Cool running heat engines

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Newcomen invented the atmospheric steam engine in 1712. This employed steam at one atmosphere pressure and a temperature of around 100 °C. In the following century, by the time of "The Great Exhibition of the Works of Industry of all Nations" in 1851, materials technology had advanced sufficiently for engineers to build far more efficient steam engines. These operated at several atmospheres of pressure and temperatures well above 100 °C. It was only later, however, in the second half of the nineteenth century, that the science of thermodynamics reached maturity and engineers were able to further improve on steam engine design by using science instead of experience. The fact that thermodynamics only emerged long after powerful steam engines were being employed to help us conquer nature and build empires has left us with several questionable legacies: (i) we have learned to live with several terms and concepts that do not make thermodynamic sense, but have been tolerated because they do not seem to do any harm either; (ii) there is a common belief that we human beings should use technology to overcome nature, rather than forming a partnership with it; (iii) cool running heat engines that recycle energy can be found in nature but humanity has chosen to move in the opposite direction, building ever hotter and higher pressure heat engines in order to increase their power. In this paper we discuss some of the accepted terms and concepts that do not make thermodynamic sense, and then use this fresh insight to propose a new class of cool running heat engines for generating electricity. Based on these insights, the author has filed patent applications describing clean cool running heat engines. However, mindful of the climate emergency facing our planet, these patents have been allowed to lapse. This means that university researchers, commercial enterprises and others are free to develop them as open source technology, without seeking the author's permission or paying him royalties.

Keywords: Bernoulli's equation, Bernoulli's principle, Carnot's equation, global warming, Kelvin

1. BACKGROUND

In 1959 William Courtney was a thirteen year-old junior member of the Manchester Astronomical Society. Using the Society's 8-inch refractor telescope, he saw the planet Jupiter for the first time. He learned from older members that the surface temperature of Jupiter was an incredibly cold –145 °C and that its most distinguishing feature, the Great Red Spot (Fig. 1), was the largest atmospheric storm in the solar system. This huge storm cloud could engulf the whole Earth and had existed since at least 1832. One member also explained that the Great Red Spot was a very efficient natural heat engine that converted low temperature thermal energy into mechanical storm energy.

In rainy Manchester, where the skies were often obscured, astronomy morphed into an interest in meteorology and cloud formation. Courtney gained a basic understanding of Earth's atmosphere as a system of reversible heat engines, where thermal energy was lost or gained depending on whether convection currents were rising or falling and the water droplets in clouds were evaporating or forming. By the time he went on to study thermodynamics as part of an Applied Physics course at Hull University, his dominant response on hearing the term "heat engine" was to visualize a cool running but highly efficient system for reversibly converting thermal energy to mechanical energy. This mindset enabled the undergraduate Courtney to spot several contradictions in the conventional teaching of heat engine theory. These examples will be discussed below and are obvious once attention has been drawn to them.

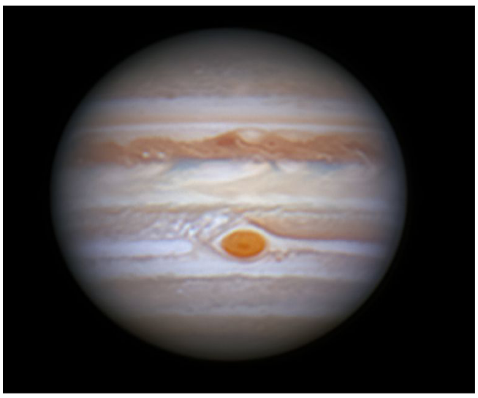

Figure 1. Jupiter's Great Red Spot is a cool running heat engine.

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2. THE TERMS "HEAT" AND "HEAT ENGINE" CAN BE MISLEADING

Heat is often used carelessly when internal energy should be used. According to the second law of thermodynamics, heat processes involve two bodies at different temperatures, with heat being the net energy flowing from the warmer body to the cooler body, whereas internal energy only has to involve one body because it is the total energy associated with the disordered motion of the molecules inside the body. Temperature is more directly linked to internal energy than to heat because it is a detectable measure of the mean energy level of these molecules. This confusion can lead to misunderstandings about how heat engines work. In particular, it encourages the belief that the temperature difference between the hot and cold reservoirs of a heat engine is the cause that allows them to do work. In fact the opposite is true: the temperature drop is a consequence of the engine doing work.

A further cause of confusion arises if the thermal energy flowing through a heat engine is envisaged as a fluid in its own right, rather than in the form of the internal energy of the working fluid. According to modern thermodynamics, this mental separation into two fluids is invalid because thermal energy is not a substance. This is probably a legacy issue because the early developers of steam engines did not differentiate between internal energy and heat, envisaging heat as an invisible, weightless fluid they called caloric. In reality, a vector is required to carry thermal energy. Most commonly this vector consists of the molecules of a working fluid, and the thermal energy takes the form of the internal energy of the molecules.

