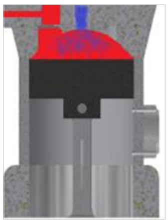
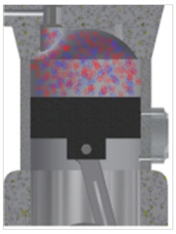
Operating Principle

The Dearman Engine operates by the vaporisation and expansion of liquid air or liquid nitrogen (cryogenic fluids). Ambient or low grade waste heat is used as an energy source with the cryogen providing both the working fluid and heat sink. The Dearman Engine process involves the heat being introduced to the cryogenic fluid through direct contact heat exchange with a heat exchange fluid inside the engine. An example power cycle is shown on the right.

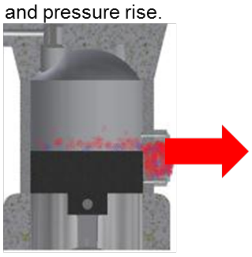
Return Stroke
Warm heat exchange fluid (HEF) enters the cylinder.



Top Dead Centre
Cryogenic liquid is injected directly into the cylinder. Heat transfer with the HEF causes rapid vaporisation and pressure rise.



Power Stroke
The vaporised cryogenic liquid expands pushing the piston down. Direct contact heat transfer continues allowing near isothermal expansion.



Bottom Dead Centre
The exhaust mixture leaves the cylinder. The gas is returned to the atmosphere and the HEF is re-heated and re-used.

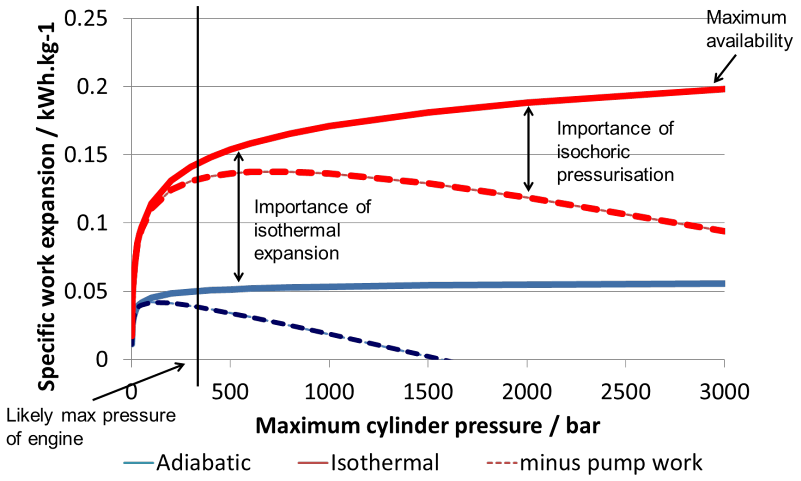
Prior Art

While cryogenic expansion engines are not new, previous embodiments have worked on an open Rankine cycle akin to a traditional steam engine but operating across a different temperature range. Under this arrangement the cryogenic fluid is pumped to operating pressure and vaporised through a heat exchanger, before expansion in the engine cylinder.

A number of drawbacks exist with this setup as the heat exchanger must be large to cope with the heat transfer rates and heavy to withstand the high pressure. Additionally, little heat transfer occurs in the expansion stage (near adiabatic expansion) reducing the work output.

Inventive Step

The novelty of the Dearman Engine lies in the use of a heat exchange fluid (HEF) to facilitate extremely rapid rates of heat transfer within the engine. This allows injection of the liquid cryogen directly into the engine cylinder whereupon heat transfer occurs via direct contact mixing with the HEF. The heat transfer on injection generates very rapid pressurisation in the engine cylinder. Direct contact heat transfer continues throughout the expansion stroke giving rise to a more efficient near-isothermal expansion.



The specific work available from an expansion over a variety of pressures is shown in figure on the right for isothermal and adiabatic cases, the dashed lines indicate the specific work from the expansion net of pumping work.

The benefit of the pressurisation process taking place in the cylinder is to reduce the amount of pumping work required to reach a given peak cylinder pressure, meaning that the likely specific work from a kg of liquid nitrogen is between the dashed and solid lines.

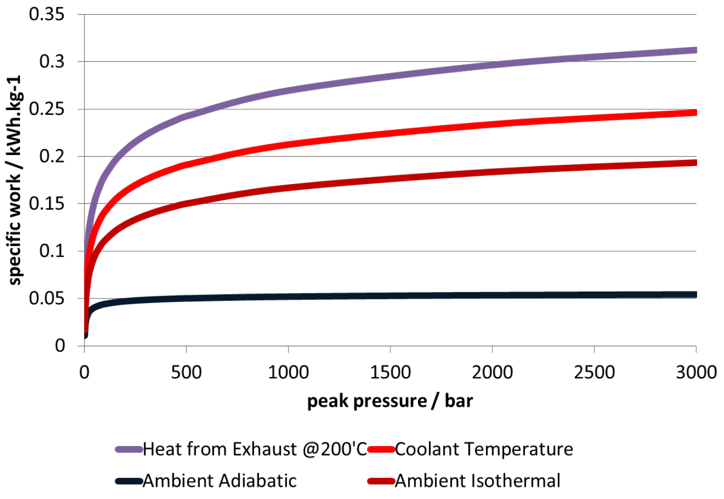
The benefit of having a heat source present (the core Dearman Engine invention) during the expansion stroke is demonstrated by the difference in specific work availability between the adiabatic and isothermal processes, meaning that the likely specific work from a kg of liquid nitrogen is between the blue and red lines.

