The atmospheric steam engine as energy converter for low and medium temperature thermal energy

Author: Gerald Müller, Faculty of Engineering and the Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK.

Te;: +44 2380 592465, email: g.muller@soton.ac.uk

Key words : low and medium temperature, thermal energy, steam engine, desalination.

Abstract

Many industrial processes and renewable energy sources produce thermal energy with temperatures below 100°C. The cost-effective generation of mechanical energy from this thermal energy still constitutes an engineering problem. The atmospheric steam engine is a very simple machine which employs the steam generated by boiling water at atmospheric pressures. Its main disadvantage is the low theoretical efficiency of 0.064. In this article, first the theory of the atmospheric steam engine is extended to show that operation for temperatures between 60°C and 100°C is possible although efficiencies are further reduced. Second, the addition of a forced expansion stroke, where the steam volume is increased using external energy, is shown to lead to significantly increased overall efficiencies ranging from 0.084 for a boiler temperature of T_0 = 60°C to 0.25 for T_0 = 100°C. The simplicity of the machine indicates cost-effectiveness. The theoretical work shows that the atmospheric steam engine still has development potential.

1. Introduction

The cost-effective utilisation of thermal energy with temperatures below 100°C to generate mechanical power still constitutes an engineering problem. In the same time, energy within this temperature range is widely available as waste heat from industrial processes, from biomass plants, from geothermal sources or as thermal energy from solar thermal converters [1]. Classic hot air engines such as the Stirling engine require temperatures above 400°, as was e.g. shown by Kongtragool and Wongwises in 2008, [2]. So-called Organic Rankine Cycle (ORC) machines utilise working fluids with boiling temperatures below 100°C, see the overview given by Lemort and Quoilin in 2009, [1]. The evaporated fluid drives a turbine and is then condensed again. Large scale (MW range) Organic Rankine Cycle converters can be found in geothermal and solar energy applications. ORC turbines are however complex due to the requirement to contain the working fluid under pressure. The concept of a low pressure hot air machine which utilises temperatures between 80 and 150°C was proposed recently. The efficiency of such a machine is however below 5% for temperatures below 100°C [3].

There is a need for a simple engine for small scale applications (below 100 kW) which can utilise low temperature thermal energy efficiently to generate mechanical energy, using water as the working fluid for simplicity. At Southampton University, the oldest steam engine – the atmospheric steam engine – was re-analysed theoretically in order to assess its potential for this role.

2. The Atmospheric Steam Engine

2.1 The Newcomen engine and James Watt's atmospheric engine

The first functional atmospheric steam engine was developed by *Thomas Newcomen* in 1712, [4]. It consists of a boiler ‘A’, a cylinder ‘B’, the piston ‘P’, the steam valve ’V’, water injection valve ‘V^{I} ‘, exit valve ‘V^{II}’, a water container ‘C’ and the rocking beam ‘D-E-F’ which in this case operates a pump, Fig. 1a. In the upstroke, the steam from the boiler ‘A’ is drawn into the cylinder ‘B’. Once the piston has reached the uppermost point, the steam valve is closed and cold water is injected through valve ‘V^l ’. The steam condenses, creating a near vacuum and the atmospheric pressures drives the piston downwards. After the piston has reached the lowermost point, the exit valve is opened in order to eject condensed and injected water. A counterweight or a slight excess pressure of the boiler then moves the piston upwards again for the next working stroke.

The efficiency of the *Newcomen*-engine was estimated as 0.5% [5]. This low value is caused by the fact that cylinder and piston cool down at every condensation; for the new working stroke both have to be heated up before steam can fill the cylinder again. *James Watt* improved the atmospheric steam engine in 1776 by introducing a separate condenser, Fig. 1b, so that the cylinder would remain hot and the condenser cold throughout the cycle. With this improvement, efficiencies of 3% were reached, [6]. For the theoretical evaluation conducted in this article the technical details are however not relevant and the interested reader is referred to the literature [7]. Because of the low efficiencies, atmospheric steam engines disappeared after the high pressure engines were developed.

