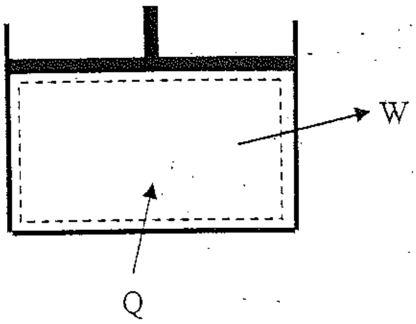
CANKAYA UNIVERSITY
FACULTY OF ENGINEERING AND ARCHITECTURE
MECHANICAL ENGINEERING DEPARTMENT

ME 211 THERMODYNAMICS I

CHAPTER 2 EXAMPLES

Example: Oxygen at 300 K expands slowly and isothermally from 100 kPa to 45 kPa. The mass of oxygen is 0.052 kg. Using ideal gas model find the work done.



$T_1 = T_2 = T_o$ $\quad$ $p_1 = 100$ kPa
$p_2 = 45$ kPa $\quad$ $m = 0.052$ kg
$T_1 = 300$ K

Choose O_2 as the system

Assume quasi-equilibrium process:

$$W = C\ln(V_2 / V_1)$$
$$p_1V_1 = p_2V_2 = mRT_o$$
$$\therefore\ W = mRT_o \ln(V_2/V_1) = \frac{m\bar{R}T_o}{M}\ln\left(\frac{V_2}{V_1}\right) = \frac{m\bar{R}T_o}{M}\ln\left(\frac{m\bar{R}T/p_2M}{m\bar{R}T/p_1M}\right) = \frac{m\bar{R}T}{M}\ln\left(\frac{p_1}{p_2}\right)$$

$$W = \frac{(0.052\,\text{kg})(8.314\,\text{kJ/kmol.K})(300\,\text{K})}{32\,\text{kg/kmol}}\ln\left(\frac{100\,\text{kPa}}{45\,\text{kPa}}\right) = 3.24\,\text{kJ}$$

2)

Example: A well insulated piston cylinder assembly contains 0.031 m^3 of air at 40°C and 102 kPa. Find the work required to compress the air slowly to 350 kPa. in a polytropic process.

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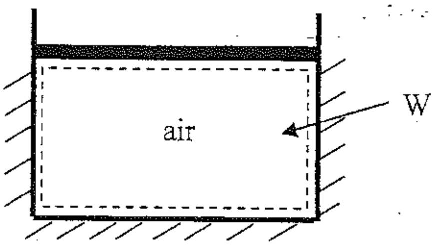


$V_1 = 0.031\,m^3$

$T_1 = 40°\,C$

$p_1 = 102\,kPa$

$p_2 = 350\,kPa$

Define the system as the air; slow process, adiabatic compression, ideal gas:

$n = k = c_p / c_v = 1.4$ $\qquad PV^n = C$

$$W = \frac{p_2 V_2 - p_1 V_1}{1-k}$$

$$p_2/p_1 = (V_1/V_2)^k \Rightarrow V_2 = V_1(p_1/p_2)^{1/k} = 0.0128\,m^3$$

$$W = \frac{-(102\,kPa)\left(1000\frac{pa}{kPa}\right)(0.031) + (350\,kPa)(0.0128\,m^3)\left(\frac{1000\,Pa}{1\,kPa}\right)}{1-1.4} = -3338.2\ J$$

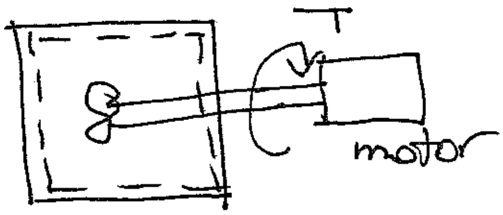
$= -3.3382\ kJ$

work is done on the system

3) A shaft rotates at a rate of 120 rev per minute against a constant torque of 1000 N.m. Calculate the power required to rotate the shaft Find the work required to rotate the shaft through 60 revolutions.

3) : $\dot{W} = T\omega$

$= (1000\,N.m)(120\,rev)$



$= (1000\ N.m)\left(120\ \frac{rev}{min}\right)\left(\frac{2\pi\, rad}{rev}\right) \times \frac{min}{60\,sec}$

$= 12566.3\ W$

b) $W = T(\theta_2 - \theta_1) = (1000)(60)(2\pi)$

$= 376991\ \ N.m$

4)

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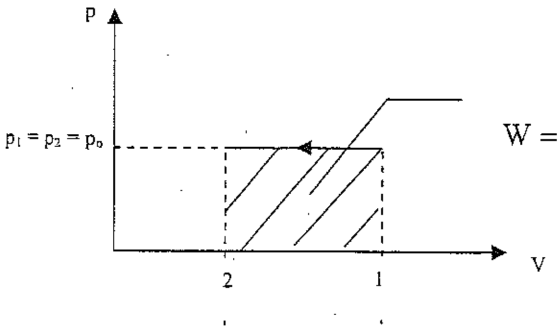
Example: One forth kg of a gas contained within a piston and cylinder assembly undergoes a constant-pressure process at 5 bar beginning at $v_1 = 0.2\ m^3/kg$. For the gas as the system, the work is -15kJ. Determine the final volume of the gas, in m^3.



