UNIVERSITY OF LINCOLN

EGR3030 – Energy Systems and Conversion

2024/25 session

Week 4 – Introduction to exergy analysis for closed and open systems

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Learning outcomes

- What is exergy
- Types
- Definitions
- Exergy balance
  - Closed systems
  - Steady flow systems
- Relationship with heat (or energy) and entropy

Exergy

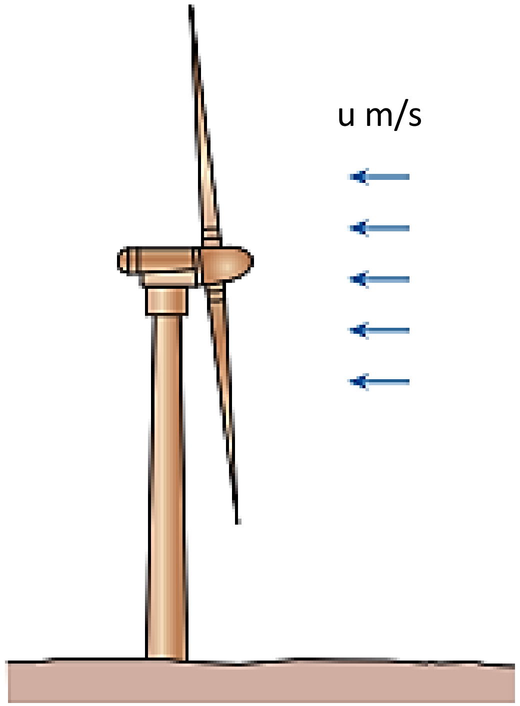
Exergy is the measure of the maximum theoretical useful work that can be obtained from a process as it is brought from its current state into equilibrium with the environment

Or

It is a property that determines the useful work potential of a given amount of energy at some specified state.

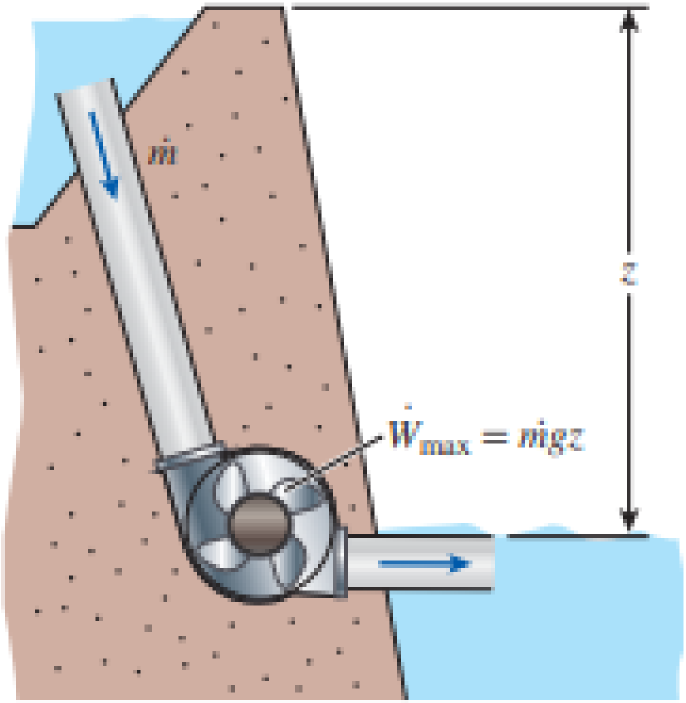
- Also known as work potential, or available energy.
- Very useful in determining the viability of new energy sources, such as wind, oil and gas reserves, or geothermal wells.