To the author’s knowledge, no theoretical or experimental work on the atmospheric steam engine was conducted for more than 200 years. Very recently, the principle of the Newcomen engine was investigated in a hybrid form to produce power using a micro-engine for the purpose of power generation for electronic devices [8]. Inside of a rippled steel container a working fluid was evaporated. The initial expansion of the steam above atmospheric pressure produced one working stroke, whilst the vacuum which developed while the cylinder cooled down to ambient temperature and the gas inside was condensed back to the fluid state produced a second stroke. An efficiency of 2.58% was reached and although this micro-engine does not constitute a true atmospheric engine, it is the only example of a recent application of this principle known to the author.

The Atmospheric Steam Engine in its historic form is not necessarily usable for the temperature range considered since it required temperatures above 100C to evaporate water. In order to increase its potential, two additional aspects need to be introduced:

1) Working temperatures need to be extended into the 50 to 100C range.
2) The efficiency needs to be increased.

Both points can be addressed by considering the vapour pressure of water in the pressure range between 0.01 and 1 bar, by analysing the energy balance of a sub-atmospheric cycle and by considering the shape of the vapour-pressure curve of water.

3. Theoretical analysis of the atmospheric steam engine

In the following, the ideal atmospheric steam engine will be analysed, whereby all losses are neglected. For the analysis, the heat capacity, steam volume and evaporation heat for water as given e.g. in [9] are employed. The volume of the condensed water is neglected, since it is small compared with the equivalent volume of steam (0.001 m³ as opposed to 1.69 m³). We consider an idealized cylinder of 1 m² cross sectional area A with a stroke of length $L = 1.69$ m, which contains 1 kg of steam at 100C. After condensation at 30°C, a near vacuum with a residual pressure p_{res} of 0.04 bar or 4 kPa is generated inside of the cylinder. The atmospheric pressure of $p_{\mathrm{atm}} = 100$ kPa acts on the outside of the piston and drives it down until the complete vacuum is replaced. During the stroke, a work W is generated:

$$W = \left(p_{atm} - p_{res}\right) \times L \tag{1}$$

For 1 kg of steam, the work W becomes $W = (100 – 4)$ kPa × 1.69 m = 162.2 kJ. With a specific heat capacity of $C_{\mathrm{V}} = 4.18$ kJ/kg K for water, a latent heat of $C_{\mathrm{L}} = 2257$ kJ/kg and assuming that the water had an initial temperature of 30 °C, the ideal efficiency η_{ideal} becomes:

$$\eta_{ideal} = \frac{W}{\Delta T + C_L} \tag{2}$$

With the values given above, the actual maximum efficiency becomes η_{ideal} = 162.2/(70 + 2257) = 0.0637.

4. Extended theory of the atmospheric steam engine

4.1 Vapour pressure of water

Water evaporates at a temperature of approximately 100°C at atmospheric pressure. If the ambient pressure is reduced, the boiling temperature reduces too. Fig. 2a shows the boiling temperature as a function of the vapour pressure. The volume of 1 kg steam increases with reducing ambient pressure, see Fig. 2b. It ranges from 1.69 m^3/kg at 100C to 7.5 m^3/kg at 60°C. The latent heat increases from 2257 kJ/kg at 100°C to 2358 kJ/kg for 60°C., see Fig. 2c. This variation is included in the following analysis.

4.2 Practical aspects

From the practical point of view a low temperature thermal engine should be a simple as possible in order to minimize investment and maintenance costs. Therefore, water as a working fluid has advantages over other fluids with lower evaporation temperatures since it is cheap and does not have negative environmental effects or operational hazards.

4.3 The sub-atmospheric cycle

The atmospheric steam engine requires thermal energy with temperatures slightly above 100°C to evaporate water at ambient pressure. The temperature of evaporation of water is however a function of the ambient pressure. With reducing pressure the evaporation temperature decreases and the latent heat of evaporation increases slightly whilst the volume of steam per unit of water increases significantly. The evaporation of water at temperatures below 100°C is used e.g. in the flash-evaporation process for water desalination, [10]. Even evaporation at very low pressures between 0.013 and 0.026 bar was suggested by Muthunayagam et al. in 2005, [11].

