

ESO 201A: Thermodynamics

2016-2017-I semester

Energy Analysis of Closed Systems: part 4

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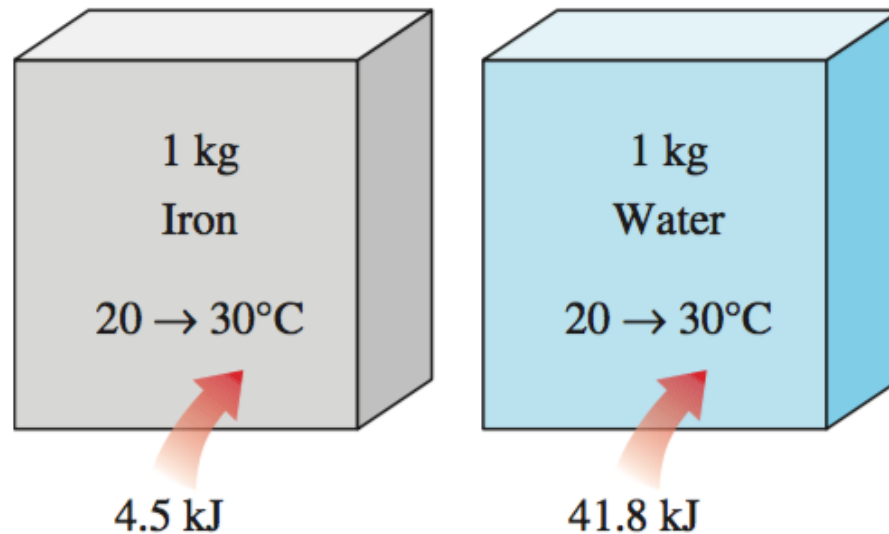
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Learning objective

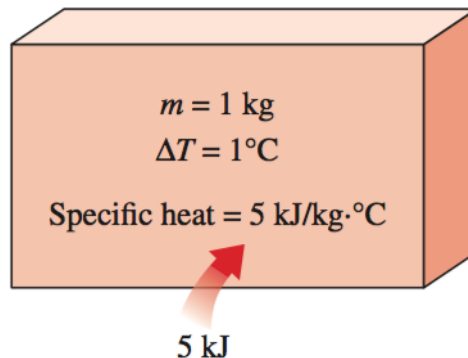
- Examine the moving boundary work or $P dV$ work commonly encountered in reciprocating devices such as automotive engines and compressors.
- Identify the first law of thermodynamics as simply a statement of the conservation of energy principle for closed (fixed mass) systems.
- Develop the general energy balance applied to closed systems.
- Define the specific heat at constant volume and the specific heat at constant pressure.
- Relate the specific heats to the calculation of the changes in internal energy and enthalpy of ideal gases.
- Describe incompressible substances and determine the changes in their internal energy and enthalpy.
- Solve energy balance problems for closed (fixed mass) systems that involve heat and work interactions for general pure substances, ideal gases, and incompressible substances.

Specific heat

It takes different amounts of energy to raise the temperature of different substances by the same amount.