$$W = \int_1^2 p dV$$

1- closed system
2- pressure is constant

$$W_{12} = \int_{V_1}^{V_2} p dV = p(\forall_2 - \forall_1)$$

$$\forall_2 = \frac{W_{12}}{p} + mv_1 = \left(\frac{-15\,kJ}{5\,bar}\right)\left(\frac{1\,bar}{10^5\,N/m^2}\right)\left(\frac{10^3\,N.m}{kJ}\right) + (0.25\,kg)(0.2\,m^3/kg)$$

$$\Rightarrow V_2 = 0.02\,m^3$$

5)

Example: A gas is compressed from $V_1 = 0.3\ m^3$, $p_1 = 1$ bar to $V_2 = 0.1\ m^3$, $p_2 = 3$ bar. Pressure and volume are related linearly during the process. For the gas, find the work, in kJ.

$\frac{30}{2}$

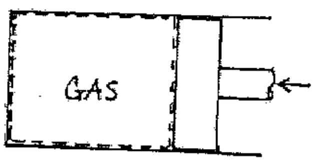
KNOWN: A gas undergoes a compression process. Pressure and volume are given at the initial and final states. Pressure and volume are related linearly during the process.

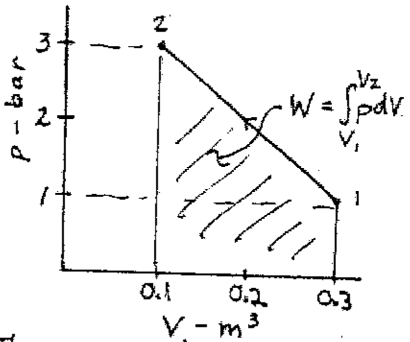
FIND: Determine the work.

SCHEMATIC & GIVEN DATA:

$p_1 = 1$ bar, $V_1 = 0.3\ m^3$

$p_2 = 3$ bar, $V_2 = 0.1\ m^3$





ASSUMPTIONS: (1) The gas is a closed system. (2) The compression is a quasi-equilibrium process with a linear relation between pressure and volume.

ANALYSIS: Based on the given data, the p-V relation can be expressed as

$$p = 4 - 10\,V \qquad \text{i.e.}\quad p - 1 = \left(\frac{3-1}{0.1-0.3}\right)(V - 0.3)$$

where p is in bars and V is in m³. The work is determined using Eq. 2.17

$$W = \int_{V_1}^{V_2} p\,dV$$

Inserting the p-V relation and integrating

$$W = \int_{V_1 = 0.3\ m^3}^{V_2 = 0.1\ m^3} [4 - 10\,V] \left|\frac{10^5\ N/m^2}{1\ bar}\right| \left|\frac{1\ kJ}{10^3\ N\cdot m}\right| dV$$

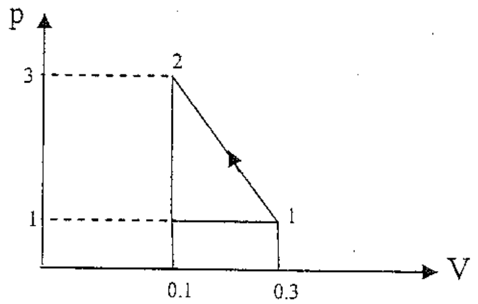
$$= \left[4V - \left(\frac{10}{2}\right)V^2\right]\Bigg|_{V_1 = 0.3}^{V_2 = 0.1} |100|$$

$$= [4(0.1 - 0.3) - 5(0.1^2 - 0.3^2)]\,|100|$$

① $= -40\ kJ$ ← W

1. The negative sign for work denotes energy transfer to the system.

another method:



$$W = 10^5[(0.3 - 0.1)(1)] + 10^5[(0.3 - 0.1)(3 - 1)/2]$$

$$\Rightarrow W = 0.2\times10^5\ J + 0.2\times10^5\ J = 0.4\times10^5\ J = 40\ kJ \text{ (work is done on the process)}$$

or compute area of trapezoid

$$W = \left(\frac{3+1}{2}\right)(10^5)\left(\frac{1}{10^3}\right)(0.3-0.1)$$

$= 40$ kJ

5

6)

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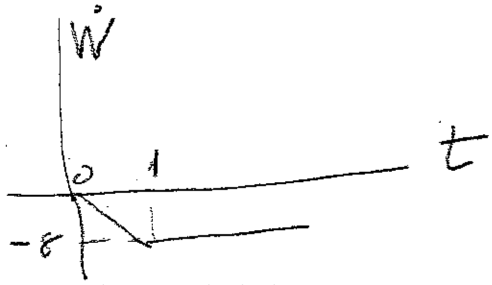
Example: A closed system undergoes a process during which there is energy transfer from the system by heat at a constant rate of 10 kW, and power varies with time according to:

$$\dot{W} = \begin{cases} -8t & 0 < t < 1\,h \\ -8 & t > 1\,h \end{cases} \quad (h\_hour)$$

where t is time in hour and $\dot{W}$ is in kW.

