The Cold Sink Is Not a Detail

A common assumption about engines

A student learns that a power station turns only part of the energy in its fuel into electricity and passes the rest to its surroundings by heating. The loss is large — often more than half — and the natural conclusion is that it reflects imperfect engineering: a better engine would waste less, and a perfect one would waste nothing, turning all the energy it takes in into work. But no engine can do that. The energy an engine sends on to a colder place is part of what lets it do any work at all; it cannot simply be kept. That an engine must have a cold side was recognised before anyone had a modern account of what heat is.

Carnot’s question

In 1824 a French engineer, Sadi Carnot, published a short book on the motive power of fire — the useful work obtainable from heat. His advance was to change the question. Engine-builders asked how much coal a machine burned; Carnot asked how much heat had to flow through it, and what that flow could be made to do.

He reasoned inside the theory of his day — caloric, the fluid the previous article overturned, though the experiments that did so were still twenty years off. Yet his central finding did not depend on the theory being right. Carnot pictured caloric flowing from the hot furnace down to a colder body, the fall doing the work, much as falling water drives a mill. The picture was wrong about heat. But it carried a conclusion that was right: an engine needs its heat to fall, hot to cold, as a mill needs its water to fall. Without a difference of temperature to drive it, the flow yields no work at all. Carnot put it plainly: “The production of heat alone is not sufficient to give birth to the impelling power: it is necessary that there should also be cold; without it, the heat would be useless.”

From the same reasoning he drew a second conclusion: the best an ideal engine can do depends only on the two temperatures it works between, not on whether the working substance is steam or air.

An apparent contradiction

There is a difficulty here. Joule’s experiments had shown that heating a body and doing work on it are two ways of changing one thing — that the energy an engine takes in by heating is energy like any other, the same in kind as the energy it gives out as work. If that is so, why can the engine not give out all of it? Why must any pass to a colder place?

Carnot’s own picture sharpened the difficulty, because in it nothing is converted: a fixed quantity of caloric enters at the top and leaves at the bottom unchanged, having done its work by falling. That picture and Joule’s could not both be right, and reconciling them fell to someone else.

Clausius's reconciliation

In 1850 Rudolf Clausius found the way through, and it began by discarding the very analogy that had served Carnot. Water turning a mill does not become the mill's work; the work comes from the water's fall under gravity, and the water reaches the bottom in the quantity it had at the top. Heat in an engine is not like that. Some of the energy taken in by heating leaves the engine as work; the rest is passed to the colder body. The account still balances, but differently: the energy an engine takes in by heating equals the work it does plus the energy it rejects to the cold side. Carnot had been right that an engine needs a hot side and a cold one, and that the working substance does not matter, and wrong that all the heat entering also leaves.

So the rejected energy is not caloric leaking from a store — there is no such fluid. Whether it is mere waste, or something the engine cannot work without, is the next question.

Why a colder body is needed

An engine is not a single push but a cycle: to keep working it must return, over and over, to the state it began in. That requirement is where the cold body becomes necessary.

Follow one turn. Energy is transferred to the gas by heating; as the gas expands, it drives the piston and energy leaves the gas as work. But an expansion that leaves the gas in a new state is not yet an engine: to work again it must bring the gas back to where it began, which means compressing it.

Compression costs work, and there is the trap. Compress the gas while it is still hot and at high pressure, and pushing the piston back can consume the work just won; the engine has gained nothing. The escape is to cool the gas first — to bring it against a colder body, so it is at lower pressure and cheaper to compress. But compressing a gas warms it, as the air in a bicycle pump warms under the plunger; so as the gas is pressed back to its starting volume, the energy added by compressing it must be passed, by heating, into the colder body — the engine's cold sink. Only then is the gas returned to its starting state, ready to begin again.

The work an engine yields is what remains after the gas is reset, and it can be reset cheaply only by shedding energy to something cold. Remove the cold body and there is nowhere for that energy to go: the gas cannot return to its starting state without spending all the work the expansion produced. A colder place to reject energy to is as much a part of the engine as the furnace — without it there is no engine, only a gas that expands once.

The second law

Clausius drew the deeper rule from the same engine, run backwards. A heat engine produces work as energy passes from a hot body to a colder one; reversed, with work put in, the same machine drives energy the other way, from cold up to hot — a refrigerator. Set an engine better than the ideal one to drive such a refrigerator, and over a cycle the pair would move energy from the cold body up to the hot one while drawing no work from outside: a refrigerator that runs on nothing. No such machine has ever worked — so no engine beats the ideal, Carnot's conclusion again, now resting on energy conservation and one new principle.

The principle, which Clausius stated as a law, is this: energy does not pass by heating from a colder body to a hotter one of its own accord. Left to itself, energy is transferred by heating from hot to cold; the reverse takes work. This is the second law of thermodynamics, standing beside the first, that energy is conserved.

It also names what the perfect engine of the opening would have to be. Such an engine need not make energy from nothing — it could honour the first law exactly, turning into work just the energy it took in. Its fault lies elsewhere: rejecting nothing, it would need no colder body at all, and an engine with no colder body is forbidden by the second law as surely as an engine making energy from nothing is forbidden by the first. The machine that would make work from nothing is perpetual motion of the first kind; the machine that would take in energy by heating from a single source and turn all of it into work is perpetual motion of the second kind. The cold sink is what the second kind lacks — and what the second law requires of every engine.

What the cold sink shows

The first law is silent on direction. It says the energy an engine takes in is fully accounted for — so much as work, the rest passed to the cold body — and nothing in that accounting forbids the rejected energy from making its way back up to the furnace. It is the second law that forbids the return, and so decides which of the energy-balanced processes can actually run.

A cyclic engine, then, cannot take in energy by heating from a single hot source and leave nothing behind but work; some must be passed to a colder place, because only then can the working substance be returned to the state it began in. Energy is conserved, but its usefulness is not. The cold sink is where an engine pays that price for any work at all — not a flaw in the machine, but part of what makes it run.

Sources

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