Engines: Crash Course Physics #24

Crash Course: Physics
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Think of all the developments throughout history that led to the conveniences you enjoy today. If I had to pick the biggest gamechanger in human technology, it would probably be...the steam engine. During the industrial revolution, the steam engine powered machines in farms and factories. And although it might not seem so, those advances eventually led to the technologies that you're using to watch me right now.

So the steam engine was a pretty big deal. Developing a practical steam engine involved a lot of time, and a lot of smart people, and about a hundred years and three main inventors. And it took a solid understanding of thermodynamic processes and heat engines to make this world-changing technology a reality.

Heat engines, like steam engines, turn thermal energy into mechanical work, and they do it in a repeating cycle. The process starts at a high-operating temperature, which we label T_H, and ends up at a lower-operating temperature, T_L. In the process, the engine takes the input heat that was used to raise the temperature, known as Q_H, and turns some of it into work (W), while also releasing some heat, Q_L, as exhaust. Then the engine's temperature is raised once more, so it can start the cycle all over again. Okay.

Now think back to the first law of thermodynamics, which says that the change in the thermal energy of a system is equal to heat and work. In the case of a heat engine, the change in thermal energy is zero because it always returns to the temperature it started from. So the engine's input heat must be equal to the work it does, plus the heat it releases. Now let's see how this plays out in a steam engine.

There are a few different types of steam engine, but we'll focus on the basic reciprocating type. As long as you have something to heat the steam like coal or oil, the engine keeps working. That's the input heat. The input heat is used to heat a volume of water, which turns to steam. Then an intake valve opens, allowing steam into the engine. The steam expands and moves a piston outward. That's the work done by the engine. Then an intake valve closes, and an exhaust valve opens. The exhaust valve leads to a condenser, which cools the steam back into water. The lower temperature also lowers the pressure, creating a partial vacuum that makes the piston move back into it's original position. Then the water gets heated back into steam, and the cycle starts over.

As the engine runs, the motion of the piston can be translated into all kinds of different movement, which is how steam engines can do things like move trains, boats, and run factory lines. But as the steam engine runs, it releases exhaust heat. The more exhaust heat it produces, the less efficient the engine is, and the more energy you have to put in for the same amount of work. Obviously, it's important for engines to be as efficient as possible to save energy. And to design an efficient engine, engineers have to be able to calculate its efficiency.

Like we said earlier, as engine's input heat is equal to the work it does plus its exhaust heat. And the more work, and therefore the less exhaust heat you get out of the input heat, the more efficient your engine is. So, efficiency is equal to the work done by an engine divided by its input heat. We can also put this just in terms of input heat and exhaust heat--pretty easily actually. We know that work is equal to input heat minus exhaust heat, so efficiency is equal to input heat minus exhaust heat, divided by the input heat. Or, simplifying those terms, efficiency is equal to one minus exhaust heat over input heat.

If your engine produced no exhaust heat at all, we'd say that its efficiency was exactly one. It would be perfectly efficient. But, there's no such thing as an engine that produces no exhaust heat at all. It wouldn't work, because the temperature needs to be lowered and then raised again for the engine to keep going.

But we can imagine an ideal engine, when none of the exhaust energy is waste heat, where there's no friction or anything like that. An ideal engine would also be reversible--meaning you could run it backward, putting in work to transfer heat from something with a lower temperature to something with a higher temperature. This kind of hypothetical engine is called a Carnot Engine, and we can use it figure out the maximum possible efficiency of a real-life engine.

Last time, we talked about the four types of basic thermodynamic processes. The Carnot Engine combines two of those types into what's known as the Carnot Cycle. But in the Carnot Cycle, those processes don't transfer heat between areas with different temperatures because if an engine involves heat transfer from and area with a higher temperature to an area with a lower temperature, then reversing the engine would involve transferring heat from lower to higher. Which would violate the second law of thermodynamics.

So in the Carnot Cycle, heat won't flow between areas of different temperatures at all. Instead, the cycle goes through two adiabatic processes where heat is held constant, and two isothermal processes where heat is transferred. But, the temperature is held constant, so the heat never flows between areas of different temperatures.

Now, you might be wondering how heat get transferred if there's no difference in temperature. Well, remember how we described the isothermal processes last time. In those cases, there are only very tiny differences in temperature, and they're immediately eliminated. So, practically speaking, there is no transfer of heat between areas of different temperatures, and this means the process can still be reversed.