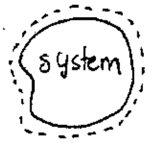


a) What is the time rate of change of system energy at t = 0.6 h, in kW?
b) Determine the change in system energy after 2 h, in kJ.

KNOWN: A closed system undergoes a process with a known heat transfer rate, and the power varies as a specified function of time.

FIND: Determine (a) the rate of change of system energy at t = 0.6 h and (b) the change in system energy after 2 h.

SCHEMATIC & GIVEN DATA:



$\dot{Q} = -10\ kW$

$$\dot{W} = \begin{cases} -8t & 0 < t \le 1\,h \\ -8 & t > 1\,h \end{cases}$$

where t is in h and $\dot{W}$ is in kW

ASSUMPTION: The system is closed.

ANALYSIS: (a) The time rate of change of energy at any time t is given by

$$\frac{dE}{dt} = \dot{Q} - \dot{W} \qquad (*)$$

At t = 0.6 h

$$\left.\frac{dE}{dt}\right|_{t=0.6h} = \left[\dot{Q} - (-8t)\right]_{t=0.6h} = (-10\ kW) - (-8 \cdot 0.6)\ kW$$

① $$= -5.2\ kW \qquad dE/dt$$

(b) The change in system energy is obtained by integrating (*) over the time period of 2 h. That is

$$\Delta E = \int_{t=0}^{t=2h} (\dot{Q} - \dot{W})\,dt$$

$$= \dot{Q}\Delta t - \left[\int_{t=0}^{t=1h} (-8t)\,dt + \int_{t=1h}^{t=2h} (-8)\,dt\right]$$

$$= (-10)(2) - \left[\frac{(-8)}{2} t^2\right]_0^1 - \left[(-8)t\right]_1^2$$

$$= -20 - [(-4)] - [(-8)(2-1)]$$

$$= -8\ kW \cdot h$$

Thus

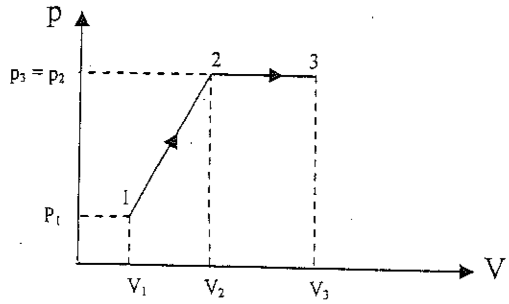
② $$\Delta E = (-8\ kW \cdot h)\left|\frac{1\ kJ/s}{1\ kW}\right|\left|\frac{3600\ s}{1\ h}\right| = -28{,}800\ kJ \qquad \Delta E$$

---

1. At t = 0.6 h, the energy of the system is <u>decreasing</u> at a rate of 5.2 kW because the rate of energy transfer <u>out</u> by heat exceeds the rate of energy transfer <u>in</u> by work.
2. The negative sign denotes a net <u>decrease</u> of energy over the time period.

7)

Example: Carbondioxide (CO_2) is slowly heated from an initial temperature of 50°C to a final temperature of 500°C. The process occurs in two steps. In the first step, pressure varies linearly with volume; in the second step pressure is constant as shown in the figure below:



The initial pressure, p_1, is 100 kPa and the final pressure, p_3, is 150 kPa. The temperature, T_2, at at the end of first step is 350°C. If the mass of CO_2 is 0.044 kg, calculate the total work done.

$$W = \int_{V_1}^{V_2} p dV = \left(\frac{p_1 + p_2}{2}\right)(V_2 - V_1) + p_2(V_3 - V_2)$$

$$p_1 V_1 = mRT \Rightarrow V_1 = \frac{m(\overline{R}/M)}{p_1} T_1$$

$$V_1 = \frac{(0.044\,kg)(8.314\,kJ/kmol.K)(323\,K)(1000\,J/1kJ)}{(100\,kPa)(44\,kg/kmol)(1000\,Pa/1kPa)} = 0.0268\,m^3$$

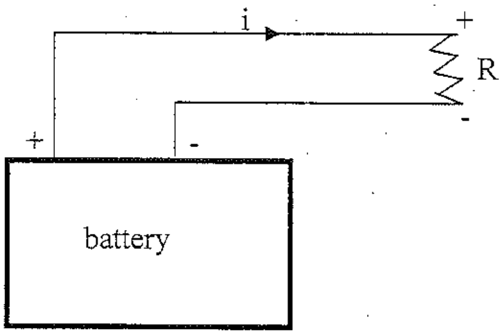
$$V_2 = \frac{m\overline{R}T_2}{p_2 M} = \frac{(0.044\,kg)(8.314\,kJ/kmol.K)(623\,K)(1000\,J/1kJ)}{(150\,kPa)(44\,kg/kmol)(1000\,Pa/1kPa)} = 0.0345\,m^3$$

$$\therefore W = \left(\frac{100+150}{2}\,kPa\right)(0.0345m^3 - 0.0268\,m^3) \times \left(\frac{1000\,Pa}{1kPa}\right)$$
$$+ (150\,kPa)\left(\frac{1000\,Pa}{1\,kPa}\right)(0.0428\,m^3 - 0.0345\,m^3) = 2200\,J = 2.2\,kJ$$

$$V_3 = \frac{m(\overline{R}/M)T_3}{P_3}$$

8)