The concept of the atmospheric steam engine allows operation at sub-atmospheric pressures. Initially, the ideal cycle will be considered, Fig, 3. The following assumptions are made:

1. Atmospheric pressure p_{atm} = 1 bar or 100 kPa.
2. No losses.
3. Condensation occurs at T_1 = 30°C.
4. The feeding water for the first stage is pre-heated by the final stage to 30°C. The additional thermal energy to increase the temperature to the initial value for the first stage is provided by the heat source.

The water in the boiler 'B' has a temperature $T_0 \leq 100°C$. It is connected with the cylinder 'C' where the piston 'P', which has an area $A = 1$, is at its lowest point. The cycle then comprises the following stages:

1. 'P' is pulled upwards from its initial position at point '1' by a force 'F_{up}', a low pressure p_0 is generated in 'C' which corresponds to the vapour pressure of water at temperature T_0. The cylinder fills with steam. Outside the cylinder atmospheric pressure is acting, whilst inside the pressure is p_0. This leads to an upward force $F_{up} = (p_{atm} - p_0) \times A$ and a work required $W_0 = F_{up} \times L_0$, where the displaced volume $V_0 = L_0 \times A$ corresponds to the steam volume V_0 at temperature T_0.
2. When 'P' reaches position '2', the connection pipe with 'B' is closed. Cold water of temperature T_{CL} is sent through the condenser. The steam condenses at a temperature $T_1 > T_{CL}$. For the following analysis, it is assumed that T_1 = 30°C.
3. The pressure inside the cylinder is now p_1, at temperature T_1. For T_1 = 30°C, p_1 = 4 kPa. The resulting force $F_1 = (p_0 - p_1) \times A$ now acts on 'P'.

4. During the stroke of length ‘L_0’, the piston ‘P’ conducts the work $W_1 = F_1 \times L_0 = (p_{\mathrm{amb}} - p_1) \times L_0$.
5. The total work W_{tot} conducted during the complete cycle then becomes $W_{\mathrm{tot}} = W_1 - W_0$.

In order to determine the efficiency, the total thermal energy input is required. Thermal energy of temperature $T_{\mathrm{in}} > T_0$ is supplied to the boiler ‘B’ from an outside source in order to maintain the temperature T_0 of the water. The thermal energy E_0 supplied to the water during the evaporation stroke corresponds to the latent heat R_0 required for the evaporation at temperature T_0 times the mass flow per stroke m_0, which is assumed to be 1 kg, so $E_0 = m_0 \times R_0$ plus the energy required to heat the mass m_0 from ambient temperature to T_0. With this energy and the mechanical energy of the working stroke, the efficiency η of the cycle can be calculated:

$$\eta = \frac{W_1}{E_0} \tag{3}$$

Fig. 4 shows the efficiency as a function of the initial temperature T_0. Efficiencies range from 0.04 for T_0 = 50°C to 0.064 for T_0 = 100°C.

4.4 The forced expansion cycle

The characteristics of the expansion of steam allow for a working cycle which includes the expansion of steam in order to increase the power conversion efficiency. Initially, the piston P is moved from position ‘1’ to position ‘2’, and steam is drawn into the cylinder at pressure p_0 and temperature T_0, Fig. 5a. The piston is hereby moved by a Force F_{up0} through the distance L_0. The work W_0 required becomes:

$$W_0 = F_{up0} \cdot L_0 = A \cdot (p_{atm} - p_0) L_0 \tag{4}$$

After the cylinder ‘C’ has been filled with steam, the valve connecting it with the boiler ‘B’ is closed. The piston ‘P’ is then moved further to position ‘3’ by a distance L_1 with a force F_{up1}, expanding the steam to a pressure p_1 with a reduced temperature T_1, Fig. 5b The wet steam with temperatures of 60 to 100°C is considered as a gas, with a value for the adiabatic expansion coefficient of $\kappa = 1.037$, [9]. The pressure p_1 and temperature T_1 for a volume increase of L_1 with a unit piston area $A = 1$ can be determined as:

$$p_1 = p_0 \cdot \left(\frac{L_1}{L_0} \right)^{\kappa} \tag{5}$$

$$\frac{T_0}{T_1} = \left(\frac{L_1}{L_0} \right)^{\kappa - 1} \tag{6}$$

The upward force F_{up1} required to move the piston 'P' from position '2' to position '3' varies from a minimum at pos. '2' to a maximum at pos. '3'. The work W_{ad} required for the adiabatic expansion of the steam becomes (e.g. [9]):

$$W_{ad} = \frac{1}{\kappa - 1} \left(p_0 \cdot L_0 - p_1 \cdot L_1 \right) \tag{7}$$