How to compare energy storage capabilities of various substances

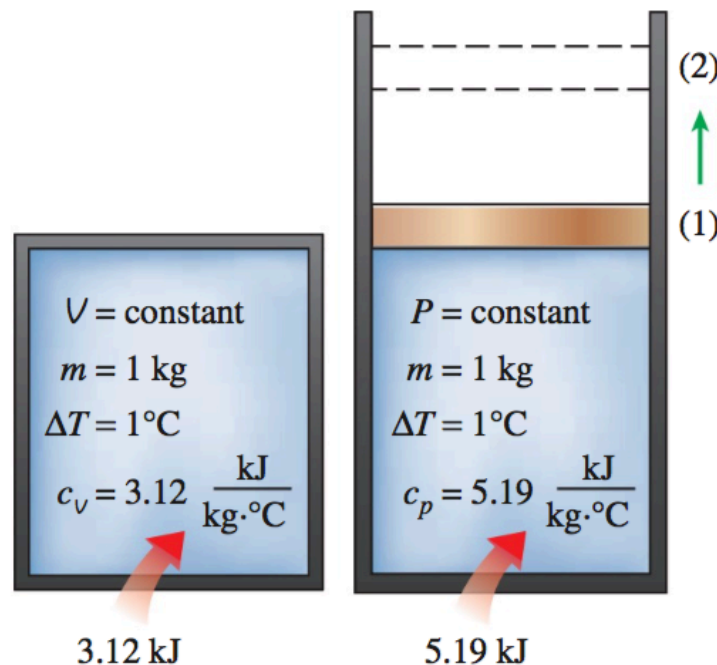


The specific heat is defined as the energy required to raise the temperature of a unit mass of a substance by one degree

Specific heat

Specific heat at constant volume, c_v : The energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

Specific heat at constant pressure, c_p : The energy required to raise the temperature of the unit mass of a substance by one degree as the pressure is maintained constant.



Note: c_p is always greater than c_v to accommodate energy needed for the expansion work

Helium gas

Specific heats in terms of thermodynamic properties

Consider a fixed mass in a stationary closed system undergoing a constant-volume process (no boundary work)

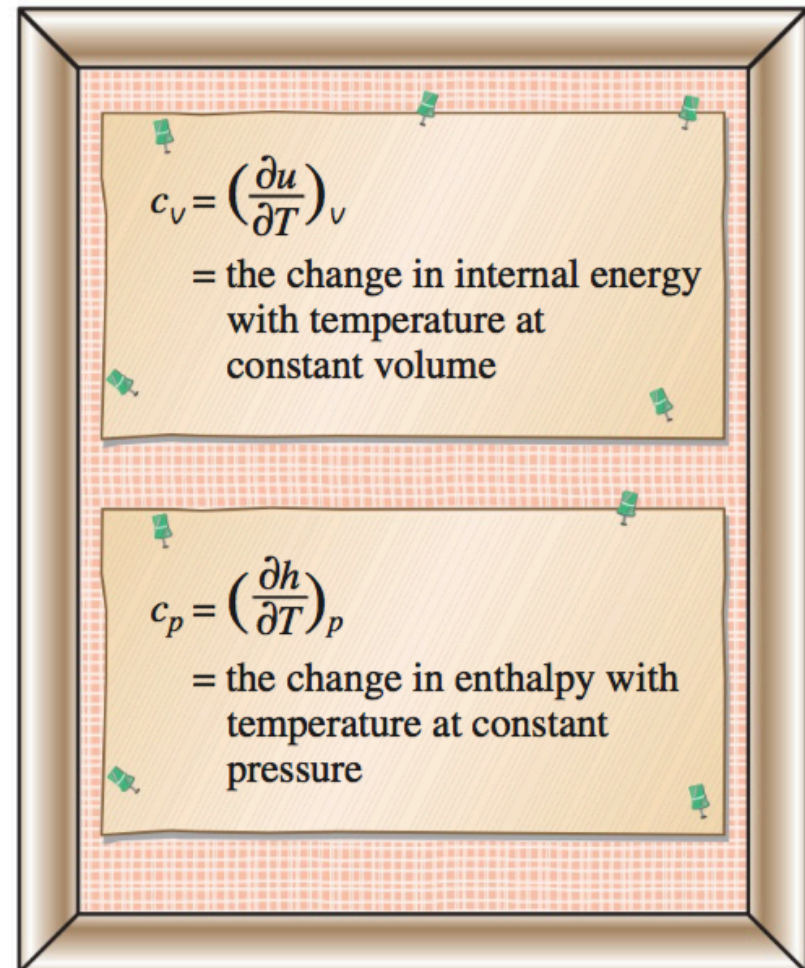
$$\delta e_{\text{in}} - \delta e_{\text{out}} = du$$

