GEOS 24705 / ENST 24705
Problem set #4
Due: Problems 1-2 due Tuesday Apr. 13, Problems 3-4 due Thursday

Problem 1: Energy use in the past
Assess the growing importance of the steam engine to England (its birthplace) at the start of the Industrial Revolution (1800-1825). The technology obviously became economically important -- the Carnot (who was French) wrote in 1825 that steam engines were the foundations of the British empire:

"To take away to-day from England her steam-engines would be to take away at the same time her coal and iron. It would be to dry up all her sources of wealth, to ruin all on which her prosperity depends, in short, to annihilate that colossal power. The destruction of her navy, which she considers her strongest defense, would perhaps be less fatal."

How much extra energy did the steam engine provide to the average Englishman? Estimate this from class readings and from some values from the literature given below. The figure below shows the growth in the power of an individual steam engine (L panel) and the growth in efficiency (R panel) from their invention in 1712 til the cessation of most use around 1950.

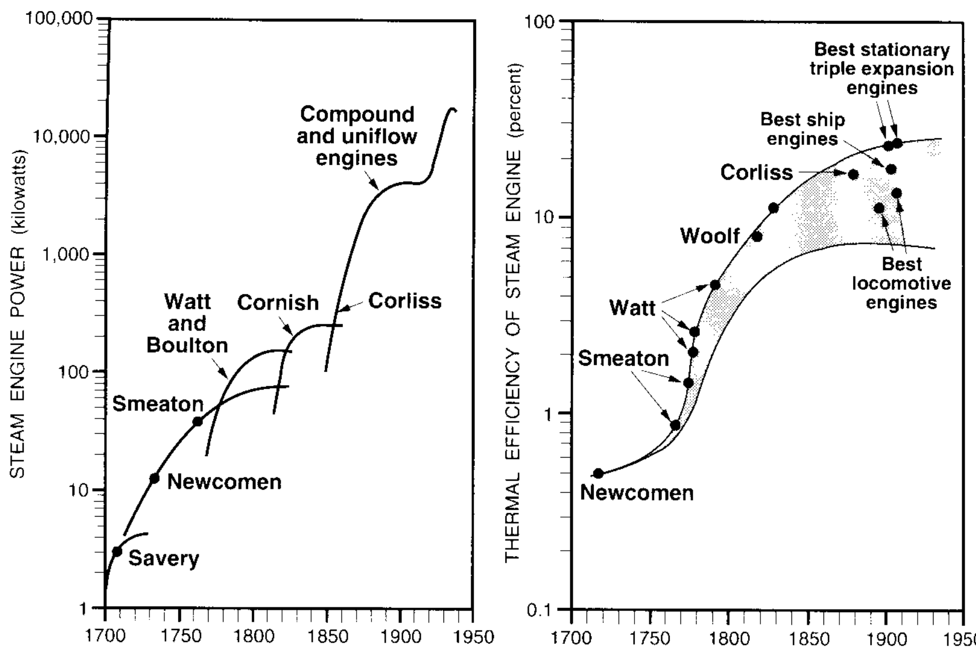


FIGURE 5.3 The rising power and improving efficiency of the best steam engines, 1700–1930. *Sources:* Plotted from data in Dickinson (1939) and von Tunzelmann (1978).

from V. Smil, "Energy in World History"

A. **Non-steam power use:** In his concluding pages, Braudel cites figures for Europe's power use in 1800 from various sources, in horsepower, for all activities other than food (excluding wind, for which he has no good estimate, and steam, which was still small – only a few hundred steam engines were operating in England, and fewer in the rest of Europe).

What is the per capita power use in Europe in 1800, in W/person? You can assume that the workers who provide the human-power in Braudel's inventory make up 1/3 of the population.

We can assume from here on that this power usage was also representative of England as well – let's assume that English steam fueled new mines and mills but didn't displace many older uses of power, so their non-steam power use looked like Europe's. For both estimates below, it's also reasonable to assume that this non-steam power use remained constant – that is, that the English added new industrial uses for steam power but didn't change their previous needs and activities.

B. **Steam power use in 1800:** In 1800, 25 years after Watt's first real production model, England has some 1200-2000 steam engines. (There were no accurate records kept, and estimates vary). You can estimate the average power of those engines from the figure above (L. hand panel), which shows the growth in power output of the best steam-engines over time. (Remember the average is lower, because older models persisted – in 1800, the fancy new Boulton and Watt engines made up less than half the steam engines in use in England). The 1801 census lists 8.3M people in England (likely a slight underestimate). What is the per capita use of steam power in England, in W/person? What fraction of England's total (steam + non-steam) power usage did steam represent?