Energy potential

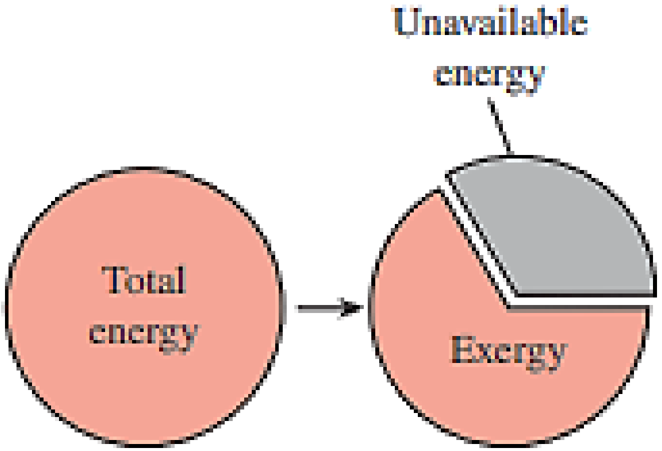


Horizontal axis wind turbine

$$P = \frac{1}{2}\rho A u^3$$



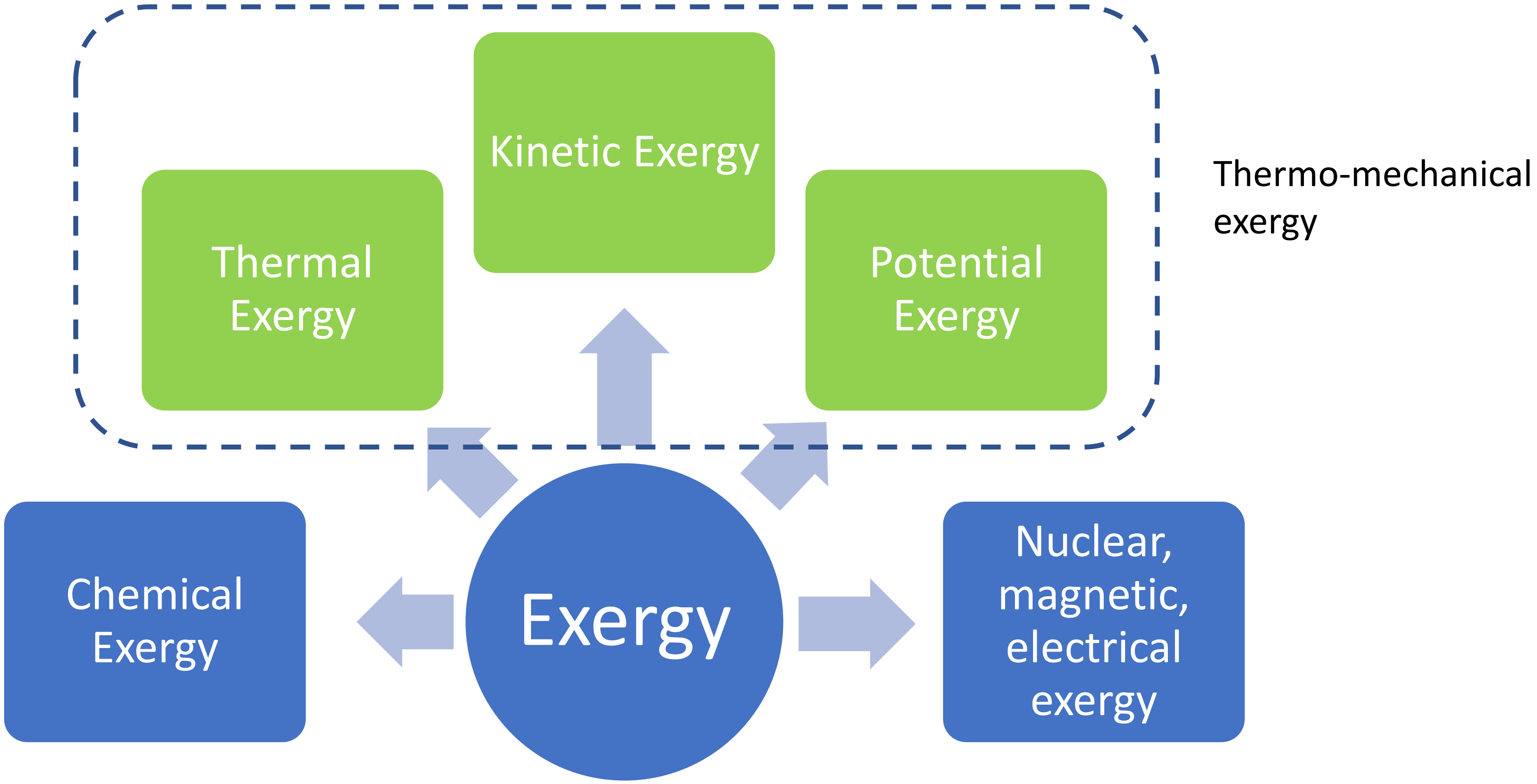
Hydro turbine



Unavailable energy is the part or portion of energy that cannot be converted to useful work even by a reversible system.

EXERGY is the available energy

Kinds of exergy



Exergy destruction and entropy

- Irreversibilities generate entropy e.g. friction, mixing, chemical reactions, heat transfer through a finite temperature difference, non-quasi-equilibrium compression/expansion

- When entropy is generated, exergy is destroyed

Hence:

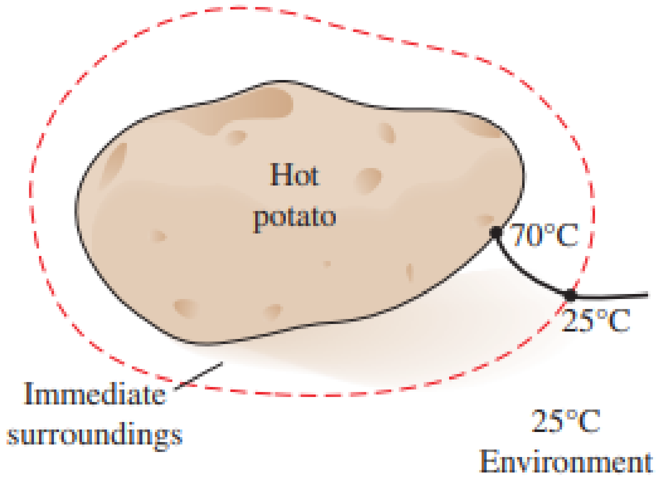
$$X_{destroyed} = T_o S_{gen} \geq 0$$

- In general

$$X_{destroyed} \begin{cases} > 0 & irreversible\ process \\ = 0 & reversible\ process \\ < 0 & impossible\ process \end{cases}$$

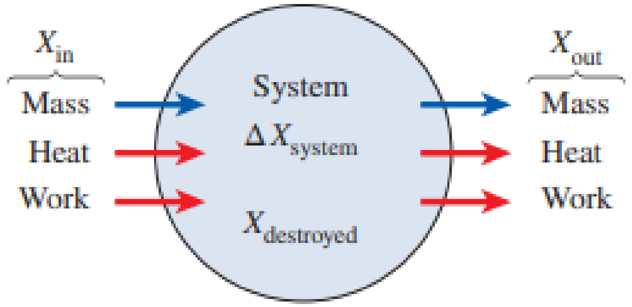
Definition of terms required for exergy analysis

Dead state	A system is said to be in a dead state when it is in equilibrium with the environment
Surroundings	Outside the system boundaries
Immediate surroundings	Portion of the surroundings affected by the process
Environment	Region beyond the immediate surroundings whose properties are not affected by the process at any point



Exergy balance

- Unlike energy, exergy is <u>not</u> conserved – it can be destroyed (but not created)
- Consider a hypothetical system undergoing a process:



- The exergy change of the system:
  - Is the difference between the **net exergy transfer** through the system's boundary and the **exergy destroyed** within boundary due to irreversibilities

Exergy balance

In mathematical form:

$$\begin{pmatrix} Change\ in \\ total\ exergy \\ of\ system \end{pmatrix} = \begin{pmatrix} total \\ exergy \\ entering \end{pmatrix} - \begin{pmatrix} total \\ exergy \\ leaving \end{pmatrix} - \begin{pmatrix} total \\ exergy \\ destroyed \end{pmatrix}$$

$$\underbrace{\Delta X_{system}}_{\text{Change in exergy}} = \underbrace{X_{in} - X_{out}}_{\text{Net exergy transfer by heat, work, and mass}} - \underbrace{X_{destroyed}}_{\text{Exergy destruction}} \quad \text{(kJ)}$$