Example: In the simple circuit shown in the figure below, the battery has a voltage of 10 Volts and the resistor has a resistance of 25Ω. In the span of 5 minutes how much work is done by battery on the resisters?



$$W = \int Ei\,dt$$

$$E = iR \Rightarrow I = \frac{E}{R} = \frac{10\,V}{25\,\Omega} = 0.4\,A$$

Let us consider resistor as the system under steady. Work is done on the resistor.

$$W = -Ei\Delta t = -(10V)(0.4A)(5\,min)\left(\frac{60\,s}{min}\right) = -1200\,J$$

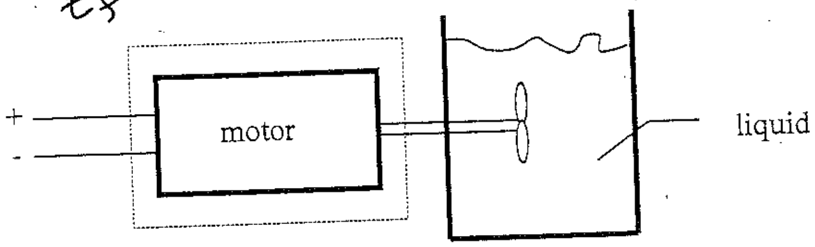
9) **Example:** A constant speed motor drives a paddle-wheel that is submerged in a viscous fluid. With time, the temperature of the liquid increases, the liquid viscosity decreases and less work is needed for the stirring action. The torque applied as a function of time is determined experimentally to be:

$$\Gamma = A + Be^{-mt}$$

~W

If the motor rotates or constant speed of [illegible] rpm, calculate the work done by motor on the liquid in the first [illegible] minutes of operation.

tf



80 rpm

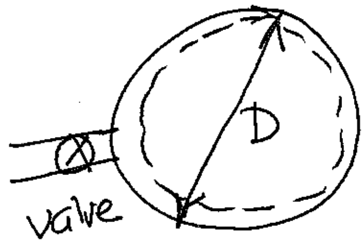
$$W = \int \Gamma d\theta$$

$$W = \int \Gamma \omega dt \qquad \omega = \frac{d\theta}{dt}$$

$$W = \int_0^{t_f} \left[A + Be^{-mt}\right](\omega dt) = A\omega t_f - \frac{B\omega}{m}\left[e^{-mt_f} - 1\right] =$$

10) An elastic balloon has a diameter of 0.5 m and is filled with gas at a pressure of 200kPa.The gas is heated so that its diameter increases to 0.6 m and a pressure to 250 kPa. During the process, the pressure is proportional to the balloon's diameter. Calculate
(a) The work done by the gas during the process
(b) The work done by the balloon on the atmosphere.

Solution



$P_1 = 200\ kPa$
$D_1 = 0.5\ m$
$P_2 = 250\ kPa$
$D_2 = 0.6\ m$

$$\forall = \frac{4}{3}\pi r^3 = \frac{\pi}{6}D^3$$

$$\forall_1 = \frac{4}{3}\pi r_1^3 = \frac{\pi}{6}D_1^3 = \frac{\pi}{6}(0.5)^3 = 0.065\ m^3$$

$$\forall_2 = \frac{\pi}{6}(0.6)^3 = 0.1130\ m^3$$

$$P = CD = (C)\left(\frac{6\forall}{\pi}\right)^{1/3} = C\left(\frac{6}{\pi}\right)^{1/3}\forall^{1/3} = K\forall^{1/3}$$

$$W_{12} = \int_{\forall_1}^{\forall_2} P\,d\forall = \int_{\forall_1}^{\forall_2} K\forall^{1/3}d\forall = K\frac{3}{4}\left(\forall_2^{4/3} - \forall_1^{4/3}\right)$$

$$= \frac{3}{4}\left[K_2\forall_2^{4/3} - K_1\forall_1^{4/3}\right]$$

$$= \frac{3}{4}\left[\frac{P_2}{\forall_2^{1/3}}\cdot\forall_2^{4/3} - \frac{P_1}{\forall_1^{1/3}}\cdot\forall_1^{4/3}\right]$$

$$= \frac{3}{4}\left[P_2\forall_2 - P_1\forall_1\right] = 11.46\ kJ$$

11) Measured data for pressure versus volume during the expansion of gases within the cylinder of an internal combustion engine are given in the table below. Using data from the table, complete the following:

(a) Determine a value of n such that the data are fit by an equation of the form, $pV^n = constant$.

(b) Evaluate analytically the work done by the gases, in kJ, along with the result of part (a).