C. **Steam power use in 1824**: J.P. Harris has estimated that nearly 25 years later, in 1824, England possessed 5000 steam engines. The 1821 census lists 11M people in England; the 1831 census 13M. What is the per capita use of steam power in England in 1825, in W/person? What fraction of England's power usage did steam represent in 1825?

D. **Context for us as Americans**: The U.S. at this time still had essentially no steam power at all. The first export of a Boulton & Watt engine to the U.S. didn't happen til 1803 (to Robert Fulton, who had been traveling in Europe, where he got fascinated by steam and invented the steamboat). Despite Fulton, by 1825 the U.S. had ordered only 7 Boulton & Watt engines. But the U.S. was industrializing by then. Where were the U.S. factories? What was their power source? Why was this a reasonable choice for the U.S.?

Problem 2: Making steam / latent heat

To make steam, any steam engine must first heat up water to its boiling point and then evaporate that water (that is, turn the liquid water into a gas). We have already discussed the "extra" heat that must be added to already-hot liquid water to get it change to a gas -- the "latent heat of vaporization", or L_v – and made an estimate of L_v from considering water evaporating in a microwave. You estimated the energy (in Joules) needed to evaporate one liter of water to derive a latent heat of in J/kg or J/m^3.

Latent heat can be thought of as a kind of energy "carried" by water vapor. You need to add energy to get liquid water to evaporate and become vapor (i.e. steam), and when water re-condenses to liquid that energy is released again as heat. (The First Law of Thermodynamics says that energy is conserved, so the heat of vaporization can't vanish, and has to be released again when you return to system to its original state by re-condensing the water). That is, water vapor condenses it dumps out its latent heat and raises the temperature of its surroundings.

Physics students especially should also see the handout on steam for more details – you'd need that for the optional problems in this problem set.

A. Compare the latent heat of vaporization of water to the the energy density of gasoline (which you looked up in PS2)? Note that the units of latent heat are the same as the units of energy density: J/kg.

B. How much gasoline would you need to burn to evaporate a liter of water? Give your answer in volume of gasoline, remembering that a liter of gasoline actually weighs only 0.7 kg. Gasoline (and oil) are lighter than water, which is why oil from an oil spill floats on top of the water instead of sinking to the bottom.

C. Explain how the numbers you've calculated above relate to the fact that burning yourself on steam in the kitchen is very painful.

D. ***(Optional)*** The latent heat of vaporization is also the reason why you evolved the ability to sweat. On hot days, your body produces liquid water in the form of sweat; as that water evaporates it takes up heat to drive the evaporation, leaving you cooler. You can actually use this to get a crude estimate of your output power when exercising. Imagine you go to exercise on a hot day (dry heat, like the desert, not Chicago summers) where you wouldn't be sweating while sitting around, but you do sweat while exercising. First, estimate how much additional water you would need to drink after exercising for say an hour. Assume you are just replacing water lost by sweating. How much additional cooling (in W) was your body producing from sweat evaporation? This cooling is the body's attempt to compensate for the excess heat you produce while exercising (because you're not perfectly efficient at turning food into work). Assuming you're some 20% efficient, what was your mechanical work output while exercising? Comment on the reasonableness of your value.

E. ***(Optional)***. It might be hard to really feel the evaporative cooling of water, but you can definitely feel evaporative cooling by splashing yourself with rubbing alcohol that then evaporates. (Try it! Even if you don't answer this question.) But the latent heat of vaporization of rubbing alcohol (isopropyl alcohol) is actually only about 1/3 that of water. Why does it feel colder?

