Principles of Energy Conversion

Part 5. The Rise of Heat Engines

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Article 10

Historical Events in the Development of Fluid Power

Expansion of a hot, compressed fluid to a cool, uncompressed fluid is arguably the most common method of converting thermal energy (heat) into mechanical energy (work). Examples of this conversion include piston-cylinder engines as well as gas or steam turbines. This type of energy conversion developed into modern engineering thermodynamics through a rather tortuous path.

The history of modern engineering thermodynamics begins in medieval Europe. There are earlier accounts of fluid power developments in ancient Greece, Rome, China, India, Turkey, Persia, and other civilizations. It is unfortunate that the understanding and technology was lost as those civilizations collapsed or, in the case of China, became isolated. Ideas and description of ancient machines were available to medieval Europe through Persian and Islamic manuscripts and through translations of earlier Greek and Roman texts. It was, however, the exploitation of coal, the infancy of the industrial revolution, colonization, and the rise of European and Russian scientific institutions all of which coincide in the late 1500's, that resulted in the rapid advance of energy conversion technologies.

The historical of discovery and development of energy concepts, use, and technology is fascinating, but beyond the scope of this course. There are, however, key concepts whose culmination directly affect the analysis, language, and theories used in engineering thermodynamics today. These events warrant some discussion.

200 B.C.: The concept is well established that air is an elastic fluid which, when pressurized, could be used to generate motion. The most prevalent example of this is the pipe organ. Ctesibius (or Ktesibios) of Alexandria (285-222 B.C.) writes *On pneumatics* dealing with use of compressed air in pumps, organs and canons. This work was lost and we know of Ctesibius through citations by Marcus Vitruvius Pollio in *de Architectura* and by references from Philo of Byzantium [1]. The water pipe organ, or *hydraulis*, reentered Europe in AD 757 as a gift to Pepin the Short (Charlemagne's father) by the Byzantine Emperor Constantine Copronymus.

~50 B.C.: Rediscovery and translation of *De Architectura* ("On Architecture") written by Marcus Vitruvius Pollio (born c. 80-70 B.C., died after c. 15 B.C.). Books VIII, IX and X describe many Roman technologies and include descriptions of the pneumatic and hydraulic work of Ctesibius.

1550 to 1650 A.D. Ideas begin to develop around the concepts that the atmosphere can impose a force and do work. This development was difficult in part because acceptance of these ideas necessitated rejection of a philosophical principal that had been around for a two thousand years. The concept that a vacuum can exist and can be created begins to take hold despite the long-standing philosophical conviction that a vacuum cannot exist. This conviction is based on Aristotle's writings (~350 B.C.). One of the stronger arguments against the existence of vacuum was that light would not be able to pass unless there was some substance present. If light is a wave, then a wave must have something to pass through.

The idea that the atmosphere had weight was fairly well established by the mid-fifteenth century. Around this same time, the weight, or pressure, of the atmospheric pressure was being investigated through displacement of mercury in a closed tube. These early barometers clearly indicated that air could impose a force through weight. Whether there was a vacuum or not in the closed end of the tube remained inconclusive in part due to the inability to properly build early barometric instruments.

1644 A.D. There has long been a working understanding of the relationship between the height of a pool or lake of water and the pressure and flow of water at some lower elevation. Every civilization has utilized irrigation for agriculture. Roman engineers developed extensive water systems of aqueducts and plumbing.[1] Chinese water clocks were technological marvels. The development and complexity of many ancient water systems is truly remarkable. However, it was not until the mid-fifteenth century that a mathematical description of the relationship between elevation and flow rate was published by Toricelli. The early mathematics relates gravitational potential energy to flow rate through an orifice, though the concept of and vocabulary of energy will not appear for another two hundred years.

~1647 A.D. The German scientist Otto von Guericke [mayor of Magdeburg] (1602-1686) builds vacuum pumps and demonstrates that work can be applied to the atmosphere. A rapidly recognized corollary is that the atmosphere may be able to do work. Magdeburg Hemispheres were a popular demonstration of atmospheric force and a common parlor game into the 1900's. Vacuum is applied to the interior of two hemispheres contacting one another to form a sphere. The difference in atmospheric pressure and the vacuum results in the necessity of a large force to separate the two halves. This also gives rise to the notion that work may be done by the atmosphere.

Several technological developments warrant a more thorough discussion and review. These include the hydraulis (pipe organ), Magdeburg spheres, Papin's powder gun, and the aeolipile.

[1]The Latin word *plumbem* means 'lead', which was one of the key materials used by Roman engineers to construct water pipes. The modern English work *plumbing* is derived from the Latin.