(c) Using graphical or numerical integration of the data, evaluate the work done by the gases, in kJ.

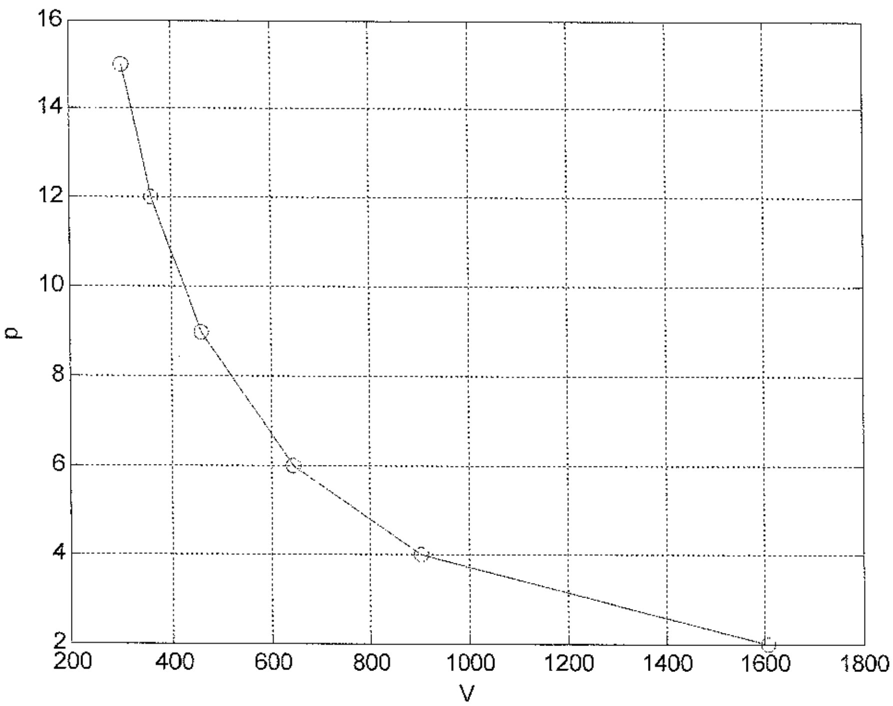
(d) Compare the different methods for estimating the work used in parts (b) and (c). Why are they estimates?

Data Point	p (bar)	V (cm3)
1	15	300
2	12	361
3	9	459
4	6	644
5	4	903
6	2	1608

Solution

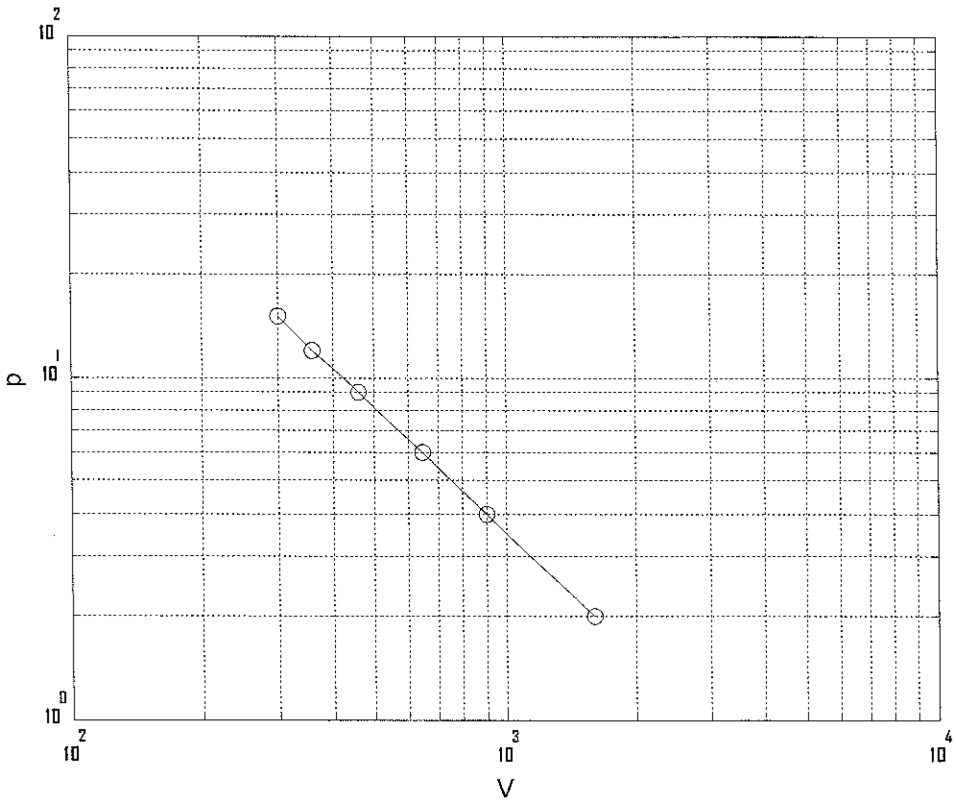
Let us plot data p=f(V) :

```
p=[15 12 9 6 4 2 ];
V=[300 361 459 644 903 1608];
plot(V,p,V,p,'O'),xlabel('V'),ylabel('p'),grid
```