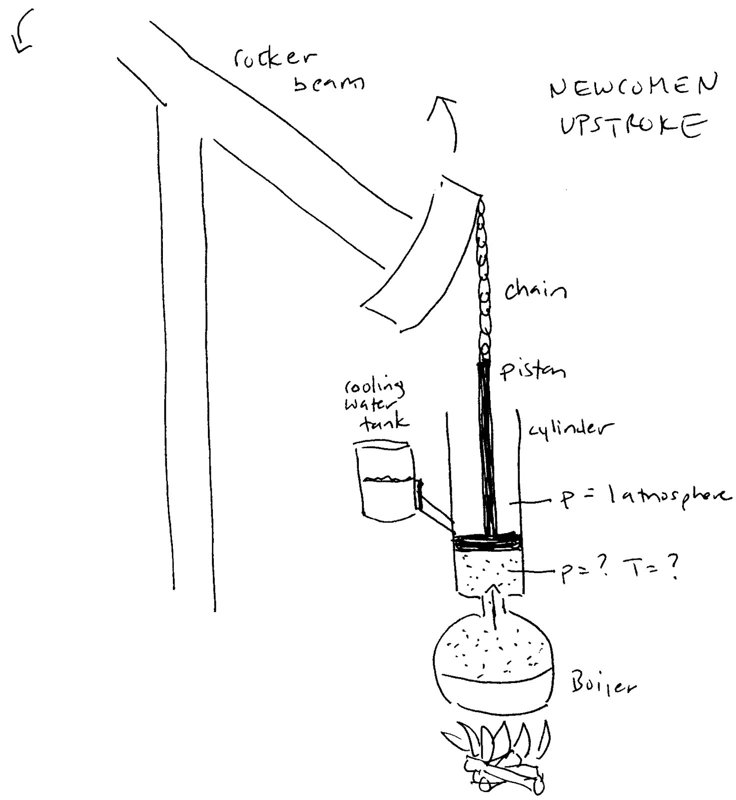
Problem 3: The Newcomen Engine

The Newcomen engine was the first commercially practical mechanism for transforming heat to work, and solved the problem of the draining of the coal mines. Galloway described the pumping of the English mines just before the invention of the steam engine, saying "In some instances, as many as fifty horses were employed in raising water at a single colliery. Many good mines were allowed to lie unwrought and drowned, it being found impracticable to drain them by means of any machine then known." *(Galloway, "A History of Coal Mining in Great Britain", p. 79).* Savery's invention of basically a "steam straw", where water was pulled up by generating a vacuum in a tube, could only lift water ~ 10 m high, and was dangerous if actually installed in a mine, since an open flame caused explosions.

Newcomen's engine offered a breakthrough. It was incredibly inefficient, but could be fed by the mines themselves. Galloway writes: "It was at this juncture that the miners had put into their hands the most wonderful invention which human ingenuity had yet produced – the Newcomen steam-engine, commonly called the "atmospheric engine"; a machine capable of draining with ease the deepest mines; applicable anywhere; requiring little or no attention; so docile that its movements might be governed by the strength of a child; so powerful that it could put forth the strength of hundreds of horses; so safe that, to quote the words of a contemporary writer, 'the utmost danger that can come to it, it its standing still for want of fire.' " *(Galloway, ibid, p. 80-81)*

The engine is called an 'atmospheric engine', remember, because the steam exerts no pushing force on the piston during the upstroke. The only net force applied is by the atmosphere itself during the engine's downstroke, when atmospheric pressure pushes the piston down. Atmospheric pressure in SI units is ~ 10^5 Pascal, where 1 Pascal = 1 kg m/s^2 per m^2)

Upstroke



In the first part of the Newcomen engine cycle, its cylinder is allowed to fill with pure steam (think: no air, or at least minimal air - just water molecules).

A. What pressure is the steam in the cylinder at?

B. What temperature is the steam in the cylinder at?

We'll call this T_{steam} in the problem. (You can likely answer A and B from common knowledge; if not, consult the handout on steam).

C. (*Optional)* Let's assume you get overenthusiastic and dump extra fuel into your firebox. Could you make higher pressure steam in the boiler while the valve to the cylinder is closed? Explain.