The laws of thermodynamics prevent the complete conversion of thermal energy into work inside a single heat engine. Consequently, some thermal energy must always be rejected into a cold reservoir at a lower temperature. The maximum theoretical efficiency η of a heat engine is always given by the equation

$$\eta = 1 - Q_C/Q_H. \quad (1)$$

Where the working fluid approximates to an ideal gas, the maximum thermodynamic efficiency is also given by [1,2] (Fig. 2):

$$\eta = 1 - T_C/T_H. \quad (2)$$

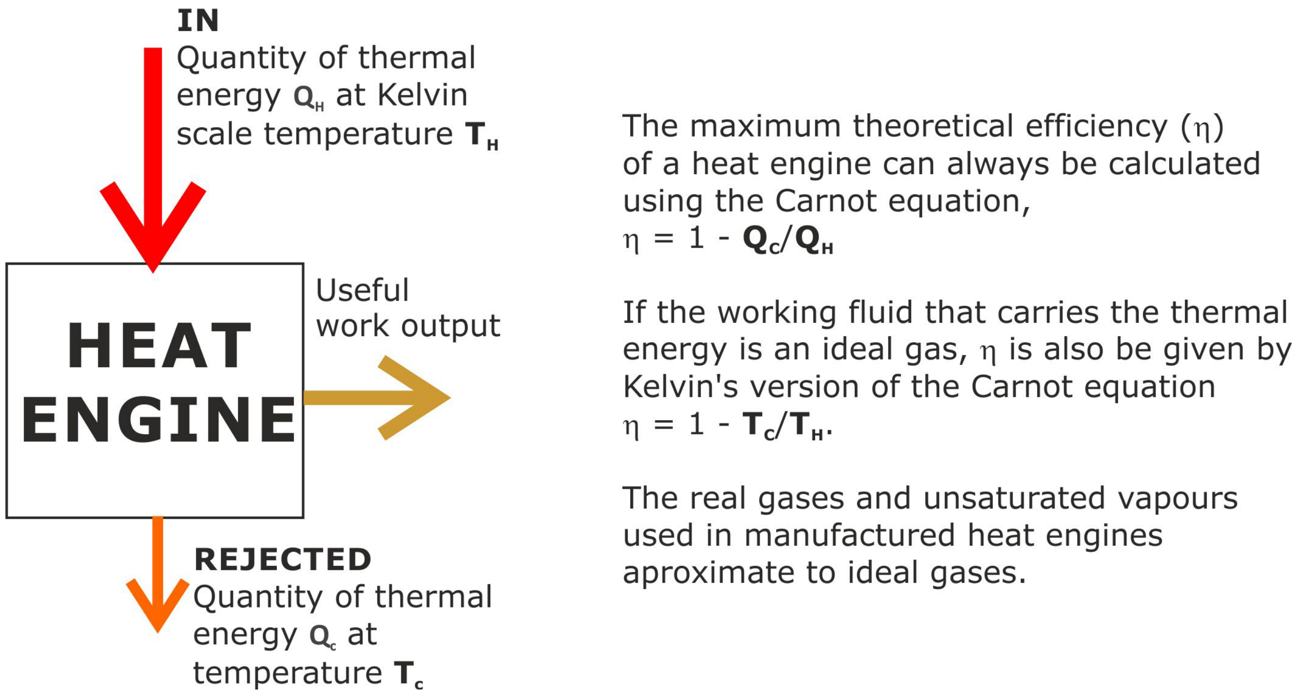

Figure 2. Two efficiency equations are commonly used in heat engine theory, but only one of them applies to phase change fluids.

3. AMBIGUITIES WHEN COMPARING MANUFACTURED AND NATURAL ATMOSPHERIC HEAT ENGINES

At least some of the assemblies of atmospheric heat engines that produce our weather tend towards 100% efficiency. This counterintuitive property can be seen in the behaviour of night-time coastal winds (Fig. 3). The following thought experiment suggests that the high efficiency of coastal wind systems is shared by atmospheric heat engine systems in general. Consider an atmosphere in which all atmospheric heat engine activities are temporarily suspended. In this case, there would be no reduction of atmospheric internal energy as a consequence of heat engine activity converting it into the kinetic energy of atmospheric winds; therefore the atmosphere will warm up, increasing its rate of radiant heat loss into space. Even a rather small increase in temperature can produce a significant increase in radiant heat losses because the radiant heat emissions from a body are proportional to absolute temperature raised to the fourth power. The rate at which Earth receives radiant heat from the sun will remain unchanged, however, hence the atmosphere will cool until the rates of incoming and outgoing radiations are again in balance. Thus, the rate of radiant heat loss from the top of the atmosphere is the same, whether or not atmospheric heat engines are operating. We can conclude from this that the assembly of atmospheric heat engines tends towards 100% efficiency, even though each individual heat engine has a low Carnot efficiency.

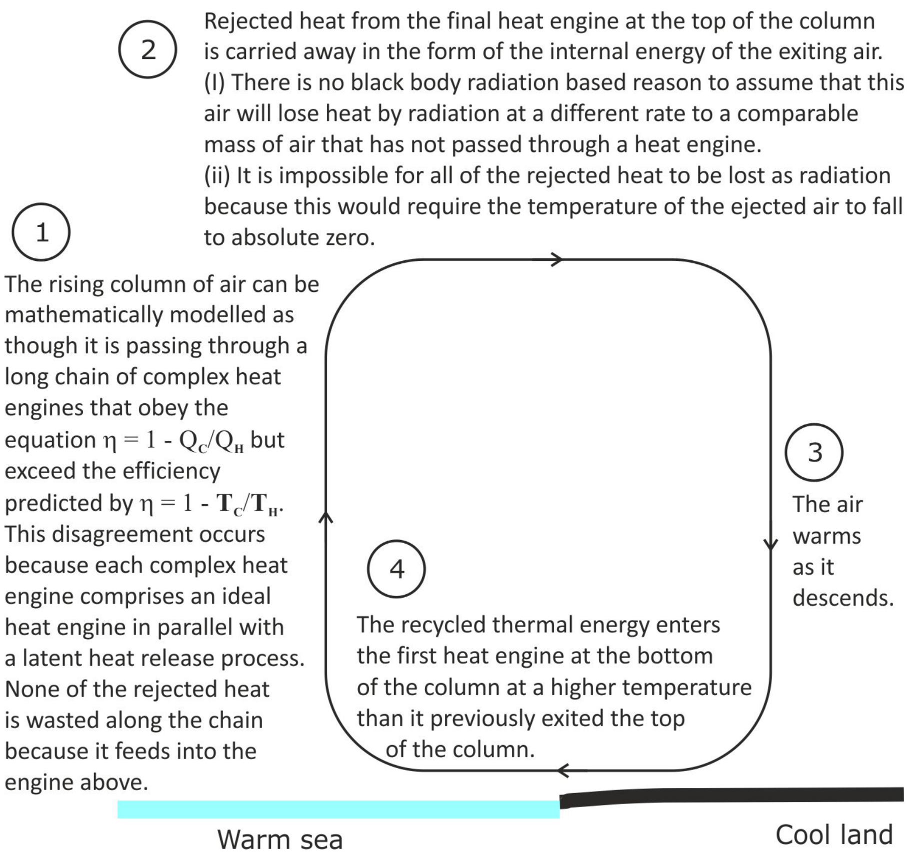

Figure 3. A snapshot of coastal wind patterns during the night. The wind directions change when the land warms faster than the sea, as happens during the day.

Table 1 (and cf. Fig. 4) illustrates the ambiguities that emerge when hot running manufactured heat engines are compared with natural cool running atmospheric heat engines. Two key Victorians provide evidence to support both sides of the ambiguity. Fitzroy established science-based weather forecasting in the 1860s and Brayton invented the petrol powered internal combustion engine in 1876. Tesla, who invented the a.c. generator in 1896 falls into neither camp because generators can be powered by hot running heat engines or cool running wind and water turbines. But wind and water power are unreliable, hence the birth of the electricity age led to a worldwide increase in the use of hot heat engines and the climate crisis that we face today.

Table 1. Engineers v. meterologists; hot v. cool running heat engines

Features of practical hot running heat engines accepted by engineers	Features of cool running heat engines accepted by meteorologists
A heat engine is separated from its environment by solid walls, with a working fluid passing through it from a hot reservoir to a cold reservoir.	Natural heat engines are part of the atmospheric environment and have no need for solid walls.
Engineers commonly use Kelvin's version of the Carnot efficiency equation, $\eta = 1 - T_C/T_H$. This tells them that $T_H - T_C$ must be as large as possible for maximum efficiency. But the lowest practical value of T_C is that of the environment.	Kelvin's version of the Carnot equation rarely applies to natural heat engines because it does not allow for working fluid phase changes. Hence the assumption that $T_H - T_C$ must be as large as possible is rarely true.
Heat must enter the heat engine at the *highest possible temperature* for maximum thermal efficiency. Typically, a high temperature means around 600 ^{o}C.	Heat engines *can run cool* and still be highly efficient. Typically, "cool" means up to about +30 ^{o}C for tropical hurricanes on Earth, but possibly as low as –145 ^{o}C on Jupiter.
They are *high pressure difference* systems. Even achieving around 50% efficiency involves gas pressures at least an order of magnitude higher than atmospheric pressure.	They are *low pressure difference* systems. Higher levels of efficiency than manufactured heat engines are achieved, even though the working fluid only suffers modest fractional atmospheric pressure changes.
Heat recycling is *impossible* because the second law of thermodynamics tells us heat cannot flow back from the cold exit reservoir to the warmer heat input reservoir. Instead, the rejected heat has to be dumped into the environment.	Heat recycling is *inevitable*. Natural heat engines are part of the atmospheric environment. Hence the rejected heat has to go back into the environment it came from.
Nature has dealt us a cruel hand. The laws of thermodynamics have doomed humanity to live in a world where heat engines are inherently wasteful and shift us towards the heat death of the universe.	*Nature has dealt us a good hand.* All life on land only exists because natural heat engines do work, pumping water from the sea to the land via the atmosphere. The rejected heat is recycled, hence the heat death of the universe comes no closer.
CONCLUSION: Manufactured heat engines are linear systems that waste energy.	CONCLUSION: Assemblies of heat engines are circular systems that conserve energy.

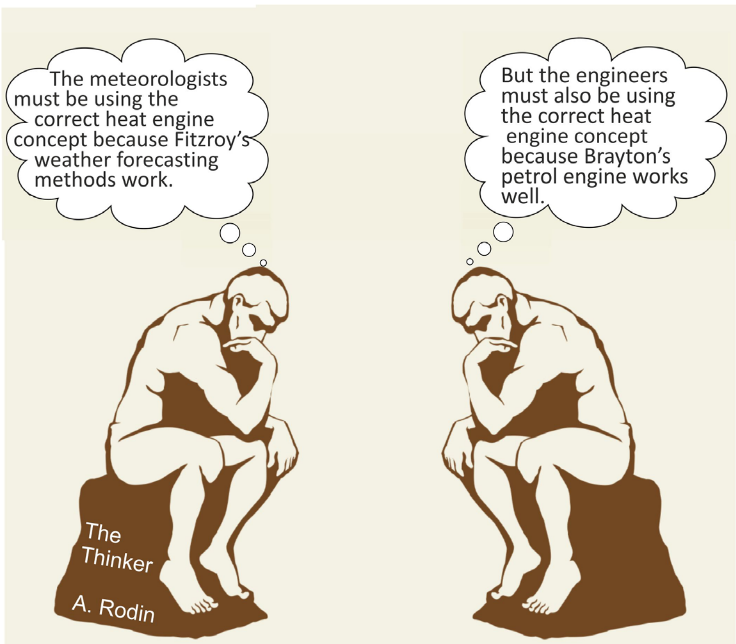

Figure 4. Heat engine doublethink has existed in plain sight since Victorian times. Rodin's Thinker would be forgiven for concluding that doublethink is the truth (Schrödinger's cat would sympathize!).

A Venn diagram comparison (Fig. 5) tells us that the meteorologists' understanding is more universal than that of the engineers. This nesting of concepts tells us that if engineers were willing to think outside their own Venn diagram element, radically different types of manufactured heat engines might be possible.

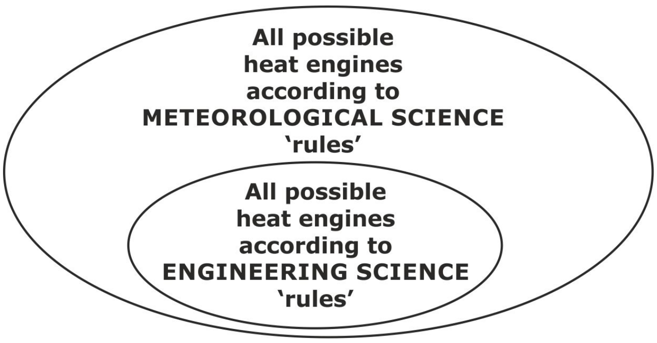

Figure 5. A Venn diagram showing that engineers' informal rules can be considered as a subset of meteorologists' rules.

4. AN INTERNAL COMBUSTION ENGINE "RADIATOR" IS NOT A RADIATOR

The internal combustion engines that power the majority of road vehicles employ several different means to dispose of their waste heat. Some escapes through the engine casing as heat and some as the internal energy of the exhaust gases. But for water-cooled engines, the vehicle's radiator plays a vital rôle. It is actually anomalous to use the term "radiator" here because nearly all the heat is dissipated by forced convection.

Maybach invented the honeycombed car radiator in 1901, long after the development of heat engines was put on a sound scientific footing. It was also around forty years after Gustav Kirchhoff had introduced the term "black body" when discussing radiant heat losses. Hence there was no excuse for this careless use of scientific language when naming vehicle radiators and its implications may have been serious.

Good teachers will explain to their students that the use of terms such as "vehicle radiator" and "heat engine" is not technically accurate. But even if the students leave the classroom correctly informed, some of them will see this careless use of language as giving them permission to be sloppy in their own scientific thinking.

5. BERNOULLI'S EQUATION AND THE CONFUSION BETWEEN PRESSURE AND ENERGY

During his 1964 pre-university school year, Courtney was taught Bernoulli's equation and was baffled by it. He encountered it again at university and was still baffled. The problem was that it appeared to contradict the law of conservation of energy. None of his tutors were able to provide a satisfactory explanation, and the course textbooks were equality unhelpful.

Bernoulli's equation (also referred to as Bernoulli's principle) states that for an incompressible, non-viscous fluid undergoing steady flow, the pressure (p) plus the kinetic energy per unit volume (½ × density ρ × velocity^2, v^2) plus the potential energy per unit volume (density × acceleration due to gravity g × height h) is constant at all points on a streamline [3]:

$$p + \tfrac{1}{2}\rho v^2 + \rho g h = \text{constant}. \qquad (3)$$

This equation is dimensionally correct but baffling because it suggests that the sum of two types of energy (potential and kinetic) plus pressure (which is not a form of energy) is always a constant. So, students have to believe that energy can be transmuted into pressure and vice versa at different points along a moving fluid. ny ? student or teacher prepared to accept this while also believing in the law of conservation of energy is practising doublethink.[1]

University textbooks in the 1960s commonly tried to ensure compatibility with the law of conservation of energy by explaining that p is actually a form of energy called *pressure energy*, defined as "the energy stored in a fluid due to the force per unit area applied onto it". Authors employing the pressure energy explanation include Starling and Woodall [5] and Newman and Searle [6]. But this interpretation is also confusing because the student has to accept several conflicting assumptions when deriving the equation.

First, before verifying Bernoulli's equation, the boundary conditions are specified, with students being told that the fluid is incompressible. Then, during the derivation the student is required to accept that somehow, the application of pressure to an incompressible fluid can be used to store energy. This means that the fluid must be both elastic and incompressible at the same time.

Then, when reinforcing their learning by doing calculations, the student has to insert values of p using units of pressure, while also accepting that p is not pressure, but pressure energy.

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[1] Pre-university textbooks tend to cope with this dilemma by simply ignoring it. For example, see the British textbooks by Muncaster [3] and Noakes [4].

Bernoulli's equation evolved in the period 1730–50, at a time when our understanding of the concept of energy was poor. Hence, provided that the equation was consistent with observations, any violations of the law of conservation of energy would have been irrelevant. It was only in the Victorian era, a century later, that our modern understanding of conservation of energy evolved. This knowledge should have allowed the contradictions in the teaching of Bernoulli's equation to be spotted and resolved.

In November 1965 a spectacular example of Bernoulli's equation hit British newspaper headlines when three of the eight cooling towers at Ferrybridge power station collapsed during a gale (Fig. 6). Gusting 136 km/h winds were funneled between the towers, hence wind speeds and pressures suffered large changes over short distances. As a consequence, vortices developed which ripped three towers apart. Courtney travelled past the destroyed towers on his way to Hull University and was intrigued by this incident. He became sidetracked from his curriculum studies and made an informal study of it. He came to the conclusion that the mechanical work done in destroying the towers ultimately came at the cost of a drop in the internal energy of the wind. This conclusion was supported by a paper published in 1967 [7].

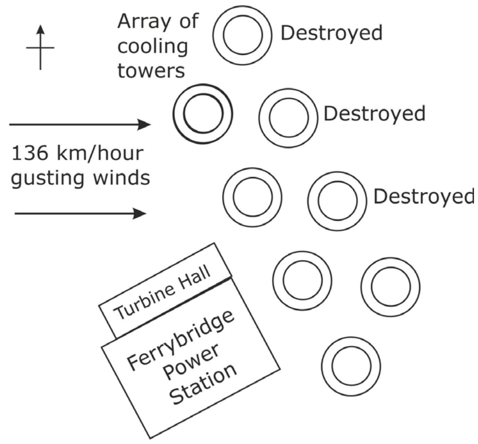

Figure 6. Cooling towers at Ferrybridge C power station, Yorkshire. The Bernoulli effect caused large air speed variations and pressure gradients in the gaps between the cooling towers. These gradients created swirling movements with sufficient energy to destroy three of the towers on 1 November 1965. The power station had not yet been commissioned at the time.

The implications for Bernoulli's equation became clear: when fluid speed and kinetic energy increase along a streamline, there is a compensating drop in internal energy. This results in the fluid temperature falling and, as a consequence, fluid pressure *p* also falls. Thus, under incompressible fluid conditions,

$$p = k\,U \qquad (4)$$

where *k* is a dimensionless constant and *U* is internal energy per unit volume (Fig. 7). For dry air, Bernoulli's equation gives numerically correct answers, even though pressure *p* is just a convenient dummy for the more elusive internal energy *U*.

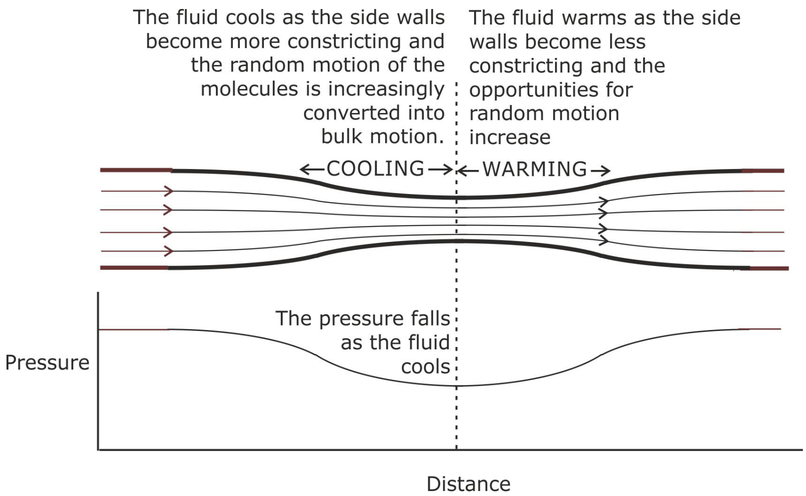

Figure 7. Changes in the pressure p can now be accounted for as a consequence of changes in the internal energy of the fluid. This makes the concept of "pressure energy" redundant.

In standard laboratory experiments, Bernoulli's equation is verified using a converging-diverging conduit. At a molecular level, the converging taper of the walls can be seen as having a limiting effect on the random motion of the forward drifting molecules. For molecules closer than one mean free path length from the walls, their number of degrees of freedom is limited, because the molecules cannot pass through the walls. The closer the walls are together, the more the drifting molecules are affected. Consequently, random motion is increasingly converted into directed or bulk motion in the direction of drift. This means that the pressure drop is a *consequence* of random motion being gradually converted into bulk movement, rather than being a *cause* of it.

The internal energy interpretation implies that the flow of an incompressible fluid along converging-diverging streamlines can be seen as a form of two-way heat engine. In the converging section, kinetic energy increases at the expense of a reduction in internal energy, with the reverse occurring in the diverging section. The equivalent of Bernoulli's equation that replaces pressure with internal energy can be stated as:

"For unit volume of incompressible fluid in steady flow

$$U + \tfrac{1}{2}\rho v^2 + \rho g h = \text{constant} \quad (5)$$

In words, "For unit volume of incompressible fluid in steady flow, internal energy + kinetic energy + potential energy equals a constant". This is essentially a simple partially integrated form of Navier–Stokes equation as used by engineers since mid-Victorian times. However, its simplicity makes it easy to use as a creative thinking tool, helping to bridge the divide between cool running natural heat engines and their hot running/manufactured counterparts.

For an ideal gas flowing along the streamlines, the maximum theoretical efficiency of this type of heat engine is given by both versions of the Carnot equation (eqns 1 and 2). The converging–diverging geometry provides some extra information, which may be useful for future computer modeling (Fig. 8):

(i) In eqn (5) the internal energy of the gas molecules U is a vector carrying the thermal energy Q;

(ii) The kinetic energy ($\tfrac{1}{2}\rho v^2$) increases as U falls. The increase is proportional to n^2, where n is the constriction ratio of the streamlines.

The efficiency with which internal energy is converted into kinetic energy only depends on n^2.

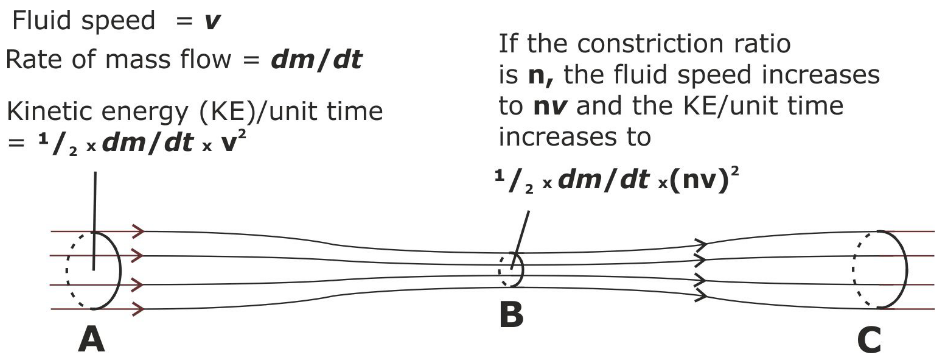

Figure 8. Effect of constriction ratio. This diagram assumes that there is no heat flow across the outer streamline boundary.

Hence, for a single phase fluid, the Carnot efficiency of the engine is independent of the temperature T_H of the hot reservoir. This has important implications for future manufactured cool running heat engines because it means that for dry air, they should (to a first approximation) run equally efficiently in tropical or arctic conditions. For convenience, this type of converging–diverging heat engine will be referred to as a "Bernoulli heat engine".

In its basic reversible form, a Bernoulli heat engine is trivial, because there is no output of work. But if it does work W on another body, for example ripping apart the Ferrybridge cooling towers or spinning a turbine rotor, then it becomes irreversible.

If external work W is done at B (Fig. 8) then, in accordance with Newton's laws of motion, the bulk movement of the molecules tends to fall. But this slowing down has to be reversed by restoring the speed to nv (for an incompressible fluid), to prevent the molecules piling up at B. In order to ensure a steady flow, it is only necessary to do sufficient work at C to maintain a lower speed v. However, kinetic energy changes with speed squared. So, in restoring the speed to v at C, it is only necessary to do an amount of work W/n^2 on the fluid. Hence, if a turbine installed at B does an amount of work W, the net external work W_{next} done by the Bernoulli heat engine is given by

$$W_{next} = W(1 - 1/n^2). \quad (6)$$

To offset the net work that is done by the gas, the internal energy U falls and the gas cools. Fig. 9 illustrates the principles of a laboratory experiment that could be done to verify this prediction.

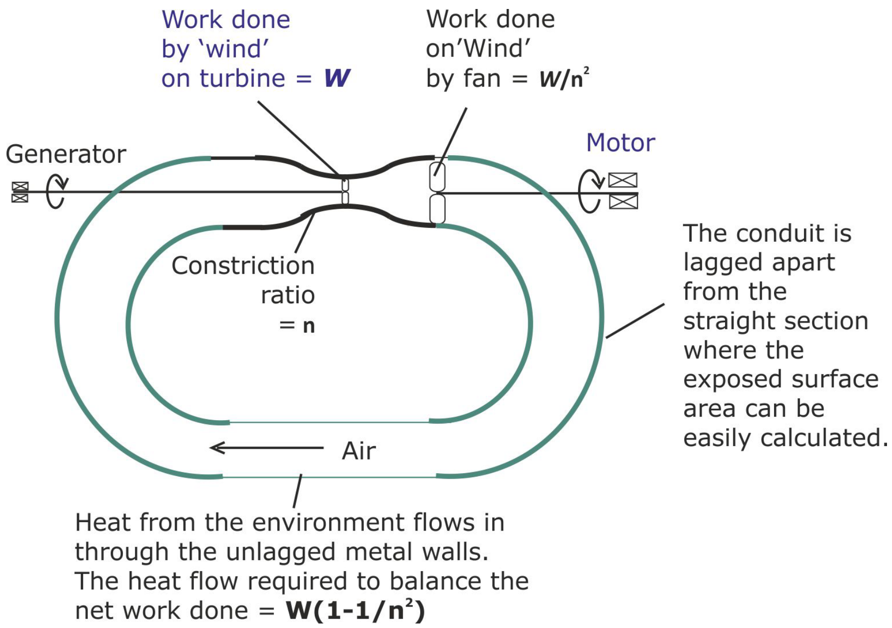

Figure 9. A laboratory experiment to verify the prediction of eqn (6) and its implications. The rate of heat flow can be calculated using basic thermal conductivity equations such as those found in Muncaster [3].

The equivalent of Bernoulli's equation that describes the *irreversible* form of this heat engine could be stated as:

$$\text{internal energy} + \text{kinetic energy} + \text{potential energy} + \text{net work done} = \text{constant} \qquad (7)$$

for unit volume of incompressible fluid in steady flow.

6. CONCLUSIONS

Thermodynamics is an amalgamation of our understanding of the thermal and dynamic properties of matter. But the thermal features of the science only emerged two centuries after Galileo, Newton and others had established the science of mechanics. In the meantime an industrial revolution had taken place, based on reliable mechanics but inaccurate thermal science.

In this paper it has been argued that the long gestation period of thermodynamics has resulted in several ambiguous legacy terms being inherited by today's workers. This legacy has reinforced a belief in the supremacy of hot running heat engines, and the unavoidable necessity of wasting low temperature thermal energy.

However a study of the cool running heat engines that produce our weather systems (and sometimes cause disasters) suggests that by imitating nature, a new clean energy future may be within our grasp.

Details of work in this direction by the present author and his business partner Richard West, with suggestions for commercial development, are published on the Cheshire Innovation website.[2] Figs 10 and 11 provide some examples.[3]

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2 *Latent Power Turbines* (http://www.cheshire-innovation.com).

3 The author and his business partner Richard West have carried out preliminary investigations into a possible new class of cool running heat engines inspired by an examination of the Bernoulli equation. However, in the uncertain times following the United Kingdom's decision to leave the European Union, they have experienced difficulties in raising funds and attracting engineering partners. Hence, with a climate emergency upon us, they have allowed their patent protection [8] to lapse and released their intellectual property for open source development. This means that any individual or organisation, working in any country, is free to exploit cool running heat engines, without requiring the consent of Courtney or West.

