Thermodynamics I

Quiz 1 6/10/03

Hello people. Please read the questions carefully. As you solve them, indicate clearly your system boundaries and any assumptions you might make. When possible, please state in words what you are trying to solve/your approach so that I can follow your work and give you credit. This is especially important if you run out of time. Most importantly, relax!

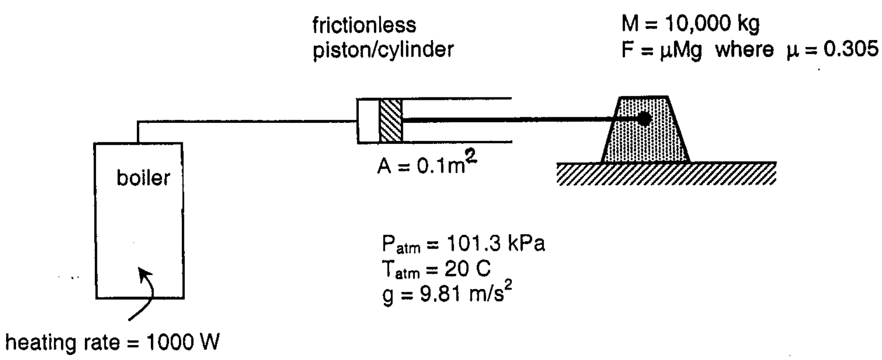
Problem 1 (5pts)

What does Ivan Illich mean by "radical monopoly"?

Problem 2 (95 pts)

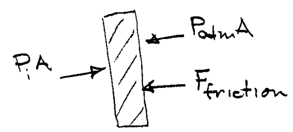
To move a heavy piece of equipment, we devised a simple piston cylinder device connected to a 1000 W boiler as shown in the figure. As heat is added to the boiler, the water initially at 20 C and 1 atm pressure, heats up and eventually begins to boil. When the pressure is great enough, the steam begins to move the piston, which in turn moves the equipment. The equipment has a friction force *F* opposing its movement as it slides on the ground. When the last drop of water evaporates, the heat source, Q, is turned off. The entire system is adiabatic, except for the heat addition in the boiler, and the volume in the pipe connecting the boiler to the cylinder is negligible. All thermal energy added to the boiler is transferred to the water. The boiler is initially full of water (water mass = 1 kg) and the initial cylinder volume is zero. Neglect changes in kinetic and potential energy.

a) what pressure must be reached in order for the piston to begin to move?
b) how long after the boiler is switched on will it take for the piston to begin moving?
c) how far will the mass have moved when the last drop of water evaporates?
d) how much heat was added up to this point?
e) what was the average piston velocity during this process? is it fair to neglect changes in kinetic energy in this problem? show quantitatively.
f) where did the input heat go during the process? calculate each component.
g) BONUS question: how much heat must be extracted from the boiler to return the piston to its initial position? why should it be different?



a) the piston will begin moving when the pressure inside the cylinder is sufficient to overcome the friction force and atmospheric pressure.

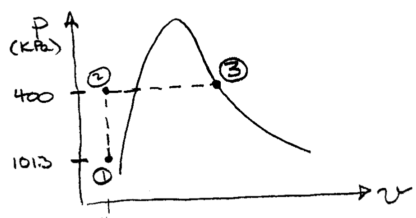
$\Sigma F_x = 0$ (assuming negligible inertial effects)



$$P_i A = P_{atm} A + \mu M g$$

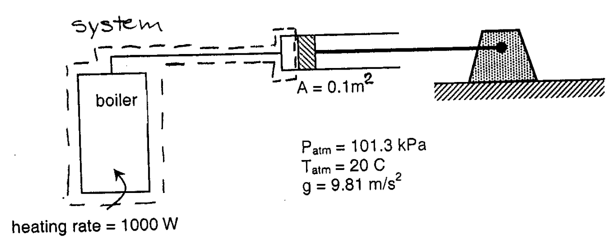
$$\Rightarrow P_i = 400 \text{ KPa}$$

b) since the system volume is fixed until the piston begins to move, we have a constant volume heating process until P = 400 KPa, at which point we have a constant pressure heat addition. On a P-v diagram for the water, we have the following:



the time it takes for the piston to begin moving is the time it takes for the water to reach state ②

using the system shown, we can apply the first law to calculate the required energy input from ① → ②