Let us plot data on log-log axis

```
p=[15 12 9 6 4 2 ];
V=[300 361 459 644 903 1608];
loglog(V,p,V,p,'O'),xlabel('V'),ylabel('p'),grid
```



One approach to find n is to begin with $pV^n = c$. Take log of both sides of this equation

$$\log p = -n \log V + \log C$$

$$y = mx + b$$

$$y = \log p$$

$m = -n$ ← slope

$b = \log C$ ← intercept

Let us now curve fit using

MATLAB polyfit command

y = log (p)

```
   2.7081    2.4849    2.1972    1.7918    1.3863    0.6931

>> x=log(V)

x =

   5.7038    5.8889    6.1291    6.4677    6.8057    7.3827

>> f=polyfit(x,y,1)

f =

  -1.1996    9.5499

>> m=f(1)

m =

  -1.1996

>> b=f(2)

b =

   9.5499
```

$\therefore \quad (-n) = -1.1996$

$n = 1.1996$

$\therefore \; pV^{1.1996} = C$

b)

(b) Using the results of part (a) and the procedure of Example 2.1, the work is

$$W = \int_{V_1}^{V_2} p\,dV = \frac{p_2V_2 - p_1V_1}{(1-n)}$$

$$= \frac{(2\text{ bar})(1608\text{ cm}^3) - (15)(300)}{(1-1.1996)} \left|\frac{10^5\text{ N/m}^2}{1\text{ bar}}\right| \left|\frac{1\text{ m}^3}{10^6\text{ cm}^3}\right| \left|\frac{1\text{ kJ}}{10^3\text{ N-m}}\right|$$

$= 0.643$ kJ $\underline{\hspace{6em}}$ W

=

```
clear;
C= 14043;
% Generate new data for Volume
V=300:100:1600;
% Generate new data for pressure

 p=C./V.^(1.1996);
% display the new data
[p' V']

% Convert bar to Pascal
p=p*1E5;

% Volume cm^3 to m^3
V=V/1E6;

% display the new data
disp('Converted New data')
[p' V']

% Calculate the work using Matlab trapz command
disp('Calculated Work')
W=trapz(V,p);
fprintf('Work W=%10.5f Joule\n',W)
```

ans =

14.994	300
10.618	400
8.1241	500
6.5281	600
5.426	700
4.6229	800
4.0138	900
3.5372	1000
3.155	1100
2.8423	1200
2.5821	1300

2.3625	1400
2.1748	1500
2.0128	1600

Converted New data

ans =

1.4994e+006	0.0003
1.0618e+006	0.0004
8.1241e+005	0.0005
6.5281e+005	0.0006
5.426e+005	0.0007
4.6229e+005	0.0008
4.0138e+005	0.0009
3.5372e+005	0.001
3.155e+005	0.0011
2.8423e+005	0.0012
2.5821e+005	0.0013
2.3625e+005	0.0014
2.1748e+005	0.0015
2.0128e+005	0.0016

Calculated Work

Work W= 644.89674 Joule

12) **Example:** A gas is contained in a piston cylinder assembly. The gas is compressed when 670 J of work are done on it. Over the same period, a paddle wheel does 182 J of work on the gas and internal energy decreases by 201 J. How much heat has been transferred during the process? Was the gas heated or cooled?

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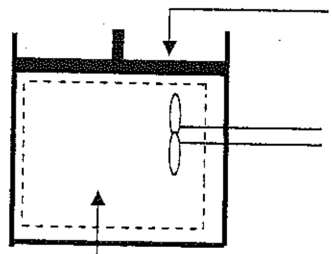
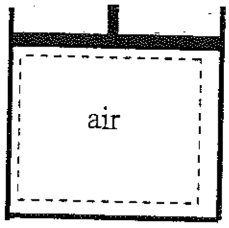


$Q - W = \Delta U$

$Q = \Delta U + W = -201 + (-182-670) = -1053$ J

Q is negative, the system is cooled.

13) **Example:** Air is contained in a vertical piston-cylinder assembly by a piston of mass 50 kg and having a face area of 0.01 m^2.

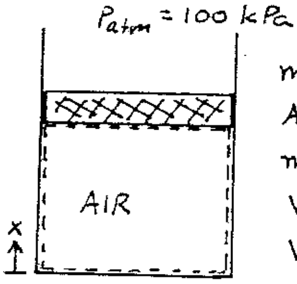


The mass of the air is 5 g, and initially the air occupies a volume of 5 liters. The atmosphere exerts a pressure of 100 kPa on top of the piston. The volume of the air slowly decreases to 0.002 m^3 as the specific internal energy of the air decreases by 260 kJ/kg. Neglecting friction between the piston and cylinder wall, determine the heat transfer to air, in kJ.

KNOWN: A known quantity of air undergoes a process in a vertical piston-cylinder assembly. The initial and final volumes are given, and the change in specific internal energy is specified.