The inventive step is covered by a granted patent valid in the EPO, US and Japanese territories. The company has also filed a subsequent application in December 2011 covering insights derived from its engine testing experience and further patents in December 2012 covering specific applications.

Additional Capabilities

The engine has two unique capabilities within the zero-emission engine space;

Heat to Power



The Dearman Engine power cycle has a bottom temperature of about -196°C and peak cycle temperature of ambient, even relatively low grade heat can increase the peak cycle temperature and be converted into additional work at very high conversion efficiencies. The waste heat is converted into additional shaft power through an increase in the specific work available from the cryogenic working fluid (shown in the figure on the right for a variety of low grade heat temperatures).

The Dearman engine can be deployed as a high yield thermal energy recovery system that could convert heat from the exhaust or coolant systems of an IC engine into shaft power at <u>practical</u> conversion efficiencies of up to 50%. This compares favourably to other waste heat recovery technologies whose maximum <u>theoretical</u> yields are limited to about 20% at 100°C. The yield advantage is the result of a significantly lower sink temperature (77K for liquid nitrogen) compared to conventional heat recovery devices whose sink temperature is ambient.

Using the Dearman Engine as a waste heat recovery device would have the advantages of;

- reducing or eliminating the loads associated with heat rejection on the IC engine,

- enabling the IC engine to be downsized or run at a more efficient point and
- displacing a material portion of transport related emissions into an energy vector (liquid air) that can be produced from renewable sources.

Initial comparison suggests that liquid air can be profitably substituted for on-highway hydrocarbons, so there is a fuel cost saving too.

Cooling and Refrigeration

The engine absorbs significant quantities of heat during its operation and so can be viewed as a heat sink or cooling source. If there is a requirement for a heat sink or cooling source (e.g. air conditioning or refrigeration) then a Dearman Engine can in addition to the shaft power it generates, displace cooling loads. The engine absorbs approximately twice as much heat as shaft power generated.

The Working Fluid – Liquid Nitrogen or Liquid Air

Production and storage

Liquid Air is an intermediate step in the production of industrial gas products like liquid nitrogen, oxygen and argon. It is made by compressing ambient air and rejecting heat in a series of stages until the air's temperature is reduced to ~-196'C where it becomes a liquid.

Typically, the air is then allowed to boil in a distillation column where it is separated into its fractions; nitrogen, oxygen and argon. Oxygen and argon are the high value products whereas the nitrogen is typically considered to be of lower value.

The marginal cost of production of liquid nitrogen is primarily the energy input which is about £25/ton in the UK at volume production scales. The cost of liquid air production is actually marginally lower because of oxygen's higher boiling temperature, however the difference is negligible.

Storage of liquid nitrogen or air is achieved in low pressure or unpressurised tanks. Typically at scales beneath 1,000m^3 tanks are vacuum insulated and capable of keeping losses to between 0.1% and 1.5% per day depending on the size of tank.

Both the capability to operate intermittently and very low cost of bulk storage means that liquefaction plants are potentially very suitable for pairing with intermittent renewables.

Liquid nitrogen or air can be transferred between vessels at quite high rates through differential vessel pressure or pumps.

Choice of Fuel (Liquid Air or Nitrogen)

The Dearman Engine exploits the expansion between liquid and gaseous phases of a cryogenic working fluid so it can operate using liquid air, nitrogen, oxygen, argon or any cryogenic liquid, with only slightly differing performance characteristics.

For first deployments (and lab testing) the fuel choice is likely to be liquid nitrogen, it is commercially available and cheap, infrastructure for its production and distribution is mature and widespread. Longer term if technology take-up is sufficient to require new infrastructure liquid air would be the preferred fuel choice because the capital cost of production plants would be lower (as the distillation column is eliminated) and the engine could be used in enclosed spaces. The industrial gas industry has previously sold liquid air as a commercial product for stage effects and companies like Highview Power Storage are using it as an energy vector in utility scale applications.

Liquid Air and Environmental Considerations

Liquid air and nitrogen are zero-emission fuels at their point of use, offering the same potential for dramatic local air quality improvement as electricity or hydrogen. Local noise emissions from a Dearman Engine are likely to be no worse than for a well-silenced gasoline ICE operating at moderate speed and load; the materials used in the engine and its fuel tank are commonly known with low environmental hazard in disposal.

Greenhouse gases from the liquefaction process require consideration as the liquefaction plant is usually electrically powered. However, most large-scale liquefaction already uses off-peak electricity with a lower carbon intensity than this average; and by 2030, it has been estimated that the Dearman Engine ZEV using fuel liquefied with off-peak electricity, including surplus renewables, would have a lifetime carbon footprint similar to a 2030 electric vehicle (with lower risk in terms of exotic materials).

For other applications, the comparison is even more favourable.

- A heat-recovery hybrid system would offer carbon break-even today (with savings in operating cost and fossil fuel use), and a CO_2 saving of 25-40% by 2030.
- A refrigeration system offers a very significant 80% saving today compared to a diesel-auxiliary system, with potential for 98% by 2030.

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