With all that in mind, here's how a Carnot Engine works, at least in theory. Because again, Carnot engines are totally hypothetical. The first process in the cycle is isothermal. The temperature is constant, but heat is slowly added. That makes the gas's volume expand and its pressure decrease--path AB on this diagram.

The second process is adiabatic. The temperature drops while the heat stays constant, which also makes the volume expand, and the pressure decrease. That's path BC on the diagram.

The third process is the opposite of the first one, and it's also isothermal. The gasses compress while the temperature is held constant, so it releases heat, and its pressure increases while its volume decreases. That's path CD.

The last process is the opposite of the second. It's adiabatic, so the gasses compress, but its heat doesn't change. That makes the gas's volume decrease and its pressure increase, like in path DA. Its temperature goes back up to the starting point.

The Carnot Engine is the ideal engine because it produces the most possible work from a given temperature difference. And because a Carnot Engine is as efficient as possible, the high or low temperatures are proportional to the input and exhaust heat. Which is important math-wise, because it means that in the equation for efficiency, you can replace Q_H and Q_L, the input and exhaust heat, with T_H and T_L, the higher and lower operating temperatures. Which can help if you don't know an engine's input and exhaust heats, but you do know its operating temperature.

So, the ideal efficiency for an engine is equal to one minus its low temperature, divided by its high temperature. The colder that lower operating temperature is, the more efficient the ideal version of the engine is.

So, say you need an engine to power a life-sized Mario Kart that you're building for yourself. You find an engine online and you're thinking about buying it, but first you want to know how efficient it is. The manufacturer's website says that for every second the engine's input heat is ten kilojoules at five hundred Kelvin, its exhaust heat is two kilojoules at three hundred Kelvin. The efficiency equation says that the engine's efficiency is equal to one minus this exhaust heat divided by its input heat. In this case, 0.8.

That would be a very efficient engine, so you should be a little bit suspicious. I mean, is that kind of efficiency even possible? You can find out by checking the ideal efficiency of the engine--the Carnot Efficiency. The ideal efficiency is equal to one minus its lower-operating temperature divided by its higher-operating temperature, which in this case is equal to 0.4. It's impossible for this engine to have an efficiency higher than 0.4, so the manufacturer's website is...well, just lying. So you probably shouldn't buy anything from them anyway.

And actually, you probably wouldn't want an engine that was close to the efficiency of a Carnot Engine, because Carnot Engines are very slow. During those isothermal processes, the temperature has to be kept constant while heat is transferred--which only works if the heat is transferred super slowly. So the engine has to be really slow.

If you had a Carnot Engine in your car, for example, it would take you a whole day to get out your driveway. Real-life heat engines are useful because they use the flow of heat from something warmer to something cooler to produce work. But what if you want heat to flow from something cooler to something warmer?

That's what things like air conditioners and refrigerators do, and they were originally developed using the principles scientists had learned from creating steam engines. These cooling machines are a lot like the opposite of heat engines in the sense that they use work to make heat flow in the opposite direction than it would normally go. The refrigerator, for example, passes a cool liquid through the inside of the fridge. The liquid absorbs heat, that's Q_L, as it evaporates. Then the fridge uses the motors to do work on the now-warmer fluid, which is turned into a gas. It's passed through coils on the outside of the refrigerator, where it releases the exhaust heat, Q_H, and cools to become a liquid again.

Then the cycle starts over. For heat engines, efficiency is measured by the work produced for a given amount of input heat. And there's a similar concept for refrigerators--the coefficient of performance, or COP, which is equal to the amount of heat removed from the lower temperature zone, divided by the work. The more heat the fridge removes for a given amount of work, the higher the coefficient of performance. Like we did with the efficiency equation, we can rewrite the COP equation just in terms of Q_L and Q_H. The coefficient of performance is equal to Q_L divided by Q_H minus Q_L.

To find the coefficient of performance for an ideal refrigerator, we do the same thing we did with the ideal Carnot Engine--replace Q_L with T_L, and Q_H with T_H. So, for an ideal fridge, the coefficient of performance would be equal to the lower-operating temperature, divided by the higher-operating temperature minus the lower-operating temperature. And of course, a real-life refrigerator can't have a higher coefficient of performance than an ideal refrigerator.

Now it may not be surprising that steam engines and refrigerators are total opposites. But, fridges and freezers and air conditioning are all game-changing inventions that were only made possible by our knowledge of steam engines.

Today you learned about how engines turn thermal energy into work and how to calculate their efficiency. We also described the Carnot engine and finally, we talked about cooling machines, like refrigerators.

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