FIND: Determine the heat transfer.

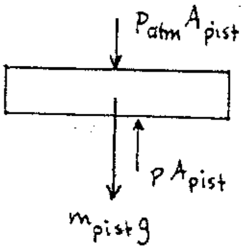
SCHEMATIC & GIVEN DATA:



$m_{pist} = 50$ kg
$A_{pist} = 0.01$ m^2
$m_{air} = 5$ g $= 0.005$ kg
$V_1 = 5$ L $= 0.005$ m^3
$V_2 = 0.002$ m^3
$\Delta u = -260$ kJ/kg

ASSUMPTIONS: (1) The air is a closed system. (2) Kinetic and potential energy effects are negligible for the air. (3) There is no friction between the piston and the cylinder wall. (4) The process occurs slowly with no acceleration of the piston. (5) The acceleration of gravity is constant, $g = 9.81$ m/s^2.

ANALYSIS: For the piston, $\Sigma F_x = 0$. Thus, if p is the pressure exerted by the air



$$pA_{pist} = P_{atm} A_{pist} + m_{pist} g$$

$$p = P_{atm} + \frac{m_{pist} g}{A_{pist}}$$

$$= 100 \text{ kPa} + \frac{(50 \text{ kg})(9.81 \text{ m/s}^2)}{(0.01 \text{ m}^2)} \left| \frac{1 \text{ N}}{1 \text{ kg}\cdot\text{m/s}} \right| \left| \frac{1 \text{ kPa}}{10^3 \text{ N/m}^2} \right|$$

$$= 149.05 \text{ kPa}$$

To find the work for the process, use Eq. 2.17. Noting that the pressure is constant

$$W = \int_{V_1}^{V_2} p\,dV = p(V_2 - V_1)$$

$$= (149.05 \text{ kPa})(0.002 - 0.005) \text{m}^3 \left| \frac{10^3 \text{ N/m}^2}{1 \text{ kPa}} \right| \left| \frac{1 \text{ kJ}}{10^3 \text{ N}\cdot\text{m}} \right|$$

$$= -0.447 \text{ kJ}$$

Now, the energy balance reduces to $\cancel{\Delta KE}^{0} + \cancel{\Delta PE}^{0} + \Delta U = Q - W$. Thus, with $\Delta U = m_{air} \Delta u$

$$Q = m_{air} \Delta u + W = (0.005 \text{ kg})(-260 \tfrac{\text{kJ}}{\text{kg}}) + (-0.447 \text{ kJ})$$

$$Q = -1.747$$

Q

14) During a cycle ,composed of 4 processes, the heat transfers were 23 BTU, -4 BTU, -10 BTU, and 2 BTU. Determine the net work for the cycle.

solution

$$\oint \delta Q = 23 - 4 - 10 + 2 = 11 \text{ BTU}$$

$$\oint \delta W = J \oint \delta W = (778)(11) = 8558 \text{ ft-lb}_f$$

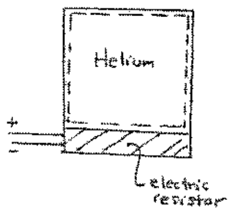
Note 1 BTU = 778.16 ft-lb$_f$

15) Helium gas is contained in a closed rigid tank. An electric resistor in the tank transfers energy *to* the gas at a constant rate of 1 kW. Heat transfer *from* the gas to its surroundings occurs at a rate of $5t$ watts, where t is time, in minutes. Plot the change in energy of the helium, in kJ, for $t \geq 0$ and comment.

KNOWN: Data are provided for helium contained in a closed rigid tank fitted with an electrical resistance.

FIND: Plot the change in energy of the helium, in kJ, for $t \geq 0$ and comment.

SCHEMATIC & GIVEN DATA:



ENGR. MODEL:

1. The helium is the system.
2. For the system, $\dot{W} = 0$.

ANALYSIS: An energy rate balance reads

$$\frac{dE}{dt} = \dot{Q} - \cancel{\dot{W}}^{\,0}$$

As the system receives energy by heat transfer from the resistor at a rate of 1 kW and loses energy by heat transfer to its surroundings at the rate of 5t W,

$$\dot{Q} = [1000 - 5t] \text{ W}$$

t (min), 5 ($\frac{W}{min}$)

Thus,

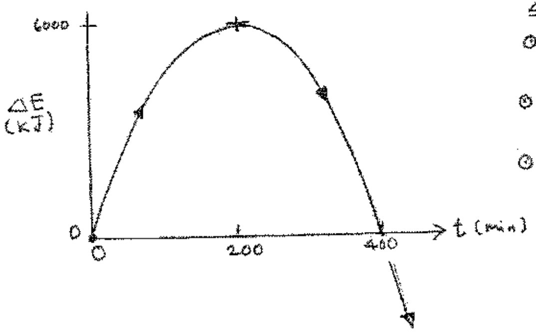
$$\frac{dE}{dt} = 1000 - 5t$$

and

$$\Delta E = \int_0^t \frac{dE}{dt}dt = \int_0^t (1000 - 5t)dt = \left[1000t - \frac{5t^2}{2}\right] \text{W}\cdot\text{min}$$

$$= \left[1000t - \frac{5t^2}{2}\right] \text{W}\cdot\text{min} \left|\frac{1 \text{ kJ/s}}{10^3 \text{ W}}\right| \left|\frac{60 \text{ s}}{\text{min}}\right| = \left[60t - 0.15t^2\right] \text{kJ}$$