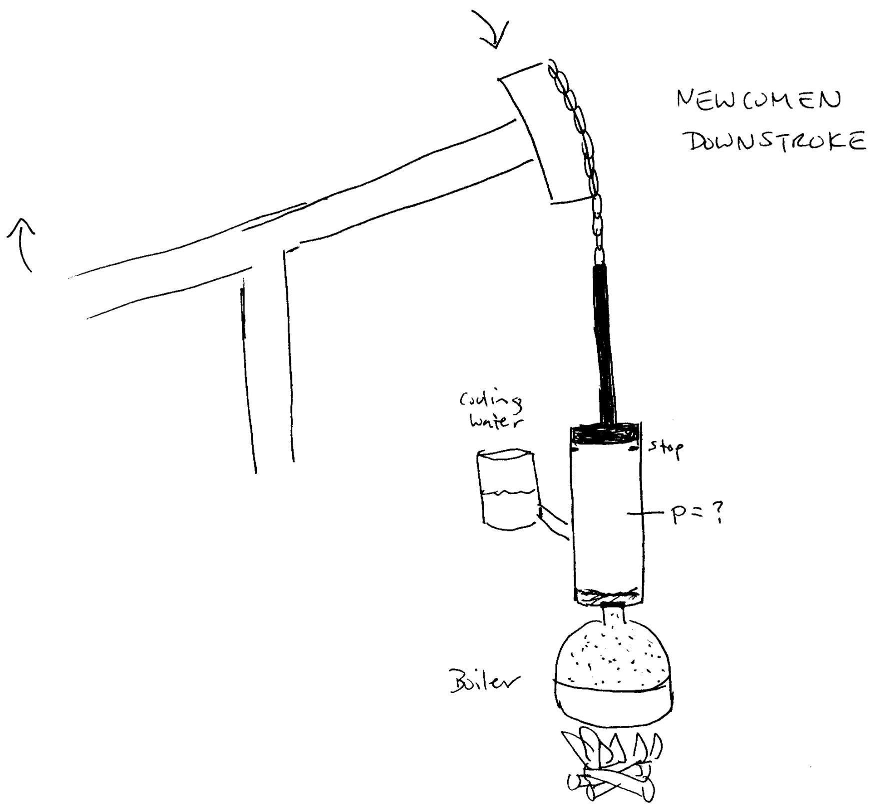
(n.b. Newcomen couldn't build a pushing engine not just because he couldn't figure out how to make a solid linkage to the rocker beam instead of chains, but also because his boiler was too leaky to support particularly high pressure – but assume for question C that your boiler is better).

D. *(Optional)* Describe what would happen to the cylinder and the rocker beam when you let that higher-pressure steam into the cylinder. Can you maintain higher T or p in the cylinder during the upstroke?

For the questions below, you'll need some size for the engine. I couldn't find the dimensions of the original 1712 engine, but a 1760 engine is listed as having a bore (cylinder inner diameter) of 28 inches and a stroke (length over which the piston travels in the cylinder) of 72 inches.

Downstroke

In the second part of the Newcomen engine cycle, cool liquid water is injected into the cylinder and the steam condenses.



Imagine that you shove in a "stop" in the cylinder just at the top of the piston stroke that keeps the piston from moving down. Then you squirt in the cooling water and condense the steam.

E. **What is the pressure inside the cylinder?** (Assume the mechanic who made it did a good job.)

F. **What is the pressure differential that the cylinder has to support?** ("Pressure differential" = the difference between outside pressure and inside pressure. If there's a pressure differential, you hope your cylinder can "support" it – be strong enough to withstand it - because otherwise it would implode or explode).

For the time being, your stop is keeping the piston from moving, and if it's not moving, there can be no net force on it. But now instantaneously pull out the stop so that the piston can move.

G. **Is there net force acting on the piston now? If so, draw an arrow showing the direction of this force and state its value.** (Imagine that you are experimenting with an engine that is not yet hooked up to a load, so nothing is pulling on the other end of the rocker arm).

H. **How much work (in J) could the engine do in one piston-stroke?**

I. **What mass of water could the engine raise each piston stroke?** (Note that you're estimating a maximum value – Newcomen couldn't typically get all the steam to condense perfectly, and of course there are frictional losses in the engine – the "stickier" the moving parts are, the less the engine can lift).

J. **The Newcomen engine whose dimensions we're using typically cycled at 14 strokes per minute. What power does this engine put out (in W and in hp)?** (Again, you're estimating a maximum value.)

K. **Which estimate of Newcomen engine power is closer to seeming correct, the one on the figure from Vaclav Smil's book (on the first page of this PS) or Galloway's claim that a Newcomen engine could do the work of hundreds of horses?**