This is equivalent to

$$c_v dT = du$$

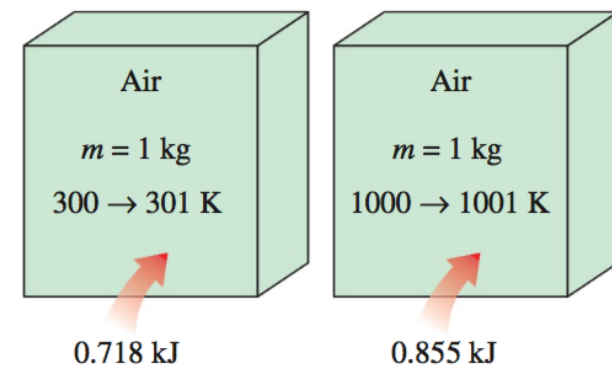
$$c_v = \left(\frac{\partial u}{\partial T} \right)_v$$

$$c_p = \left(\frac{\partial h}{\partial T} \right)_p$$

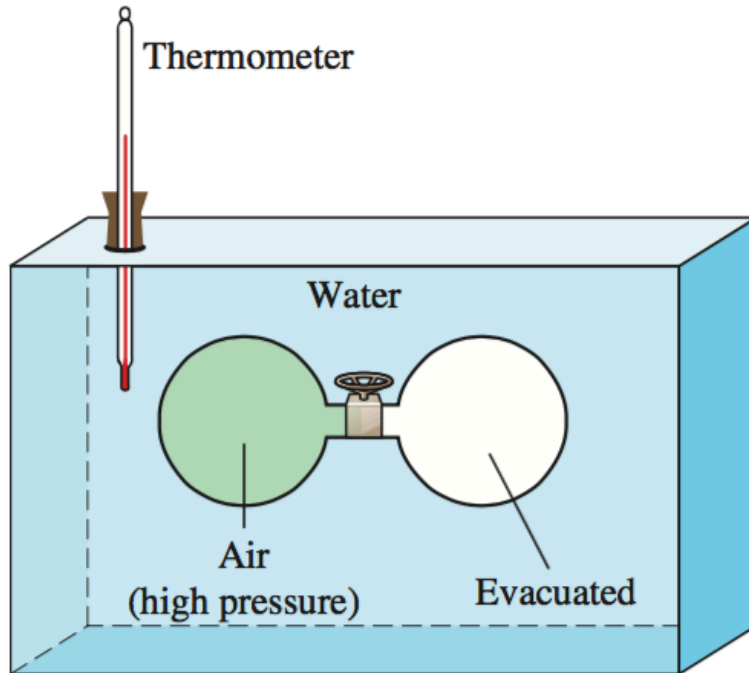


Specific heats in terms of thermodynamic properties

- The equations are valid for *any* substance undergoing *any* process.
- Specific heats are expressed in terms of other properties; thus, they must be properties themselves
- Like any other property, the specific heats of a substance depend on the state that, in general, is specified by two independent, intensive properties
- i.e. the energy required to raise the temperature of a substance by one degree is different at different temperatures and pressures
- c_v is related to the changes in *internal energy* and c_p to the changes in *enthalpy*.
- A common unit for specific heats is $\text{kJ/kg} \cdot ^\circ\text{C}$ or $\text{kJ/kg} \cdot \text{K}$.
 - **Are these units identical?**



Internal energy, enthalpy and specific heats of ideal gas



Joule showed using this experimental apparatus that $u = u(T)$

Using the definition of enthalpy and the equation of state of an ideal gas,

$$\left. \begin{array}{l} h = u + Pv \\ Pv = RT \end{array} \right\} h = u + RT$$

$$h = h(T)$$

$$c_v = \left(\frac{\partial u}{\partial T} \right)_v \longrightarrow c_v(T) = \frac{du(T)}{dT}$$

$$du = c_v(T) dT$$

$$dh = c_p(T) dT$$

Internal energy, enthalpy and specific heats of ideal gas

$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T) dT \quad (\text{kJ/kg})$$