(t in min)

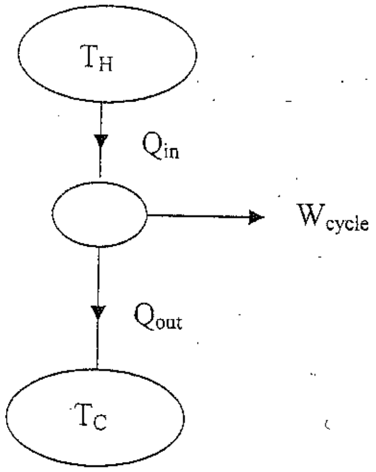


$\Delta E = E(t) - E(0) = E(t) - E_0$

- 0→200 min. Energy increases from the initial value at $t=0$: E_0.
- 200→400 min. Energy decreases to its initial value, E_0.
- 400 min →. Energy decreases from its initial value, E_0.

Note that since any arbitrary value E_0 can be assigned to the energy of the system at $t=0$, no particular significance can be attached to the value of energy at the initial state or at any other state. Only changes in the energy of the system have significance.

16) **Example:** For the power cycle operating as shown: 37/2

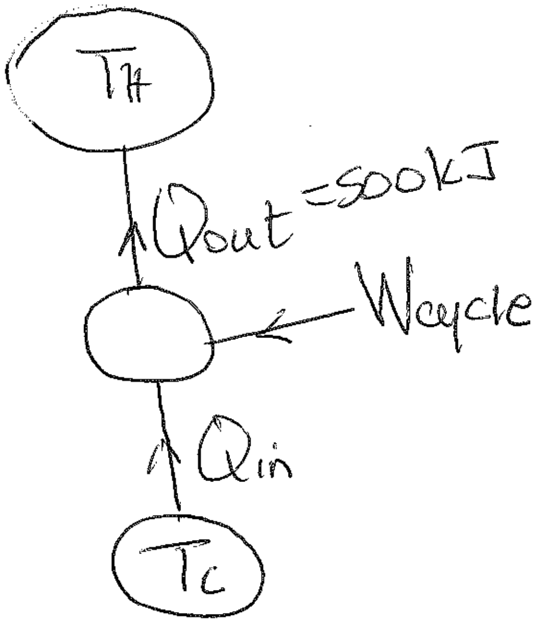


The heat transfers are $Q_{in} = 50$ kJ and $Q_{out} = 35$ kJ. Determine the net work, in kJ and the thermal efficiency.

a) $W_{cycle} = Q_{in} - Q_{out} = 50 - 35 = 15$ kJ

b) $\eta = \dfrac{W_{cycle}}{Q_{in}} = \dfrac{15}{50} = 0.3\ (30\%)$

17) A refrigeration cycle operates as shown in figure given below with a coefficient of performance $\beta = 1.5$ .For the cycle , $Q_{out} = 500\,\text{kJ}$. Determine Q_{in} and W_{cycle} each in kJ.



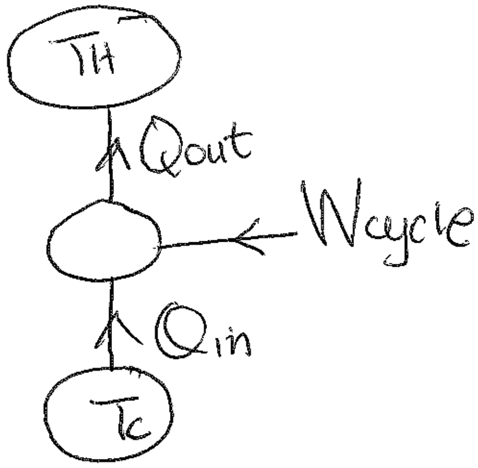
$\beta = 1.5$

$$\beta = \frac{Q_{in}}{W_{cycle}} = \frac{Q_{in}}{Q_{out} - Q_{in}}$$

$$1.5 = \frac{Q_{in}}{500 - Q_{in}} \Rightarrow Q_{in} = 300\ \text{kJ}$$

$$W_{cycle} = \frac{Q_{in}}{\beta} = \frac{300}{1.5} = 200\ \text{kJ}$$

18) A heat pump cycle whose coefficient of performance is 2.5 delivers energy by heat transfer to a dwelling at a rate of 20 kW. Determine the net power required to operate the heat pump in kW.



$$\gamma = \frac{\dot{Q}_{out}}{\dot{W}_{cycle}}$$

$$\dot{W}_{cycle} = \frac{\dot{Q}_{out}}{\gamma}$$

$$= \frac{20\,kW}{2,5}$$

$$= 8\,KW$$