hot Block Is Dropped in a Lake

\[ S_{\text{in}} - S_{\text{out}} + S_{\text{gen}} = \Delta S_{\text{system}} \]

- Net entropy transfer by heat and mass
- Entropy generation
- Change in entropy

\[ -\frac{Q_{\text{out}}}{T_b} + S_{\text{gen}} = \Delta S_{\text{system}} \]

or

\[ S_{\text{gen}} = \Delta S_{\text{total}} = \Delta S_{\text{system}} + \Delta S_{\text{lake}} \]

Entropy Generation in a Heat Exchanger

\[ \dot{S}_{\text{in}} - \dot{S}_{\text{out}} + \dot{S}_{\text{gen}} = 0 \quad \text{(steady)} \]

\[ \dot{m}_{\text{steam}} s_1 + \dot{m}_{\text{air}} s_3 - \dot{m}_{\text{steam}} s_2 - \dot{m}_{\text{air}} s_4 + \dot{S}_{\text{gen}} = 0 \]

\[ \dot{S}_{\text{gen}} = \dot{m}_{\text{steam}} (s_2 - s_1) + \dot{m}_{\text{air}} (s_4 - s_3) \]
Graphical representation of entropy generation during a heat transfer process through a finite temperature difference.
Summary

- Entropy
- The increase of entropy principle
- Entropy change of pure substances
- Isentropic processes
- Property diagrams involving entropy
- What is entropy?
- The $T \, ds$ relations
- Entropy change of liquids and solids
- The entropy change of ideal gases
- Reversible steady-flow work
- Minimizing the compressor work
- Isentropic efficiencies of steady-flow devices
- Entropy balance