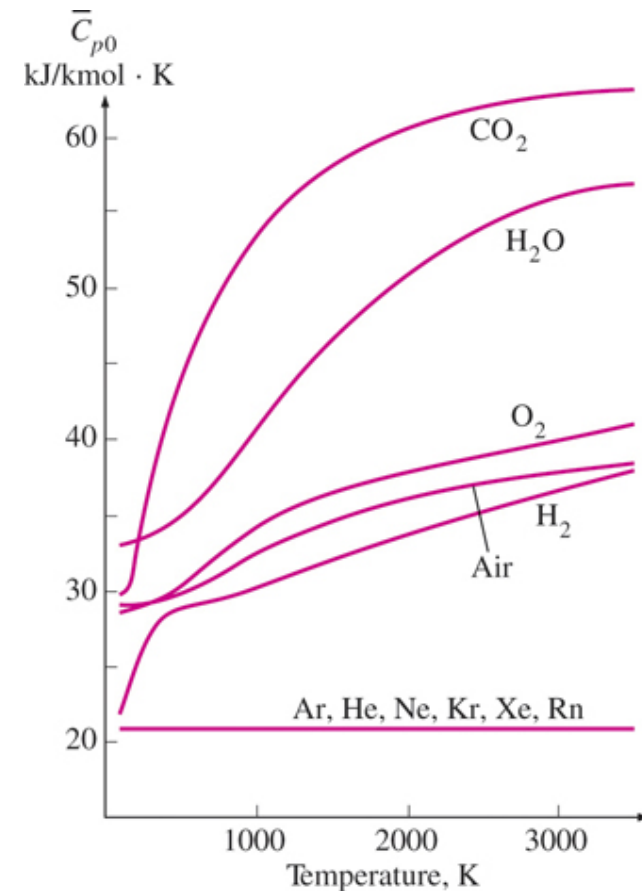
$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T) dT \quad (\text{kJ/kg})$$

Internal energy and enthalpy change
of an ideal gas

Need relation of C_v and C_p as a function of temperature

Specific heats of real gas at low pressure

- At low pressures, all real gases approach ideal-gas behavior, and therefore their specific heats depend on temperature only.
- The specific heats of real gases at low pressures are called *ideal-gas specific heats*, or *zero-pressure specific heats*, and are often denoted c_{p0} and c_{v0} .



Ideal-gas constant-pressure specific heats for some gases

Ideal-gas constant pressure specific heats for some gases

APPENDIX 1

TABLE A-2

Ideal-gas specific heats of various common gases (*Concluded*)

(c) As a function of temperature

$$\bar{c}_p = a + bT + cT^2 + dT^3$$

(T in K, c_p in kJ/kmol·K)

Substance	Formula	a	b	c	d	Temperature range, K	% error	
							Max.	Avg.
Nitrogen	N ₂	28.90	-0.1571×10^{-2}	0.8081×10^{-5}	-2.873×10^{-9}	273–1800	0.59	0.34
Oxygen	O ₂	25.48	1.520×10^{-2}	-0.7155×10^{-5}	1.312×10^{-9}	273–1800	1.19	0.28
Air	—	28.11	0.1967×10^{-2}	0.4802×10^{-5}	-1.966×10^{-9}	273–1800	0.72	0.33
Hydrogen	H ₂	29.11	-0.1916×10^{-2}	0.4003×10^{-5}	-0.8704×10^{-9}	273–1800	1.01	0.26
Carbon monoxide	CO	28.16	0.1675×10^{-2}	0.5372×10^{-5}	-2.222×10^{-9}	273–1800	0.89	0.37

The use of ideal-gas specific heat data is limited to low pressures, but these data can also be used at moderately high pressures with reasonable accuracy as long as the gas does not deviate from ideal-gas behavior significantly.

Internal energy, enthalpy and specific heats of ideal gas

- The integrations are straightforward but rather time-consuming and thus impractical.
- u and h data for a number of gases have been tabulated.
- These tables are obtained by choosing an arbitrary reference point and performing the integrations by treating state 1 as the reference state.