This work corresponds to the integral of the pressure against displacement curve and therefore includes the contribution of the residual pressure p_1. For the case of an initial sub-atmospheric evaporation (i.e. $T_0 < 100$°C, and $p_0 < p_{\mathrm{atm}}$), the pressure difference $\Delta p = p_{\mathrm{atm}} - p_0$ also needs to be taken into account when determining the work required to lift the piston. The required work W_1 is therefore the thermal work (Eq. 7) minus the work resulting from the residual pressure p_1 plus the work needed to overcome the pressure difference $\Delta p = p_{\mathrm{atm}} - p_0$:

$$W_1 = W_{ad} - p_1 \cdot L_1 + \left(p_{atm} - p_0 \right) \cdot L_2 \tag{8}$$

The initial displacement work is determined similar to the sub-atmospheric cycle described in the previous section.

Fig. 6 shows the different components for an initial pressure $p_0 = p_{\mathrm{atm}}$, i.e. $T_0 = 100$°C. The displacement work is generated by the evaporation of the steam. The expansion work W_{e} then increases with increasing volume $\Delta V/V$ or distance $\Delta L/L$. It has a value of $W_e = 0$ for $p = p_0$, and increases until the final pressure p_1 is reached. Equation (4) determines the total work conducted for an initial pressure p_0, and a final pressure p_1.The expansion stroke however starts with $p_0 = p_{atm}$, and ends with $p_1 > 0$, so that the component $p_1 \times L_1$ (the atmospheric work) needs to be subtracted. After completion of the expansion stroke, the steam is condensed to a residual pressure p_2 (here assumed to be 0.04 bar or 4 kPa) and the mechanical work W_2 conducted during the working stroke becomes $W_2 = (p_{atm} - p_2) \times L_2$, Fig. 5c. The total work for a stroke W_{tot} is:

$$W_{tot} = W_2 - W_1 \tag{9}$$

For the evaporation of steam, the energy per unit volume is given in Eq. (2) as a function of the initial pressure. Fig. 7a then shows the efficiency for the expansion cycle as a function of the initial temperature of the steam T_0 for a pressure p1 = 20 kPa (0.2 bar) at the end of the expansion stroke. Efficiencies range from 0.050 for T_0 = 60°C to 0.25 for T_0 = 100°C. The variation of the latent heat with temperature is considered in the analysis. The temperatures at the end of the expansion stroke are between 64°C (T_0 = 69°C) and 79°C (T_0 = 100°c), and above the evaporation temperature of 60°C for a pressure of 0.2 bar, so that the steam remains a gas. By choosing a lower temperature T_1, the efficiency could be increased for lower range of temperatures T_0. For T_0 = 60°C e.g. the efficiency increases from 0.05 to 0.084 if the pressure p_1 is reduced to 0.1 bar.

At first glance, the efficiencies with the expansion cycle 0f 0.255 for T_0 = 100°C exceed the Carnot efficiency, which for a working temperature of 100°C and an exit temperature of 30°C is only 18.7%. The Carnot engine is a hypothetical engine with a high temperature inflow, and low temperature and mechanical energy outflow, [9]. In the atmospheric steam engine with expansion however, additional mechanical work is put into the system to perform the expansion stroke. This can be visualised as part of the condensation work being fed back into the system. In order to determine a theoretical maximum efficiency. The author suggests to introduce this additional mechanical work W_{ad} into the Carnot equation as an equivalent initial temperature increase equal to the additional work W_{ad} divided by the specific heat capacity of steam c_{st}, with $\Delta T = W_{ad}/c_{\mathrm{st}}$. The specific heat of steam varies between 2.027 kJ/kg K at 100°C and 1.94 kJ/kg K at 60°C. Fig. 7a also shows this 'modified' Carnot efficiency, and it can be seen that it is always higher than the maximum theoretical efficiency for the cycle.