10.1 Hydraulis

The inventions of Ctesibius of Alexandria (285 - 222 B.C.) are reported in manuscripts by Vitruvius, Athenaeus, and Philo of Byzantium. He is referred to by these ancient writers as the father of pneumatics because of his inventions using compressed air. Of interest here is his invention of the pipe organ, more specifically, the hydraulis. As far as we know, Ctesibius developed the first pipe organ. In a pipe organ air is compressed in a chamber to which multiple pipes are attached. Air passing through each pipe generates a tone and a keyboard is used to open and close valves to individual pipes. Figure 10.1 illustrates the working principles. Air is compressed using a piston-cylinder air pump.

Of interest to this course is the concept of storing energy within the hydraulis. Playing a continuous note on the pipe organ was a challenge due to the reciprocating nature of the air pump. The air in the valve chamber could not be maintained at a constant pressure. Ctesibius solved this issue by pumping the air into an water-filled chamber so that the water level inside and outside of the chamber would not be level. This generated a hydraulic pressure that could maintain a constant air pressure below the valves to the pipes. Check valves in the reciprocating pistons kept the air from leaking out during cycling of the air pump.

Ctesibius also reversed this idea with a piston-powered water pump and used it to force water into a closed reservoir where it trapped air. That compressed air could then expel water through, say, a fire-fighting nozzle or a projectile from a cylinder (air cannon). [1, 2]

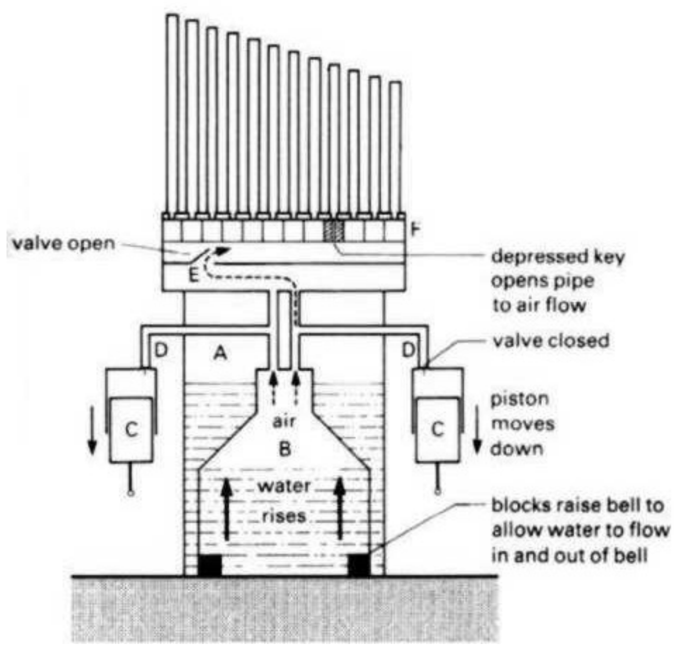


Figure 10.1: Working principles of the hydraulis. [1]

10.2 Magdeburg Spheres

The German scientist Otto von Guericke [Mayor of Magdeburg] (1602-1686), while working with gases, developed an improved air pump that enabled him to draw and maintain a strong vacuum inside a sealed vessel. He applied this to two-halves of a sphere and found that the two halves could not be separated in the absence of air inside the sphere. He staged elaborate demonstrations of this effect as illustrated in Figure 10.2, including a demonstration before the Reichstag at Regensburg on May 8, 1654.

His public demonstrations pitted animal labor (work) against the atmosphere. With a vacuum his horse teams could not pull the spheres apart (likely with help from well-rehearsed teamsters), but once the valve was opened and air reentered the two halves would simply fall apart. Because the horse teams could not separate the two halves, it gave rise to the notion that work might be done by the atmosphere.