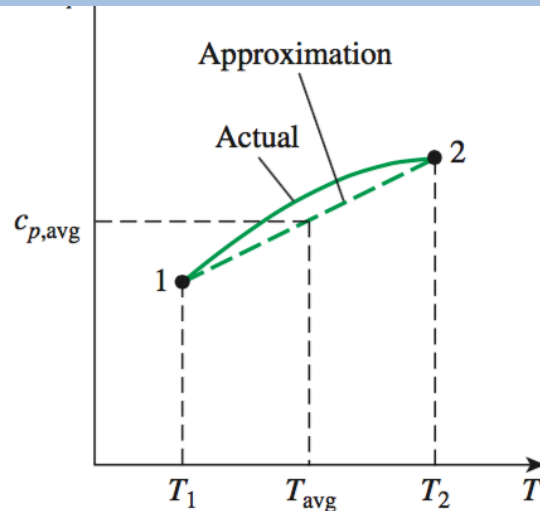
$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T) dT \quad (\text{kJ/kg})$$

$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T) dT \quad (\text{kJ/kg})$$

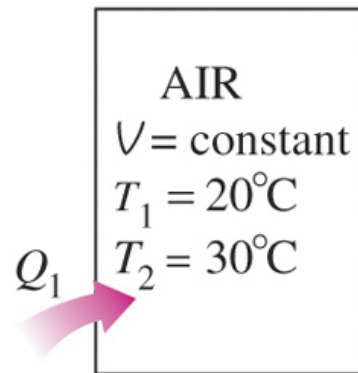
TABLE A-17				
Ideal-gas properties of air				
T K	h kJ/kg	P_r	u kJ/kg	v_r
200	199.97	0.3363	142.56	1707.0
210	209.97	0.3987	149.69	1512.0
220	219.97	0.4690	156.82	1346.0
230	230.02	0.5477	164.00	1205.0
240	240.02	0.6355	171.13	1084.0
250	250.05	0.7320	178.28	979.0

In the preparation of ideal-gas tables, 0 K is chosen as the reference temperature.

Internal energy, enthalpy and specific heats of ideal gas

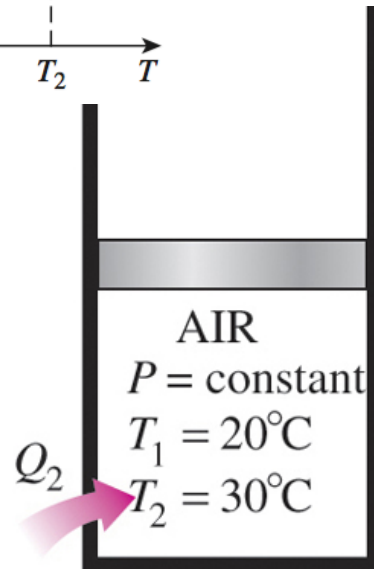


For small temperature intervals, the specific heats may be assumed to vary linearly with temperature.



$$\Delta u = c_v \Delta T$$

$$= 7.18 \text{ kJ/kg}$$



$$\Delta u = c_v \Delta T$$

$$= 7.18 \text{ kJ/kg}$$

$$u_2 - u_1 = c_{v,\text{avg}}(T_2 - T_1) \quad (\text{kJ/kg})$$

$$h_2 - h_1 = c_{p,\text{avg}}(T_2 - T_1) \quad (\text{kJ/kg})$$

The relation $\Delta u = c_v \Delta T$ is valid for *any* kind of process, constant-volume or not.

Similarly argument can be given for c_p

Internal energy, enthalpy and specific heats of ideal gas

1. By using the tabulated u and h data. This is the easiest and **most accurate** way when tables are readily available.
2. By using the c_v or c_p relations (Table A-2c) as a function of temperature and performing the integrations. This is very inconvenient for hand calculations but quite desirable for computerized calculations. The results obtained are **very accurate**.
3. By using average specific heats. This is very simple and certainly very convenient when property tables are not available. The results obtained are **reasonably accurate** if the temperature interval is not very large.

$$\Delta u = u_2 - u_1 \text{ (table)}$$

$$\Delta u = \int_1^2 c_v(T) dT$$

$$\Delta u \cong c_{v,\text{avg}} \Delta T$$

Next lecture

- Examine the moving boundary work or $P dV$ work commonly encountered in reciprocating devices such as automotive engines and compressors.
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