In Fig. 7b, the volume increase for the expansion stroke is shown. The volume of the initial steam increases by a factor of 4.7 for T_0 = 100°C to 0.48 for T_0 = 69°C.

5. Discussion

5.1 Operation

The atmospheric steam engine is a very simple machine. Even with water as a working fluid, the analysis has shown that operation for boiler temperatures between 60°C and 100°C is possible. Theoretical efficiencies however reduce from 0.064 for 100°C to 0.04 for T_0 = 60°C. The inclusion of an expansion stroke means that a significant increase in efficiency is possible. With a final expansion pressure of 0.2 bar or 20 kPa, the maximum theoretical efficiency reaches 0.255 for an initial temperature of T_0 = 100°C, and 0.09 for T_0 = 60°C.

Water has the advantage of being readily available, cheap when compared with organic fluids employed in Organic Rankine Cycle (ORC) machines, and being not inflammable or poisonous. The utilisation of water with temperatures below 110°C and 0.5 bar pressure means that the system does not come under the Health and Safety Executive's regulations for steam and hot water boilers, which require e.g. testing of the boiler, regular inspection, additional safety systems, limitation of location etc. [12]. This reduces construction and operation / maintenance costs compared with high pressure steam engines. The operation at sub-atmospheric pressure however introduces other aspects such as implosions and air leakage into the system. Implosions are considered as unlikely, since the maximum pressure is known and small compared with operating pressures of high pressure steam engines. Air leakage into the cylinder was a problem with *Newcomen's* machine already. The intermittent operation of the cylinder however allows to expel air at every stroke (in the *Newcomen* engine this was done with a so-called ‘snifter valve’), so that low pressures can be maintained.

The required change in temperature possibly brings back another problem of the *Newcomen* engine although in a reduced magnitude, namely that the cylinder temperature changes within a stroke so that the cylinder needs to be reheated when a new cycle starts. Metal cylinders conduct heat well, so that they transmit heat to the outside. When steam is drawn in, the steam temperature drops / steam condenses as it enters the cylinder until the cylinder wall temperature is high enough, leading to energy loss.

This problem can probably be reduced by employing materials such as plastics which do not conduct heat as well as metal, due to their low thermal inertia combined with thermal insulation for the cylinder. The low temperatures and pressures (compared with standard steam engines) of the atmospheric cycle mean that cheaper materials such as plastics can be employed for piston and cylinder.

5.2 Theory

The analysis described in the previous section is strongly affected by the actual value of the adiabatic expansion coefficient, which in turn depends on the type of the steam (saturated, wet). For the analysis, a typical value of κ for wet steam was chosen so that the pressure and temperature of the expanded steam correspond approximately to the values for evaporation temperature and pressure as listed in standard material property tables for steam, [9]. In reality, water droplets will fall out, causing a change in steam volume and temperature, and possibly a reduction in efficiency. These characteristics need to be investigated experimentally. Currently, an experimental programme to assess the theoretical work is under preparation at Southampton University.

The extension of the theory of the atmospheric steam engine indicates that this very old machine still has development potential, and specifically so for the area of renewable energies where low grade thermal energy is produced by many processes.

5.3 Limitations

The atmospheric steam engine with expansion stroke has significant potential advantages as outlined before, but there are also restrictions and disadvantages:

- The condensation process produces a significant amount of water with a temperature of 30°C. A small part of this can be fed back into the boiler, the rest will need to be cooled down to 20°C or lower to be re-used for condensation.
- The expansion stroke requires a large cylinder volume. For an initial temperature of 100°C e.g., the steam volume is expanded by a factor of 3.7. This will lead to large machines.
- A further increase in efficiency may be possible by lowering the condensation temperature further below 60°C, this however will increase the machine dimensions and may cause problems because of the very low pressures.

6. Conclusions

The theory of the atmospheric steam engine was extended to include operation at temperatures below boiling point, and by adding an expansion stroke. The following conclusions could be drawn:

- The atmospheric steam engine is a very simple machine. With water as a cheap and readily available working fluid, it offers the potential for a low cost energy converter for temperatures up to 100C.
- The operation with temperatures below 100C is possible although theoretical maximum efficiencies are reduced from 0.064 for an initial temperature of 100°C to 0.05 for an initial temperature of 60°C.

- The introduction of an adiabatic forced expansion stroke increases the theoretical efficiency significantly to 0.25 for an initial boiler temperature of 100°C. Efficiencies drop to 0.10 for 69°C boiler temperature.

Despite its age, it appears that the atmospheric steam engine still has development potential.

References

[1] Quoilin S and Lemort V. Technological and Economical Survey of Organic Rankine Cycle Systems. 5th European Conference on Economics and Management of Energy in Industry, Vilamoura/Protugal; 2009.

[2] Kongtragool B. and Wongwises S., A four power-piston low-temperature differential Stirling engine using simulated solar energy as a heat source. Solar Energy, 82 (2008) 493-500.

[3] Müller G., Low pressure solar thermal converter. Renewable Energy, 35, (2010) 318-312.

[4] Hoblyn R.D. A manual of the steam engine. London: Scott, Webster and Geary; 1842.

[5] Matschoss C. Geschichte der Dampfmaschine: ihre kulturelle Bedeutung, techn. Entwicklung u. ihre grossen Männer (History of the steam engine, its cultural importance, technical development and its great men, in German). 3. Ed. Berlin, Reprint: Hildesheim: Gerstenberg; 1901.

[6] Dickinson HW. A short history of the steam engine. Cambridge: Cambridge University Press; 1938.

[7] de Pambour, François Marie. Neue Theorie der Dampfmaschine, oder vollständige Anleitung zur Berechnung des Effectes und der Dimensionen aller Arten von Dampfmaschinen : Nebst eines Anhanges: Meyer Verlag, Braunschweig; 1839.

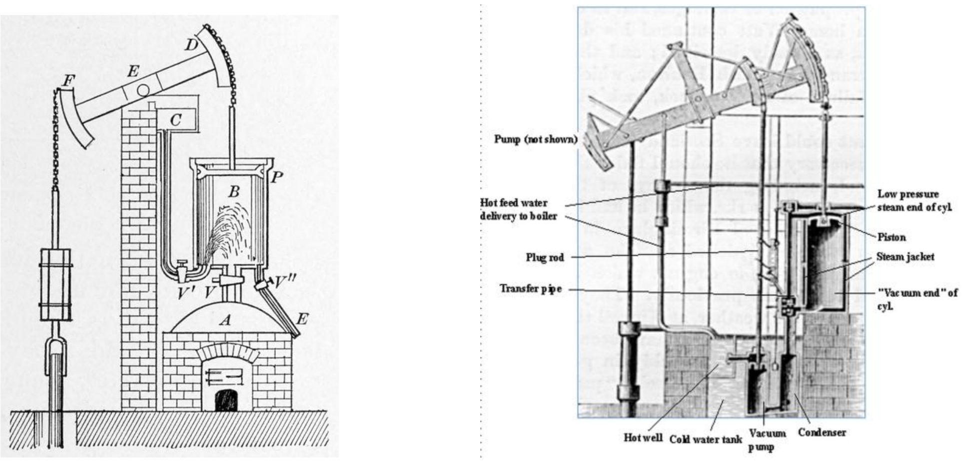
[8] Yang Wang, Zhijun Zhou, Junhu Zhou, Jianzhong Liu, Zhihua Wang, Kefa Cen, Micro Newcomen steam engine using two-phase working fluid. Energy 36 (2011) 917-921.

[9] Dietzel F. and Wagner W. Technische Wärmelehre (Technical thermodynamics), 9th Ed., Vogel Verlag: Würzburg/Germany; 2006.

[10] Kalogirou S.A. Seawater desalination using renewable energy sources. Progress in Energy and Combustion Science 31 (2005) 242–281.

[11] Muthunayagam A.E., Ramamurti K. and Paden J.R., Low temperature flash evaporation for desalination. Desalination 180 (2005) 25-32.

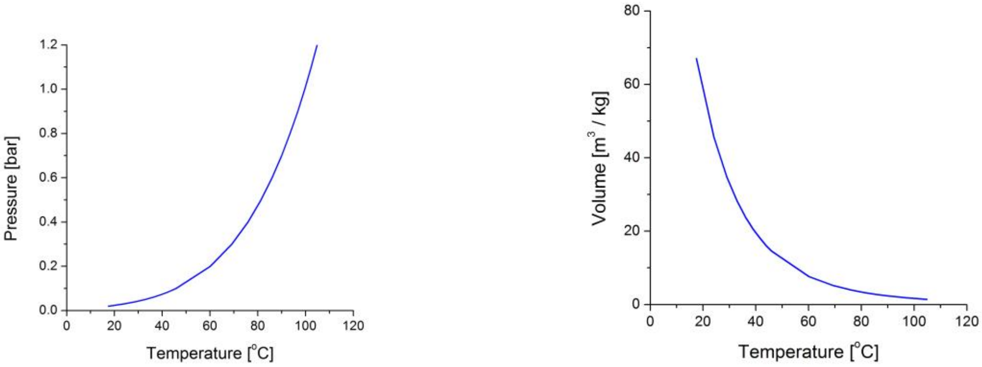
[12] Health and Safety Executive, Safe Management of industrial steam and hot water boilers, http://www.hse.gov.uk/pubns/indg436.pdf (accessed 06.10.2012)



a. *Newcomen* engine, [5]

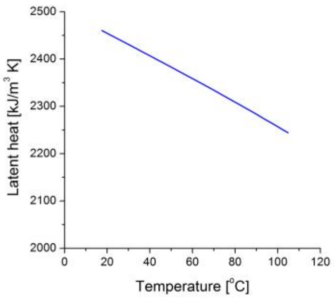
b. *James Watt's* engine with separate condenser, [6]

Fig. 1: Atmospheric engines



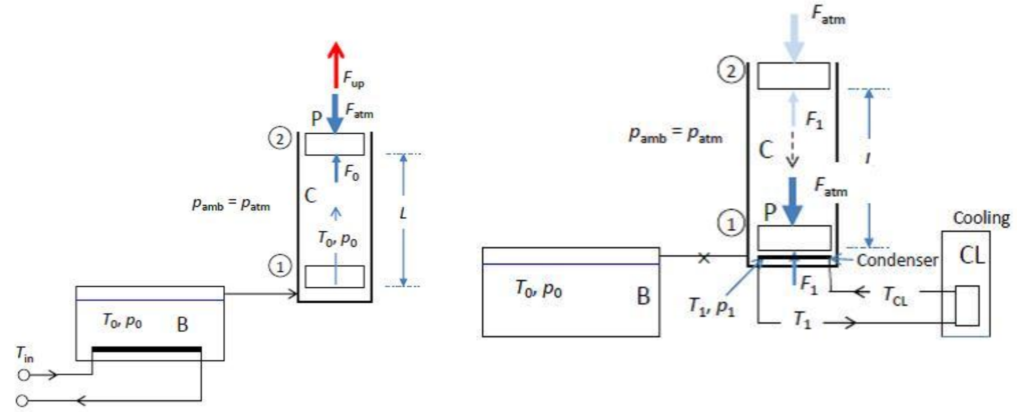
a. Pressure of steam

b. Volume of steam



c. Latent heat of water

Fig. 2: Properties of steam and water as function of temperature for 20C ≤ T ≤ 100C, [9]