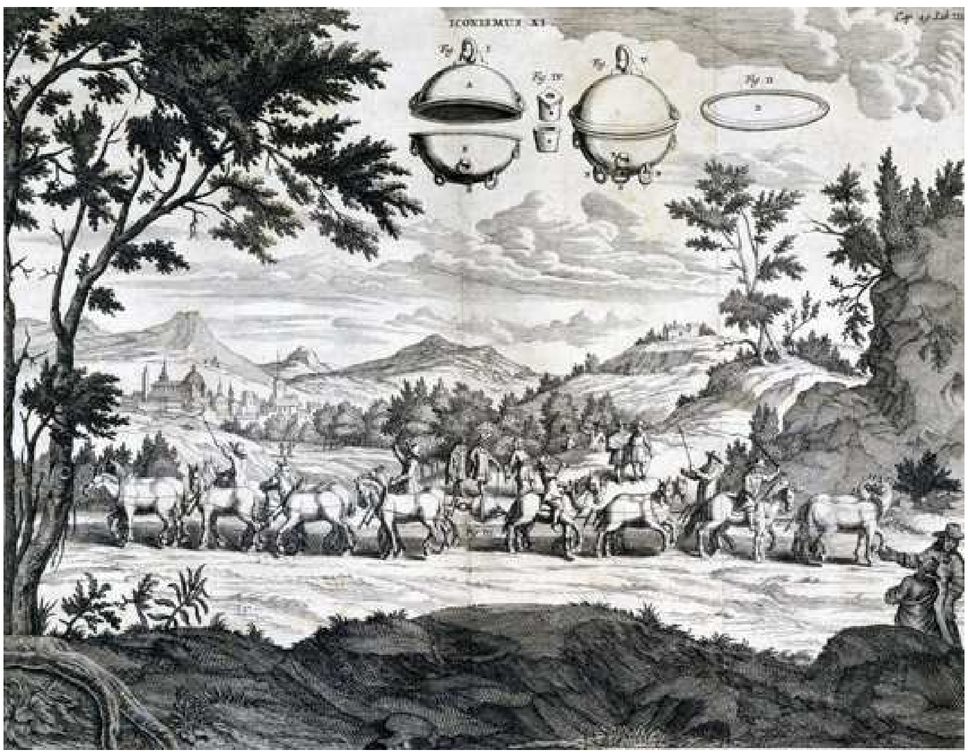


Figure 10.2: Magdeburg Spheres in engraving from 'Experimenta nova' (1672). [3]

10.3 Bone Digesters and the Safety Valve

The conceptual leap from elastic fluids (gases) and inelastic fluids (liquids) to vapors was not straightforward. Slowly, a number of people recognized that vapors could be generated from application of heat and that the elasticity of the vapors could be manipulated. The earliest evidence is from writings that indicate David Ramsey received a patent from King Charles I of England sometime between 1618 and 1638 for an engine that could 'raise water from low pits by fire.' A more detailed description of such an engine, by the Marquis of Worcester, is described in a 1655 manuscript, though there is uncertainty as to whether the engine was ever built or operated. The description of the engine is generally regarded as having all of the elements of later atmospheric engines.

An necessary step in engine development was made by Denis Papin (b. 1647). Papin studied medicine and while working for Christian Huygens in Paris. During this period, Papin and Huygens made many advances which were key to the development of atmospheric engines. Together, they built a vacuum pump per Huygens directions, with the intention to study food preservation. There was constant danger of blowing up early pressure cookers, known as bone digesters, leading Papin to develop a safety valve that is essentially the same used today on modern pressure cookers. As part of their work, Huygens suggested using gun powder to drive a piston-cylinder engine. However, when Papin attempted the gun powder engine he found the cylinder full of non-condensible gases after each firing, which prevented cyclic operation. Papin decided that a better design would be to condense steam in the cylinder thereby creating a vacuum. He published his his design in 1690.

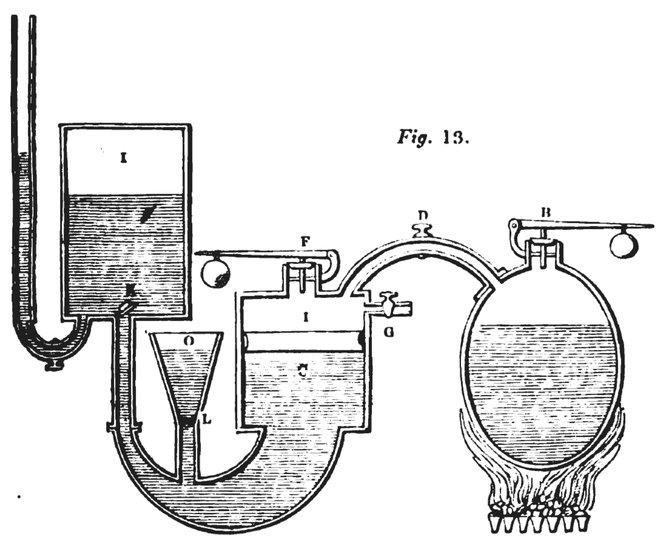


Figure 10.3: Conceptual illustration of Papin's engine showing safety valves. [4, Chapter II. Engines of Savory and Newcomen]

10.4 Aeolipile

Papin's engine condensed the steam in order to pull a vacuum relative to the atmosphere. The early development of steam power followed this approach. There were, however, attempts to convert the energy in steam directly into mechanical work via expansion. The earliest known example is the aeolipile.

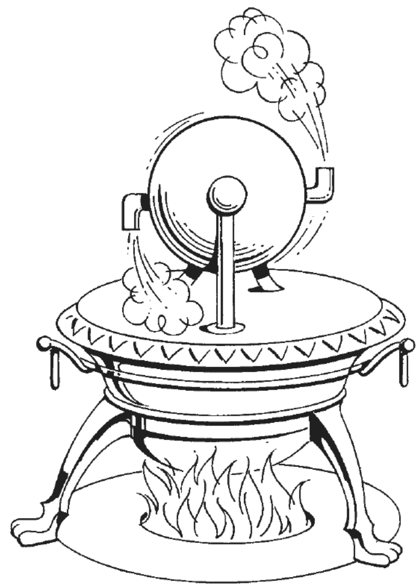


Figure 10.4: Aeolipile [5, Chapter 2. Introduction to Steam]

The *aeolipile* is credited to Hero of Alexandria (c. 10-70 AD).[2] Water in a cauldron is heated by fire. Two pipes that serve as supports and pivots allow steam to pass from the cauldron to a sphere. The sphere has two tangential nozzles. As the water boils and steam pressure builds, the steam velocity escaping the nozzles creates an impulse resulting in the rotation of the sphere.

While the Aeolipile was primarily for entertainment. There are illustrations that show the idea of harnessing the momentum of escaping steam has been around for a long time. Giovanni Branca (April 22, 1571 - January 24, 1645) describes a number of devices in *Le machine* in 1629. Included in the machines was a stamp mill powered by a steam turbine (Figure 10.5). It is not known if this machine was built.

[2] There are accounts of this device being used 100 to 150 years earlier by Marcus Vitruvius Pollio (born c. 80-70 B.C., died after c. 15 B.C.). Some of the confusion may be that Hero was a common name and Alexandria was the center of learning and engineering in ancient Greece. By some accounts, the Hero that developed the *aeolipile* was a student of Ctesibius, which would place the *aeolipile* development much earlier.