$$\Delta E = E_{in} - E_{out} = Q_{in} + \cancel{W_{in}}^{0} - \cancel{Q_{out}}^{0} - \cancel{W_{out}}^{0} = \Delta U + \cancel{\Delta PE}^{0} + \cancel{\Delta KE}^{0}$$

$$\Rightarrow \quad \Delta U = Q_{in} = m(u_2 - u_1)$$

we need the internal energy at (1) & (2), both of which correspond to the state of compressed liquid. to a good approximation, the internal energy of a compressed liquid is equal to the internal energy of a saturated liquid at the same temperature therefore:

$$u_1 = u_f(20°C)$$

$$u_2 = u_f(400\,kPa)$$

$$Q_{in} = (604.3 - 83.95)\,1 = 520.3\ KJ$$

since $Q = \int \dot{Q}\,dt = \dot{Q}\,\Delta t$ ($\dot{Q}$ is constant)

then $\Delta t = \dfrac{520.3 \times 10^3\ J}{1000\ J/s} = \boxed{520\,s}$

c) when the last drop evaporates, the specific volume of the water corresponds to that of saturated vapor at 400 kPa

$$v_3 = v_g(P = 400\,kPa) = 0.4625\ m^3/kg$$

so $V_3 = v_3\,m = 1(0.4625) = 0.4625\ m^3$

since $V = A \cdot S$ $\quad S = \dfrac{0.4625\ m^3}{0.1\ m^2} = \boxed{4.625\,m}$

d) using previously shown system boundaries:

$\Delta E = Q_{in} - W_{out}$ since $\Delta KE, \Delta PE$ are negligible, $\Delta E = \Delta U$

$\Rightarrow m_3 u_3 - m_1 u_1 = m(u_3 - u_1) = Q_{in} - W_{out}$

$W_{out} = \int P dV$ since we only have boundary work

$= P\Delta V$ since $P = const = 400\ kPa$

$= 400\times10^3 \frac{N}{m^2} \times 0.4625\ m^3 = 185\ kJ$

$u_3 = u_g(400\ kPa) = 2553.6\ kJ/kg \cdot K$

$u_1 \approx u_f(20°C) = 83.95\ kJ/kg \cdot K$

$\Rightarrow Q_{in} = 1(2553.6 - 83.95) + 185\ kJ = 2655\ kJ$

$t = \frac{Q}{\dot{Q}} = \frac{2655\times10^3\ J}{1000\ J/s} = 2655\ s = \boxed{44.2\ min}$

e) average piston velocity $= \frac{distance}{time} = \frac{4.625\ m}{2655\ s} = 1.74\times10^{-3}\ m/s = \boxed{1.74\ mm/s}$

$KE = \frac{1}{2} mV^2 = \frac{1}{2}(10000)(1.74\times10^{-3}) = \boxed{8.7\ J \ll 2655\ kJ}$

so yes, its valid to neglect KE!!

f) the input heat of 2655 kJ went to:

a) heating, then vaporizing the water:

$\Delta U = m(u_3 - u_1) = \underline{2470\ kJ}$

b) doing work against the atmosphere

$W_{b,atm} = P_{atm}\Delta V = (101.3\ kPa)(0.4625\ m^3) = \underline{46.9\ kJ}$

c) doing work against friction

$W_f = F\times S = (10{,}000\ kg)(9.81\ m/s)(0.305) \times 4.625\ m \times \frac{J}{1000\ k}$

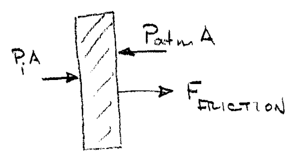
$= \underline{138.\ kJ}$

(note: $\Sigma(a-c) = 2470 + 46.9 + 138 = 2655\ kJ$, same as in part d))

g) the piston can't go back to its original position

here is why:

$$\Sigma F_x = 0$$



$$P_i A + F = P_{atm} A$$

$$P_i = \frac{P_{atm} A - F}{A} = \frac{(101.3 \times 10^3)(0.1) - (10{,}000)(0.305)(9.81)}{0.1}$$

$$= \underline{-198 \text{ kPa}} \quad (!)$$

no matter how much we cool the water, we can't get to a negative pressure (absolute). the best we can do is zero (in theory)

the only way to return the piston to its original position is to modify the apparatus. one possibility: