HEAT, WORK AND ILLUSION: THE CASE OF THE RANKINE CYCLE

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ABSTRACT – It is argued that no net conversion of heat to work occurs in the Rankine engine, and that the putative work obtained originates in the higher pressure at which the vaporized liquid is maintained. Thus, although heat is employed to convert the working liquid to vapour, this remains as such upon performance of the work (typically, rotation of a turbine). The heat is let out to the surroundings upon condensing the vapour, which is then compressed for the next cycle of operations. This ensures that the vapour is again produced at a relatively high pressure. Thus, the expansion work obtained would only depend on the pressure drop experienced by the vapour within the turbine. Therefore, the above compression stage is the sole driver of the process. The invalidity of the Rankine cycle – much like that of the Carnot cycle – indicates the improbability of converting heat to work in a sealed system operating within a closed loop.

In fact, the traditional steam engine is based on the build-up of pressure brought on by the rapid vaporization of a mass of water in a confined space. The resulting steam then expands directly within a chamber designed to capture the work. The process is driven by the transfer of a large mass of steam, with a concomitant pressure drop, through a turbine. In the Rankine cycle, however, the vapour produced initially is allowed to expand at constant pressure – thus expending its thermal energy acquired during vaporization – before being led into the turbine.

KEYWORDS: Carnot; expansion; steam engine; thermodynamics; turbine

INTRODUCTION

The flowering of the science of thermodynamics during the eighteenth century was driven by concomitant developments in the construction of steam engines. Thus, the need to design machines for the efficient conversion of heat to mechanical motion led to investigations on the precise relationship between energy and work. Of particular interest, apparently, was the theoretical study of cyclical processes that could obtain heat at a high temperature source, convert the heat to work and return to the high temperature source, ready for the next repeat cycle of operations. This clearly was an attempt to model the basic workings of a steam engine.

However, although steam engines performed cyclically – essentially via the conversion of heat to rotational motion – they were also open systems. Thus, the steam used to drive each cycle was vented into the surroundings before the commencement of the reverse stroke of the cycle. In this way, the work obtained from the expansion of the steam could be partly utilized for the reversal of the system to its original state. The theoretical models employed, on the other hand, were sealed systems which could only be reverted to the original state via the compression of the working (ideal) gas. This implied that – in principle – no net work could be obtained from such theoretical model systems.

The above analysis has been discussed elaborately in a previous submission demonstrating the invalidity of the Carnot cycle.[1] The Carnot cycle is perhaps the most idealized of the theoretical models employed to analyze the workings of a steam engine (and also the earliest). Thus, the Carnot cycle employed a hypothetical ideal (or perfect) gas in a sealed container, which was taken through several expansion and compression stages, all performed reversibly.

A related model, proposed apparently as a sequel to the Carnot cycle, is the Rankine cycle. This is less idealized than the Carnot cycle and – ostensibly – resembles a working steam engine more closely. Thus, the ideal gas employed in the Carnot cycle is replaced by a normal liquid that is vaporized *in situ* at a relatively high pressure (by employing a pump along with a heat source). The resulting pressurized vapour is then led into a turbine to obtain mechanical work, following which the vapour is condensed *via* cooling to recover the working substance in the liquid state. This is again compressed and heated as above to repeat the cycle of operations.

However, the Rankine cycle resembles the Carnot cycle in being a closed system. Also, the Rankine cycle employs a combination of pressure and heat to drive the turbine. The theoretical analysis of the Rankine cycle stresses overall energy flow and work output (in terms of entropy changes), rather than the ideal-gas based estimate of expansion work which is the crux of the Carnot cycle.

All the same, the Rankine cycle resembles the predecessor Carnot cycle closely, and is apparently bedevilled by similar inconsistencies. The Rankine cycle is thus equally invalidated as argued below. (The Rankine cycle is described in most standard texts dealing with thermodynamics and this background need not be repeated here.)

DISCUSSION

The Rankine engine

The Rankine cycle employs four stages: (1) compression of a liquid working substance; (2) heating the liquid at constant pressure, thus converting it into a pressurized vapour; (3) leading this vapour through a turbine, thus obtaining mechanical work; (4) cooling the vapour exiting the turbine thus condensing it back to the liquid state.

The key to the cycle, however, is stage 2. In this, heat is absorbed into the system at a high constant pressure, apparently readying it for the performance of work in the next stage. In fact, the amount of heat absorbed can be estimated, in principle, from: (a) the heat required to raise the temperature of the liquid to its boiling point, and (b) the latent heat of vaporization of the liquid. The value of part (a) would be the product of the specific heat of the liquid at constant pressure and the temperature change involved, whilst part (b) requires a knowledge of the latent heat at the pressure employed. Also, clearly, the absorbed energy must reside in the vapour produced as above.

The total energy residing in the vapour, however, would consist of: (i) that derived from the heat absorbed during the vaporization process, and (ii) that derived from the pressure exerted upon the vapour. Now, as long as the expansion of the vapour within the turbine (stage 3 above) does not lead to the condensation of the vapour, the energy from (i) remains in the vapour, *i.e.* unconverted to work. Hence, the work obtained in the turbine solely originates from (ii)! Thus, none of the heat absorbed in stage 2 above is converted to work, but rather is lost to the surroundings upon the condensation of the vapour to the liquid.

It is particularly noteworthy, in the above analysis, that the turbine is driven solely by a drop in pressure. <u>Thus, the turbine is driven by expansion work, *via* the conversion of the linear momentum of the impacting vapour to the angular momentum of rotational motion by the helicity of the turbine</u>. The turbine would initially be at a lower temperature than the vapour, which would thus be cooled upon the impact; but the turbine would then be heated up correspondingly. The rotation of the turbine would stop once the pressure inside the chamber housing it becomes equal to that of the impacting vapour.