a. Filling stroke at $T = T_0$ b. Condensation and working stroke at $T = T_1$

Fig. 3: Sub-atmospheric cycle

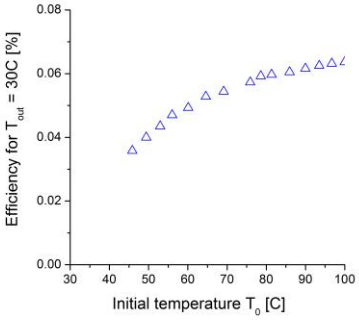
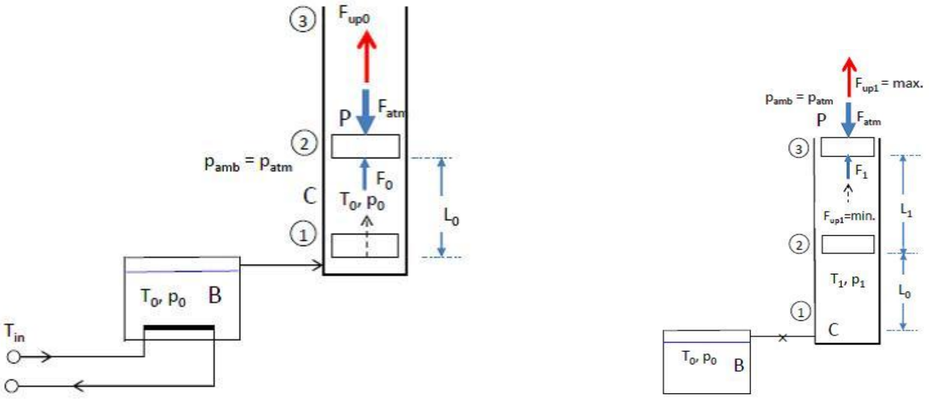
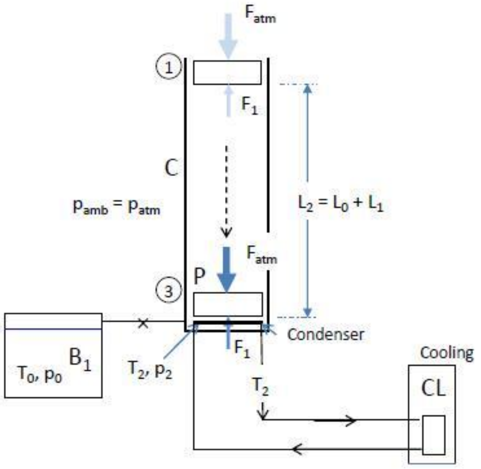


Fig. 4: Efficiency as function of temperature



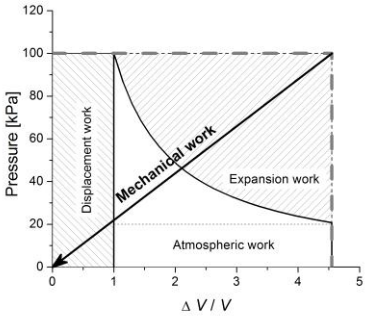
a. Filling stroke

b. Expansion stroke

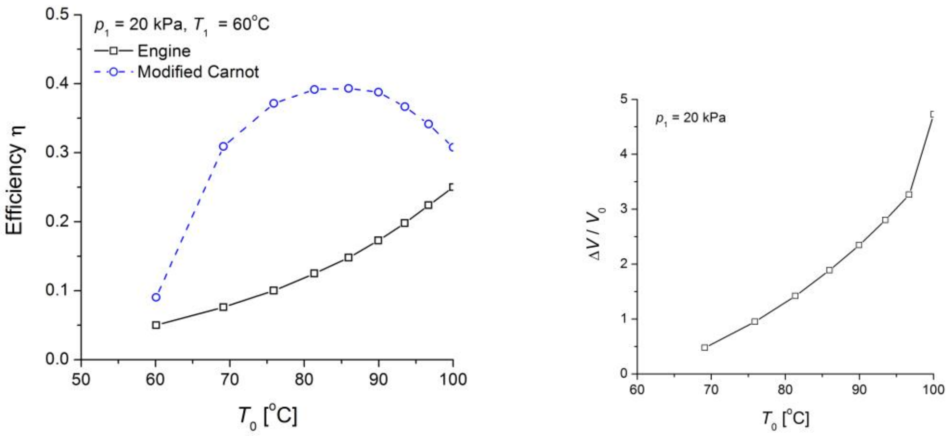


c. Working stroke

Fig. 5: The forced expansion cycle



Fig, 6: Typical work diagram ($p_0 = p_{atm}$)



a. Efficiency b. Volume increase in expansion stroke

Fig. 7: Efficiency and volume increase for expansion cycle