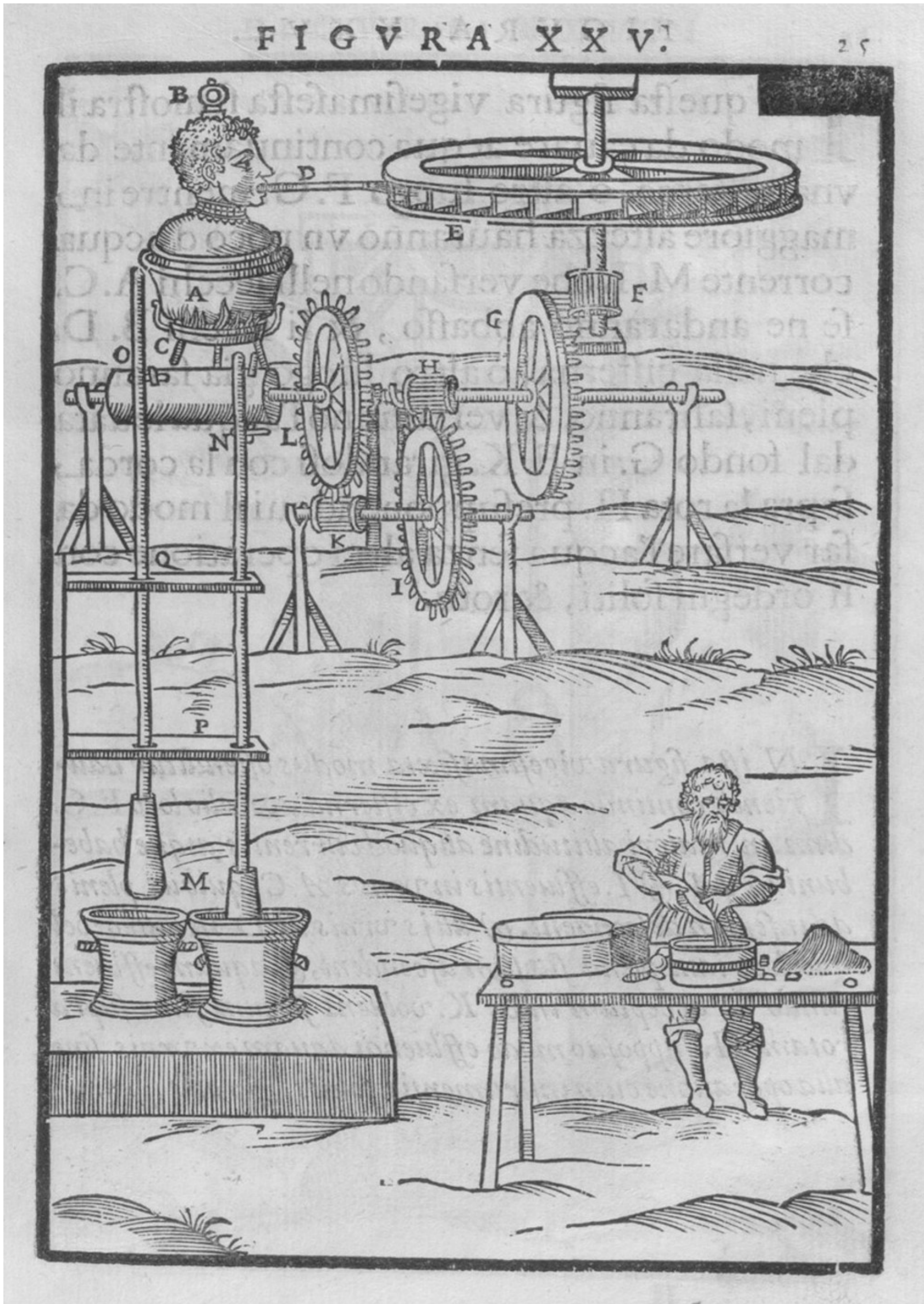


Figure 10.5: Plate 25 from *Le machine*, Giovanni Branca, 1629. [6]

Article 11

Atmospheric Engines

The ideas that the atmosphere could work against a vacuum, a vacuum could be created by condensing steam, and steam could be created by heat, gave rise to the earliest heat engines. The need for these engines was to pump water from mines that were getting to deep for human or animal labor. These engines are collectively known as *Atmospheric Engines* since the atmosphere was the principal source of work. Work is generated by the expansion of the atmosphere against the change in volume created by the condensing steam. The use "live steam" to do work had to wait for the development of metal alloys for boilers and cylinders that could handle higher pressures without bursting. The progression from these early atmospheric engines to modern steam engines in power plants can be traced through four major developments by Savory, Newcommen, Watt, and Evans.

11.1 Savory's Engine - "The Miner's Friend"

Savory (1697) used the vacuum created by condensing steam in a closed container to pump water from mines. He patented the concept in 1698 and called the engine the 'Miner's Friend'. The construction and principle are illustrated in Figures 11.1 and 11.2, respectively. Steam from a boiler enters into a large vessel at the top, then the steam valve is closed. Cold water is poured on the outside of the vessel inducing condensation of the steam inside. Because of the resulting vacuum, the atmosphere pushes water from the mine up into the vessel. A check valve on the suction pipe prevents the water from returning to the mine. Then the steam valve is opened to increase the pressure in the vessel and the the condensate and mine water are pushed out the bottom of the vessel and up the delivery pipe through a second check valve that prevents the water from flowing back to the steam vessel. Water for cooling of the outside of the steam vessel is from a portion of the previously pumped mine water. Some of this water is also returned to the boilers, and the rest is discarded.

In practice, each pump had two vacuum vessels side-by-side with common suction and delivery pipes. One vessel would be pumping while the second vessel was filling with water. The engine was very inefficient. The chamber had to be warmed up to the steam temperature with each charging and then cooled during the condensation/vacuum generation. The presence of the air (non-condensible gas) reduced the vacuum which could be generated.