In rate form: $\frac{\mathrm{d}X_{system}}{dt} = \dot{X}_n - \dot{X}_{out} - \dot{X}_{destroyed}$ (kW)

In unit mass form: $\Delta x_{system} = x_{in} - x_{out} - x_{destroyed}$ (kJ/kg)

Exergy balance

- Rate of exergy transfer by heat:

$$\dot{X}_{heat} = \left(1 - \frac{T_o}{T}\right)\dot{Q}$$

$$\dot{X}_{heat} = \eta_c \dot{Q}_{in}$$

- Rate of exergy transfer by work

$$\dot{X}_{work} = W_{useful}$$

- Rate of exergy transfer by mass:

$$\dot{X}_{mass} = \dot{m}\psi$$

Where ψ is the flow (or stream) exergy given by:

$$\psi = (h - h_o) - T_o(s - s_o) + \frac{V^2}{2} + gz$$

Exergy balance for a closed system

- Starting from our first law energy balance:

$$\Delta E_{system} = E_{in} - E_{out} \Rightarrow E_2 - E_1 = Q - W \qquad (1)$$

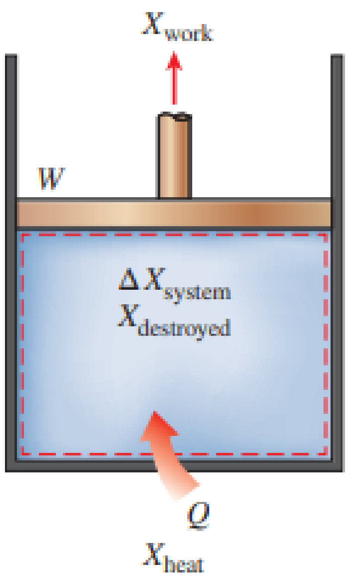
- Entropy balance:

$$\Delta S_{system} = S_{in} - S_{out} + S_{gen} \Rightarrow S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_{boundary} + S_{gen} \qquad (2)$$

Multiplying (2) by T_o and subtracting from (1),

$$E_2 - E_1 - T_o(s_2 - s_1) = Q - T_o \int_1^2 \left(\frac{\delta Q}{T}\right)_{boundary} - W - T_o S_{gen} \qquad (3)$$

For heat transfer between the two states 1 and 2, $Q = \int_1^2 \delta Q$ and the LHS of (3) can be shown to be $X_2 - X_1 - P_o(V_2 - V_1)$ (See eq. 8-17 in Cengel & Boles 4th Ed.)



Exergy balance for a closed system

Hence,

$$X_2 - X_1 - P_o(V_2 - V_1) = \int_1^2 \delta Q - T_o \int_1^2 \left(\frac{\delta Q}{T}\right)_{boundary} - W - T_o S_{gen}$$

Rearranging

$$X_2 - X_1 = \int_1^2 \left(1 - \frac{T_o}{T_b}\right) \delta Q - [W + P_o(V_2 - V_1)] - T_o S_{gen}$$

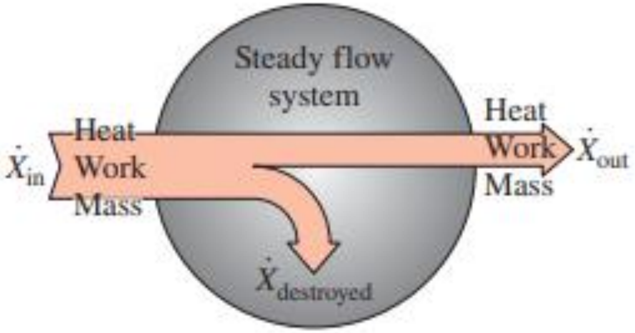
Exergy balance of steady flow systems

For a steady flow system, $\frac{dX_{CV}}{dt}$ =?

