Introduction to Aerospace Propulsion

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Lecture No - 11
In this lecture ...

- Reversible and Irreversible Processes
- Irreversibilities
- Internally and Externally Reversible Processes
- Clausius inequality and entropy
- Property of entropy
- Temperature-entropy plots
- Isentropic processes
Reversible and irreversible processes

• 2\textsuperscript{nd} law: no heat engine can have 100% efficiency

• What is the highest efficiency that an engine could have?

• Reversible process: a process that can be reversed without leaving any trace on the surroundings.

• The system and the surroundings are returned to their initial states at the end of the reverse process.
Reversible and irreversible processes

• Reversible process: Net heat and work exchange between the system and surroundings (for original + reverse process) is zero.

• Why reversible processes are of interest?

• Consume least work in the case of work-consuming devices and generate maximum work in the case of work-producing devices.
Reversible and irreversible processes

• Reversible processes serve as theoretical limits for the corresponding irreversible ones.

• Reversible processes lead to the definition of the second law efficiency for actual processes, which is the degree of approximation to the corresponding reversible processes.
Irreversibilities

• Commonly encountered causes of irreversibilities
  – friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions.
Irreversibilities

Heat transfer through a finite temperature difference is irreversible.
Irreversibilities

Fast compression

Fast expansion

800 kPa → 25 kPa
Unrestrained expansion
Internally and Externally Reversible Processes

• Internally reversible process
  – if no irreversibilities occur within the boundaries of the system during the process.
  – the paths of the forward and reverse processes coincide for an internally reversible process
Internally and Externally Reversible Processes

• Externally reversible process
  – no irreversibilities occur outside the system boundaries during the process.
  – Heat transfer between a reservoir and a system is an externally reversible process if the outer surface of the system is at the temperature of the reservoir.

• Totally reversible or reversible
  – no irreversibilities within the system or its surroundings.
Internally and Externally Reversible Processes

Thermal energy reservoir at 35.000001°C
(a) Totally reversible

Thermal energy reservoir at 45°C
(b) Internally reversible
Reversible adiabatics

- Two reversible adiabatic paths cannot intersect
- Through one point, only one reversible adiabatic can pass
- Violation of Kelvin-Planck statement
Reversible adiabatics

Process \( m-n \)
\[ Q_{m-n} = U_n - U_m + W_{mn} \]

Process \( m-a-b-n \)
\[ Q_{m-a-b-n} = U_n - U_m + W_{m-a-b-n} \]

Since, \( W_{m-a-b-n} = W_{mn} \)
\[ Q_{m-n} = Q_{m-a-b-n} \]
\[ = Q_{m-a} + Q_{a-b} + Q_{b-n} \]

Since \( Q_{m-a} = 0, Q_{b-n} = 0 \)
\[ Q_{m-n} = Q_{a-b} \]

Reversible path can be substituted by two reversible adiabatics and a reversible isotherm
Clausius inequality

Thermal energy reservoir ($T_R$)

Rev. Cyclic device

$\delta Q_R$

$\delta W_{rev}$

$T$

$\delta Q$

$\delta W_{sys}$

System

Combined system (system and cyclic device)
Clausius inequality

- Applying the energy balance to the combined system identified by dashed lines yields: \( \delta W_C = \delta Q_R - dE_C \)
- where \( \delta W_C \) is the total work of the combined system \((\delta W_{rev} + \delta W_{sys})\) and \( dE_C \) is the change in the total energy of the combined system.
- Considering that the cyclic device is a reversible one \( \frac{\delta Q_R}{T_R} = \frac{\delta Q}{T} \)
Clausius inequality

• From the above equations:

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

• Let the system undergo a cycle while the cyclic device undergoes an integral number of cycles

\[ W_C = T_R \oint \frac{\delta Q}{T} \]

• Since the cyclic integral of energy is zero.
Clausius inequality

• The combined system is exchanging heat with a single thermal energy reservoir while involving (producing or consuming) work $W_C$ during a cycle. Hence $W_C$ cannot be a work output, and thus it cannot be a positive quantity.