Clearly, the vapour is perforce created at the pressure that is externally exerted on the system during the process of vaporization. The exerted pressure would, of course, elevate the boiling point correspondingly, leading to the vapour being superheated. However, this is incidental, the pressure of the vapour being only what is applied on it, and it remains that the pressure determines the work obtained at the turbine.

In fact, the same effect would be obtained by vaporization followed by further heating and compression, so it is irrelevant how the pressurized vapour is produced. It is also particularly noteworthy that the turbine would be driven even if its temperature were to be the same as that of the incoming vapour!

The mystery unravelled

The above analysis of the Rankine cycle indicates that the latent heat absorbed during the vaporization of the liquid in stage 2 [part (b) above] has been captured as work during the expansion of the vapour against a constant external pressure (before it enters the turbine). Thus, the only expansion work it can still perform derives from the pressure being exerted upon it. Clearly, the system cannot be converting the heat it has absorbed to work at the turbine.

How does a steam engine work?

As seen above, the Rankine cycle does not perform the conversion of heat to work, because the work obtained at the turbine is determined solely by the applied pressure. So, how would a steam engine work? (Not only do steam engines exist but they also perform efficiently indeed!)

In fact, an important difference between the Rankine engine and a working steam engine lies in the fact that the former is a closed system whereas the latter is an open one. Hence, the Rankine engine is invalidated by the limitations imposed by the need to devise a cyclic process, in which the working liquid cannot leave the system. Thus, the two critical steps involving the capture of heat and its subsequent conversion to work (stage 2 and 3 above), are conceived as disconnected unit operations. It is for this reason that the heat absorbed is converted to work prematurely, by the expansion of the vapour during its formation (rather than at the turbine).

A working steam engine, in contrast, is an open system in which the formation of the steam and its expansion into a working device (typically, a cylinder-piston arrangement) are coupled together. Thus, a large part of the energy acquired by the steam during its formation from water can be captured as work. The venting of the steam to the surroundings at an appropriate stage in the process implies that it need not be recovered, so each cycle of operations needs a fresh input of steam. (This again contrasts with the Rankine cycle, in which the expanded vapour is condensed and pumped back into the heating chamber.)

It is also noteworthy that, although the above analysis is applicable to any vapour-driven engine, steam possesses certain unique features which apparently confer distinct advantages. One of these is clearly the ready availability of water, but the higher boiling point of water and the higher density of steam (relative to other liquid-vapour pairs) likely constitute the key to the success of the steam engine. In fact, reference to the ideal gas law is instructive in this regard (Eq. 1, R being the gas constant).

$$PV = nRT \tag{1}$$

(Steam, of course, is hardly an ideal gas, but Eq. 1 is still a useful approximation!) It is seen from Eq. 1 that an increase in the pressure (P) of a gas at constant volume (V), can be achieved by an increase in either temperature (T) or molar mass (n). The vaporization of water (or indeed any liquid) is accompanied by the constancy of the temperature at the boiling point, which also implies constant pressure. However, the rapid vaporization of a relatively large mass of water would lead to a corresponding rise in the value of n, and hence of P (Eq. 1 and *vide infra*).

Also, between two liquids the one with a higher boiling point would lead to a higher vapour pressure at the boiling point. This is an oversimplification, of course, as it requires that the system not be in equilibrium with the surroundings; however, a process may be envisaged in which a liquid is boiled in a partially closed vessel, resulting in a build-up of pressure at the boiling point. In such a case, the higher boiling liquid would produce vapour at a higher pressure, by Eq. 1.

In fact, it seems likely that a steam engine works in this manner. Thus, the high density of water implies that a large mass of water can be stored in a small volume. The high boiling point of water then produces a large mass of steam that is at a very high pressure, by virtue of large values of both n and T in Eq. 1 (not to mention low V). The high density of steam also implies lower mobility, and a corresponding rise in the value of n in the partially enclosed space in the boiling reservoir.

All these features possibly conspire to imbue steam power with its characteristic vigour. Essentially, in a steam engine, the steam vapour is not produced in equilibrium with the surrounding, but rather builds up in a gathering manner within a confined space, which is practically a part of the engine that captures the work of expansion. The unique physical properties of the water-steam pair also contribute importantly to the success of steam power. (However, the high latent heat of vaporization of water *per se* does not contribute to the work obtained in a steam engine, insofar as the engine is not driven by the condensation of steam.)

CONCLUSIONS

The Rankine cycle is apparently unviable as a means of converting heat into mechanical work, essentially because the expansion of the vapour occurs during its production from the working liquid. Thus, the acquired thermal energy corresponding to the latent heat of vaporization would have been spent before the vapour enters the turbine meant to convert thermal energy to work. Hence, the only work possible at the turbine would originate in the pressure applied to the liquid and maintained during its vaporization.

A working steam engine, however, apparently functions by coupling the expansion of steam vapour, as it is produced, with mechanical work. This is possible because the expansion chamber (typically, a cylinder-piston set-up) is closely integrated with the boiler in which the steam is produced. Other factors that possibly drive the steam engine to function efficiently are the high boiling point of water and the high density of water and steam (relative to most other liquids). These ensure the rapid production and mobilisation of a large mass of steam, thus leading to a rapid rise in pressure, that directly impacts the expansion chamber designed to convert energy to mechanical work.

The invalidity of the Rankine cycle parallels the previously argued invalidity of the related Carnot cycle.[1] Both the cases apparently indicate the impossibility of converting heat to mechanical work in a closed cycle of operations conducted in a sealed system.

REFERENCE

(1) Sosale Chandrasekhar. 'Classical thermodynamics: a web of convoluted myths. The Carnot cycle and the Joule-Thomson effect unravelled'. **viXra:1511.0011** (2 November 2015).