$$\frac{dX_{CV}}{dt} = 0$$

For steady flow, we simply substitute this into the closed system equation and replace the PdV part with the "stream" exergy ψ. Hence:

$$0 = \int_1^2 \left(1 - \frac{T_o}{T_b}\right) \delta \dot{q}_b - \dot{W} + \dot{m}\,(\psi_1 - \psi_2) - \dot{X}_{destroyed}$$

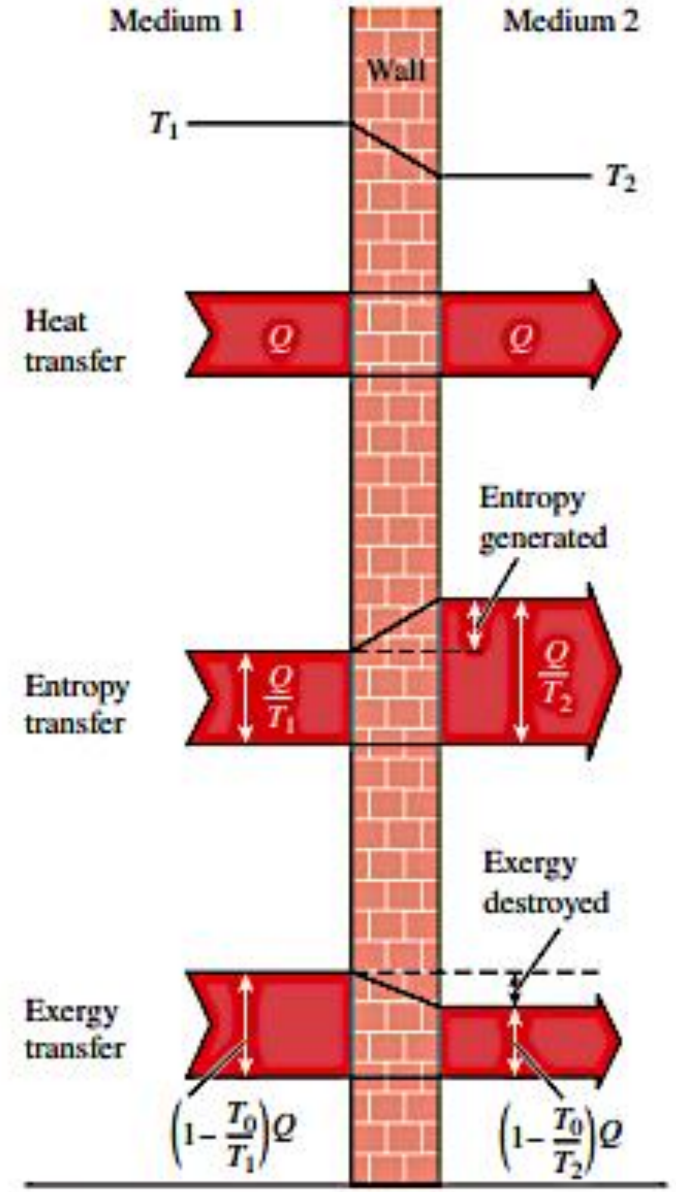


If the process involves >1 streams (not a one-inlet, one-outlet system),

$$0 = \int_1^2 \left(1 - \frac{T_o}{T_b}\right) \delta \dot{q}_b - \dot{W} + \sum_{in} \dot{m}\psi - \sum_{out} \dot{m}\psi - \dot{X}_{destroyed}$$

Relationship between heat, entropy, and exergy transfer in general…

Heat transfer Q at a location at temperature T is always accompanied by entropy transfer in the amount of $\frac{Q}{T}$ and exergy transfer in the amount of $\left(1 - \frac{T_0}{T}\right) Q$.