• Considering $T_R$ to be a positive quantity,

$$\int \frac{\delta Q}{T} \leq 0$$

• This is the Clausius inequality.
Clausius inequality

- Clausius inequality is valid for all thermodynamic cycles, reversible or irreversible, including the refrigeration cycles.
- If no irreversibilities occur within the system as well as the reversible cyclic device, then the cycle undergone by the combined system is internally reversible.

\[
\int \left( \frac{\delta Q}{T} \right)_{\text{int.rev}} = 0
\]
Clausius inequality

• Clausius inequality provides the criterion for the irreversibility of a process.

\[ \oint \frac{\delta Q}{T} = 0, \text{ the process is reversible.} \]

\[ \oint \frac{\delta Q}{T} < 0, \text{ the process is irreversible and possible.} \]

\[ \oint \frac{\delta Q}{T} > 0, \text{ the process is impossible.} \]
Clausius inequality and entropy

- The cyclic integral of work and heat are not zero.
- However, the cyclic integral of volume (or any other property) is zero.
- Conversely, a quantity whose cyclic integral is zero depends on the state only and not the process path, and thus it is a property.
- Clausius realized in 1865 that he had discovered a new thermodynamic property, and he chose to name this property entropy.
The property of entropy

\[ \int_{R_1}^{R_2} \frac{dQ}{T} = 0 \]

\[ \int_{R_1}^{b} \frac{dQ}{T} + \int_{R_2}^{a} \frac{dQ}{T} = 0 \]

or,

\[ \int_{R_1}^{b} \frac{dQ}{T} = -\int_{R_2}^{a} \frac{dQ}{T} \]

Since \( R_2 \) is a reversible path,

\[ \int_{R_1}^{b} \frac{dQ}{T} = \int_{R_2}^{b} \frac{dQ}{T} \]

or,

\[ \int_{R_1}^{a} \frac{dQ}{T} = \int_{R_2}^{a} \frac{dQ}{T} \]
The property of entropy

\[ \int_{a}^{b} \frac{dQ}{T} \] is independent of the reversible path connecting \( a \) and \( b \).

This property whose value at the final state minus the initial state is equal to \( \int_{a}^{b} \frac{dQ}{T} \) is called entropy, denoted by \( S \).

\[ \int_{a}^{b} \frac{dQ}{T} = S_b - S_a \]

When the two equilibrium states are infinitesimally near,

\[ \frac{dQ_R}{T} = dS \]

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Entropy

• Entropy is an extensive property of a system and sometimes is referred to as total entropy. Entropy per unit mass, designated $s$, is an intensive property and has the unit kJ/kg · K.

• The entropy change of a system during a process can be determined by

$$\Delta S = S_2 - S_1 = \int_{1}^{2} \left( \frac{\delta Q}{T} \right)_{\text{int. rev.}} (\text{kJ/kg})$$
Entropy

• Entropy is a property, and like all other properties, it has fixed values at fixed states.

• Therefore, the entropy change $dS$ between two specified states is the same no matter what path, reversible or irreversible.
Temperature-entropy plot

\[ dS = \frac{dQ_{rev}}{T} \]

If the process is reversible and adiabatic, \( dQ_{rev} = 0 \)
\[ \therefore dS = 0 \text{ or } S = \text{constant} \]

- A reversible adiabatic process is, therefore, and *isentropic process*.

\[ dQ_{rev} = TdS \]

or, \( Q_{rev} = \int TdS \)
Temperature-entropy plot

- The area under the reversible path on the T-S plot represents heat transfer during that process.

\[ Q_{\text{rev}} = \int_{a}^{b} T \, dS = T \left( S_b - S_a \right) \]
Isentropic processes

• A process where, $\Delta s = 0$
• An isentropic process can serve as an appropriate model for actual processes.
• Isentropic processes enable us to define efficiencies for processes to compare the actual performance of these devices to the performance under idealized conditions.
• A reversible adiabatic process is necessarily isentropic, but an isentropic process is not necessarily a reversible adiabatic process.
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In the next lecture...

- Increase of entropy principle
- Entropy change in liquids and solids
- Entropy change in ideal gases
- Third law of thermodynamics
- Absolute entropy
- Entropy change of a system and entropy generation