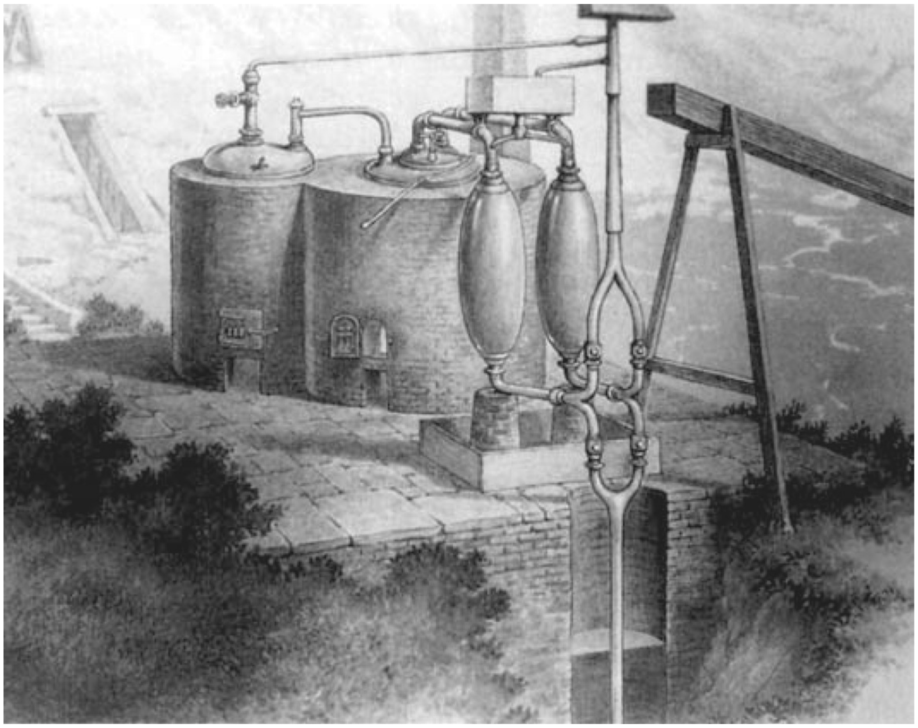


Figure 11.1: Illustration of a Savory engine. [5, Chapter 2. Introduction to Steam]

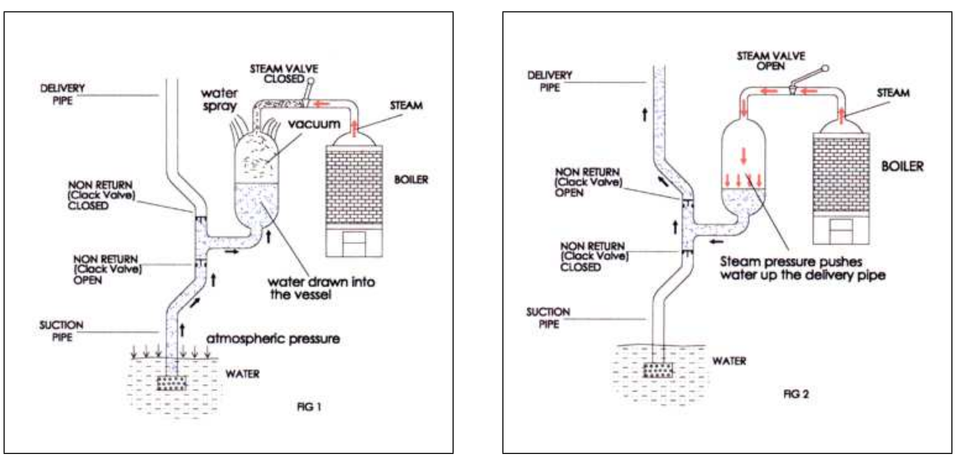
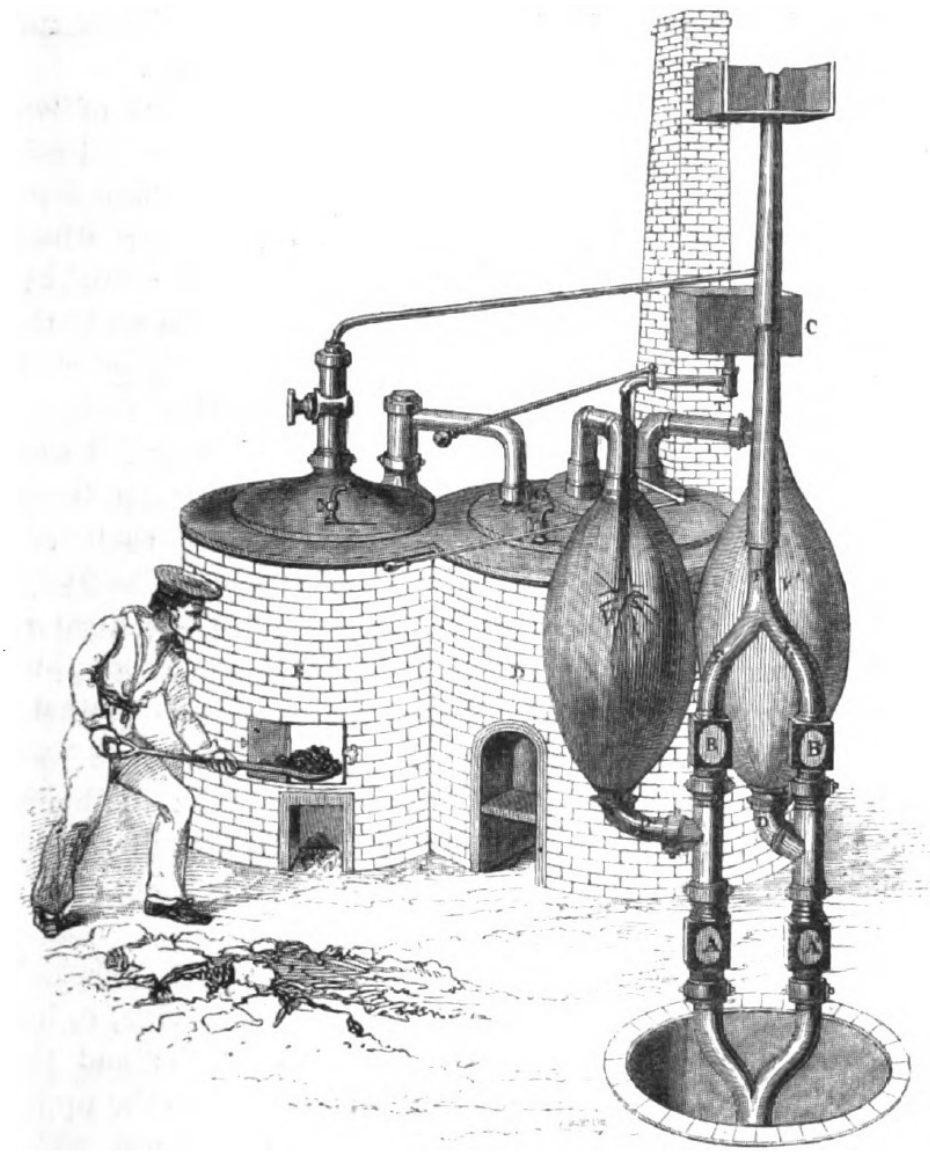