Summary

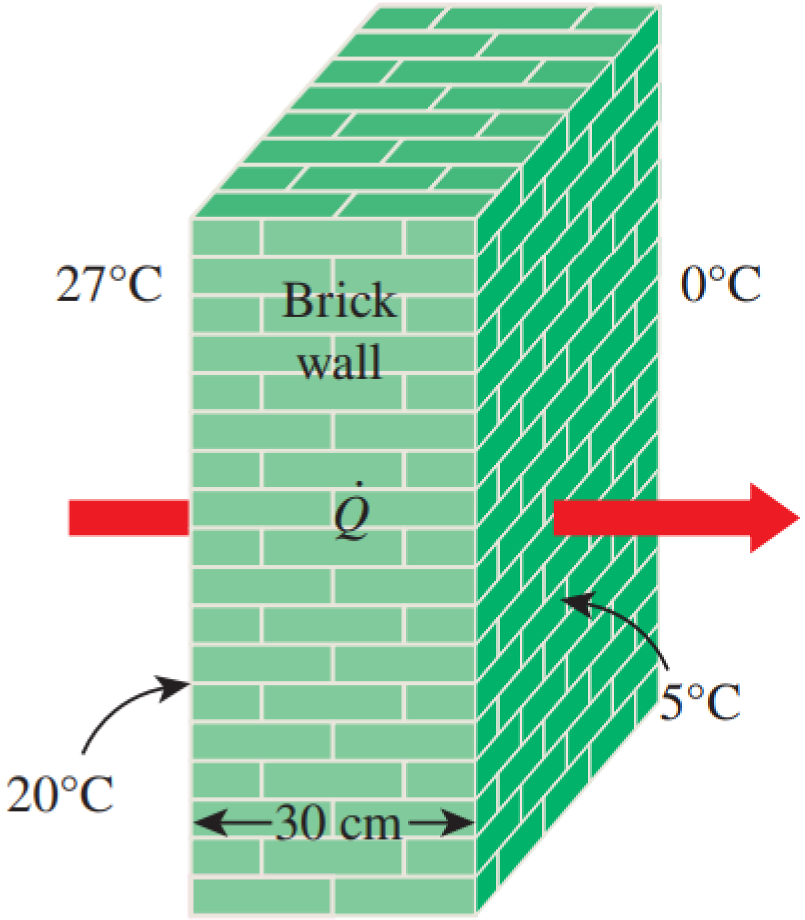
- We defined exergy
- Types
- Definitions necessary for understanding exergy
- Exergy balance
  - Closed systems
  - Steady flow systems
- Relationship with heat (or energy) and entropy

Tutorial Q1 - exergy without work

– Exergy destruction during heat conduction

Heat is transferred through a brick wall as shown in the figure. On a certain day, the temperature of the outdoors is 0°C and the internal of the house is maintained at 27°C. The temperatures of the inner and outer surfaces of the brick wall are measured to be 20°C and 5°C, respectively, and the rate of heat transfer through the wall is 1100 W. Determine

(a) the rate of exergy destruction in the wall and
(b) the rate of total exergy destruction associated with this heat transfer process.



Tutorial Q2 – exergy with work

Exergy destruction of steam expansion

A piston–cylinder device contains 0.05 kg of steam at 1 MPa and 300°C. Steam now expands to a final state of 200 kPa and 150°C, doing work. Heat losses from the system to the surroundings are estimated to be 2 kJ during this process. Assuming the surroundings to be at T_0 = 25°C and P_0 = 100 kPa, determine the

(a) exergy of the steam at the initial and the final states,

(b) exergy change of the steam,

(c) exergy destroyed, and

(d) second-law efficiency for the process.

Homework

– exergy analysis of a steam turbine

Steam enters a turbine steadily at 3 MPa and 450°C at a rate of 8 kg/s and exits at 0.2 MPa and 150°C. The steam is losing heat to the surrounding air at 100 kPa and 25°C at a rate of 300 kW, and the kinetic and potential energy changes are negligible. Calculate the

(a) actual power output,

(b) maximum possible power output

(c) second-law efficiency

(d) exergy destroyed, and

(e) exergy of the steam at the inlet conditions.