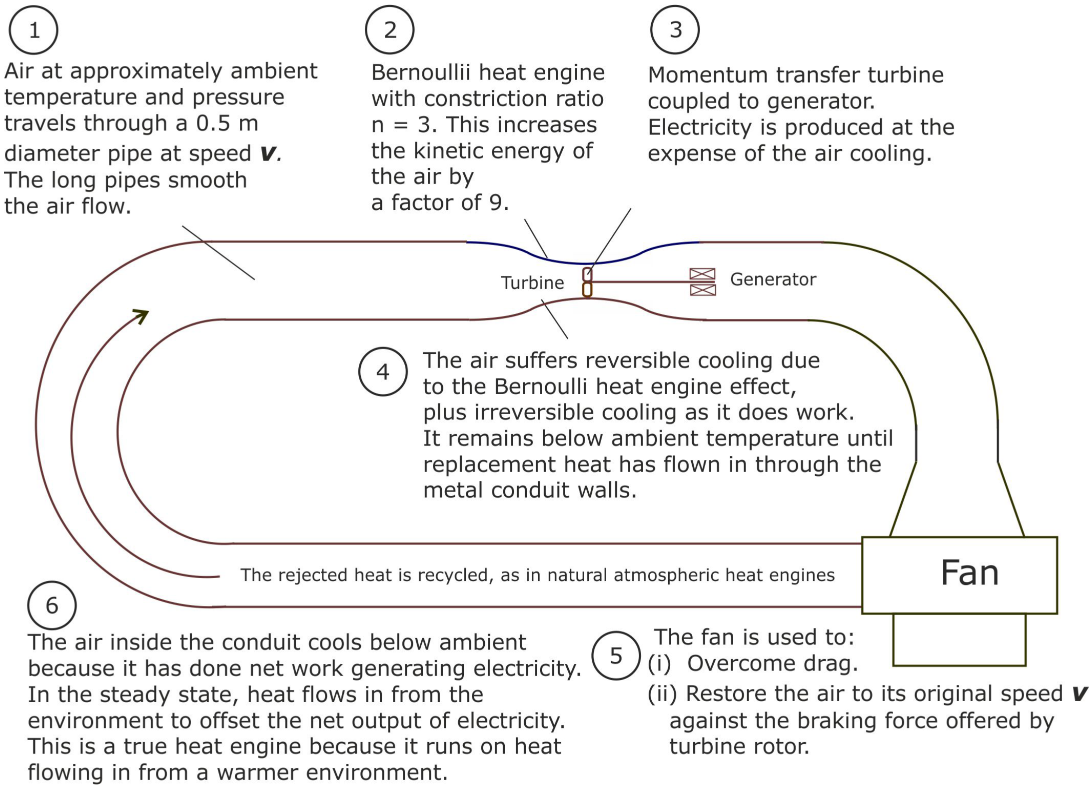

Figure 10. Possible realization of a cool running heat engine. Sketch of the test rig that was being used before political issues resulted in the work being abandoned. Photographs of the rig can be seen on the Cheshire Innovation website.[2]

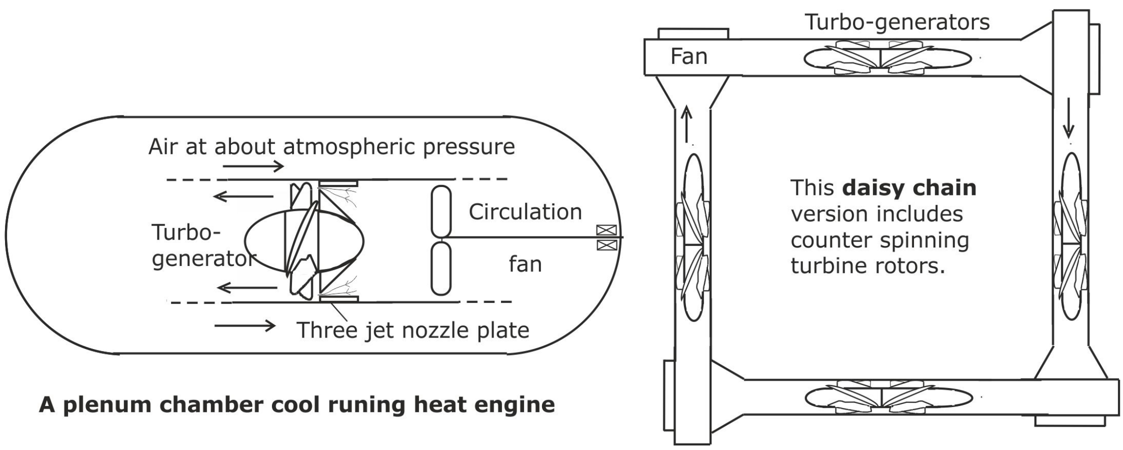

Figure 11. Possible realization of a cool running heat engine. Examples of potential production designs.

ACKNOWLEDGMENT

The concept of cool running heat engines was only kept alive over several difficult years thanks to the support and expertise of Richard West.

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