Figure 11.2: Principle of operation for Savory's "Miner's Friend" [7]



SAVERY'S ENGINE.

Figure 11.3: Illustration of Savory's engine with water spray cooling the steam vessel. [4]

11.2 Newcomen's Engine

Newcomen was a Cornish mining engineer. He made a major advance in the development of atmospheric steam engines in 1707 by separating the working fluid (steam) from the pumped fluid (mine water) using a piston-cylinder instead of a fixed volume chamber. He also incorporated the oscillating beam for transmitting the work of the piston to the water pump.

As with Savory's engine, the atmosphere worked against a vacuum generated by condensing steam. Initially, he attempted to condense steam in the piston-cylinder by running cold water through a lead jacket on the outside. This approach was not successful. During testing of these lead jackets, however, one engine operated quite satisfactorily. He discovered that a hole had developed between the lead jacket and the cylinder wall and water was getting injected directly into the cylinder. From that time forward he abandoned the water jacket and induced condensation through direct injection of cold water into the steam-filled cylinder. Work was generated by the atmosphere expanding (pushing the piston) against the vacuum in the cylinder.

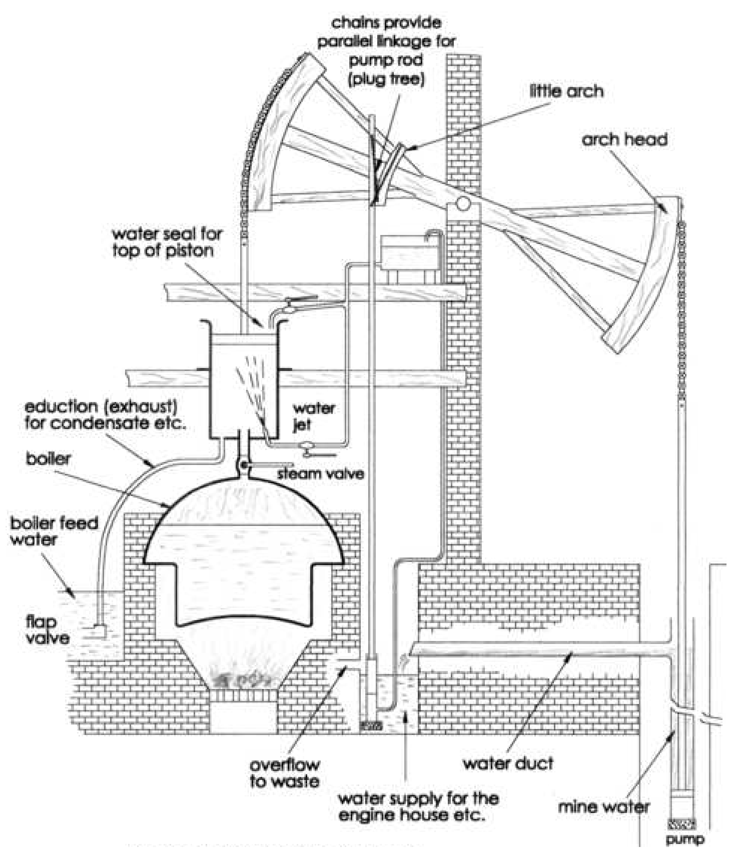


Figure 11.4: Operating principle of a Newcomen steam engine. [7].