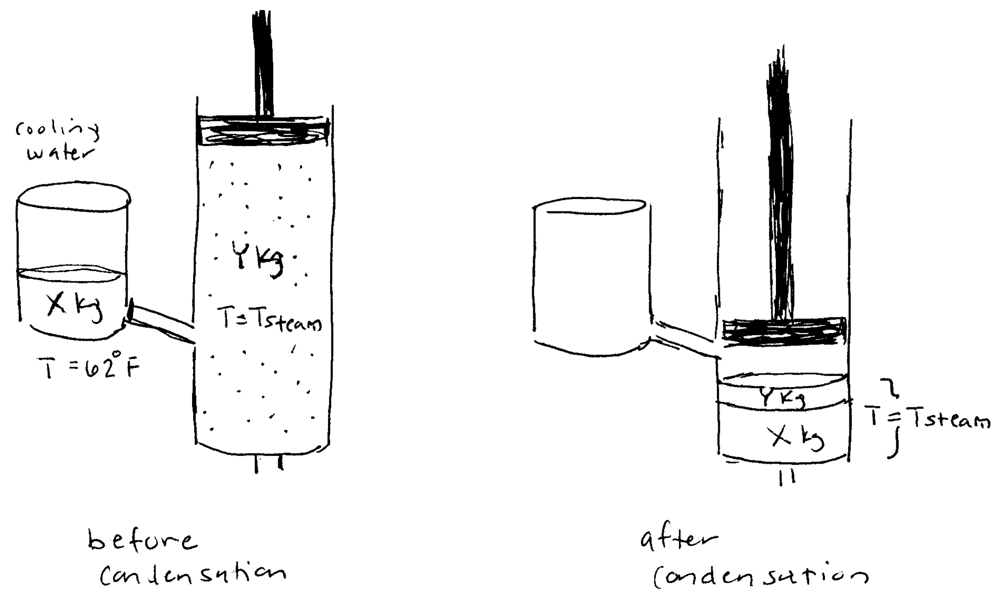
L. ***(Optional)*** **What is the maximum bore of the pump to which a Newcomen engine could be connected and successfully pump? What happens if you connect the engine to a larger-bore pump? To a smaller-bore pump?**

Problem 4: Design problems with the Newcomen Engine

James Watt got interested in steam engines when he was asked to work on a model Newcomen engine. (He was a mechanic working for Glasgow University). He was surprised by how much water had to be squirted into the cylinder on each engine cycle to condense the steam. After some experimenting with a full-scale Newcomen engine, he found that the minimum amount of water he could add per stroke and keep the engine going was 24 kg of liquid water (from his reservoir tank, which was at 62 Fahrenheit). That amount of water condensed only one kg of water in the form of steam.

That seemed excessive to him, and he started investigating in a more controlled way.

The picture below shows how condensation should be working in the cylinder. Some mass of cold liquid water (X kg) is added to hot steam (Y kg). If you did this just right, to waste no energy at all, you'd have perfectly insulated cylinder walls. In that case the temperature of the cylinder would never change. You'd condense the steam, releasing its latent heat, and in the process you'd heat up the cold water, but the walls wouldn't change temperature - the only transfer of energy would be between the steam and the liquid water. The end result (if you added *just* enough cool water to condense the steam) would then be X + Y kg of liquid water at T_{steam}.



A. For this system, describe what happened to the latent heat that was dumped out when the steam condensed.

B. Describe what would happen if you didn't add cold water but instead added hot liquid water (just at steam temperature). Would the engine function?

First, Watt did some careful experiments to determine how much energy he could derive from condensing steam. He made the first definition and measurement of the latent heat of vaporization of water, L_v.

Then, Watt thought about the energy going to heat the cooling water. All material has a characteristic "specific heat", i.e. a characteristic amount of energy required to raise the temperature of a given mass of water. (The specific heat, or c_p, actually varies a little with temperature, but for the purpose of this class we'll consider it a constant). Watt also did enough experiments to effectively derive the specific heat of water vapor. (Though he didn't have standard units to describe it in – the calorie wasn't defined until fifty years later, by exactly this physics, as the amount of energy required to raise 1 gram of liquid water by 1 degree Celsius.)

Watt then calculated:

C. How much cooling water (in kg) should ideally be needed to condense 1 kg of steam? (If you need to break this into steps, first calculate the amount of energy needed to condense 1 kg of steam, then the energy needed to raise the temperature of 1 kg cooling water, then combine to figure out how much cooling water you need).

And finally, Watt estimated the wastefulness of the Newcomen engine by asking:

D. What is the ratio

kg cooling water actually used to condense steam
--- ?
kg cooling water that should be used

Watt concluded from his ratio that the Newcomen cylinder was wastefully designed. Some of his cooling water must be cooling the cylinder walls themselves, i.e. pulling energy from them on each stroke. The cylinder was cooling on each downstroke, then heating up again on each upstroke stroke when steam was re-introduced. That meant that some of the steam energy had to go into reheating the cylinder rather than into mechanical work, and that the engine operator was having to burn more fuel to boil more water on each stroke.

E. *(Optional)* From your previous answers, estimate the efficiency of the Newcomen engine (work out/energy in to make steam), if its cylinder walls were perfectly insulated.