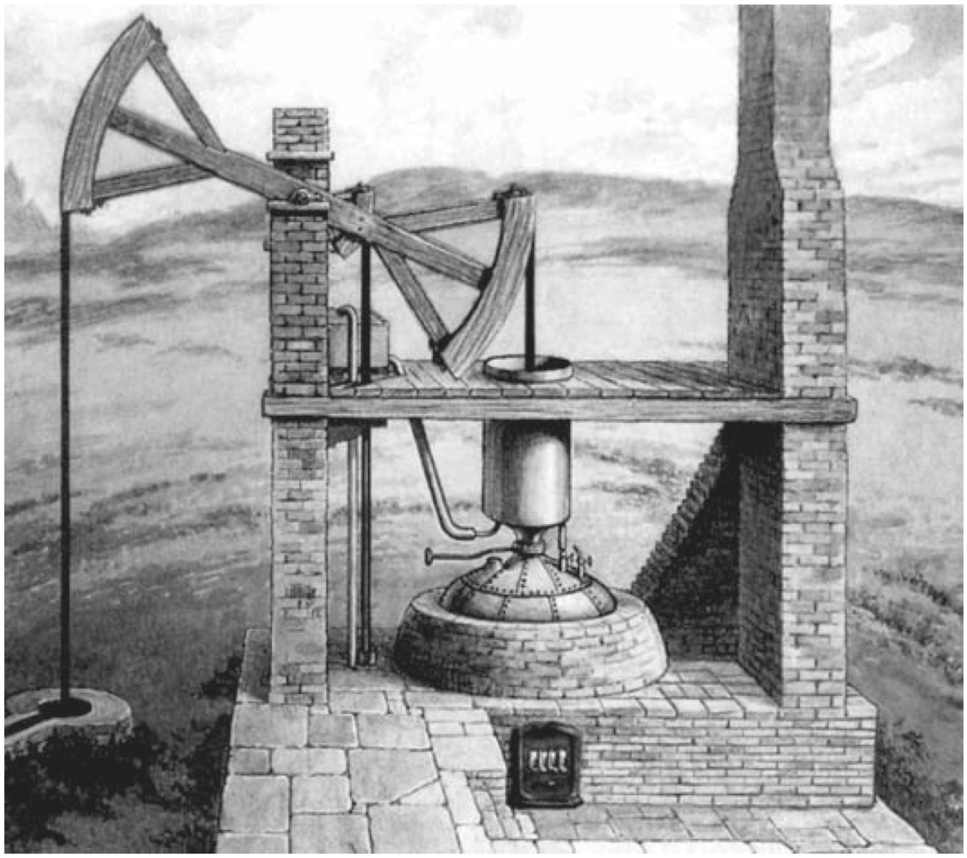


Figure 11.5: Newcomen engine. [5, Chapter 2. Introduction to Steam]

In 1712, a Newcomen engine with a 2-foot diameter piston and an 8-foot stroke pumped 130 Imperial gallons for water per minute from a depth of 150 feet. The power was approximately 5.52 horsepower. The Newcomen engines were roughly twice as efficient as Savory's engines. Though, as with Savory's engines, there was a lot of air injected with the water in the cylinder so that the vacuum pressure was far from negative atmospheric pressure. In addition, the piston-cylinder had to be warmed by the steam and then cooled during every cycle.

11.3 Watt's Engine

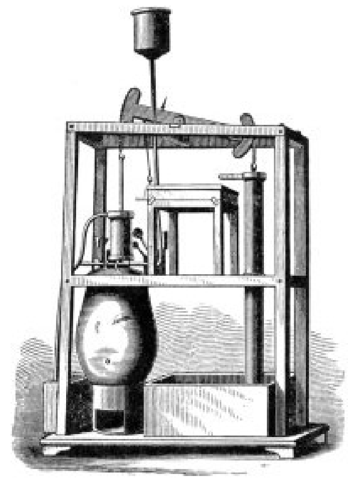


Figure 11.6: Model engine. [8]

The Newcomen engine remained virtually unchanged for fifty years until James Watt made a remarkable observation. In 1763, Watt was asked to try and fix a small Newcomen engine used in engineering lectures at the University of Glasgow (illustrated in Figure 11.6). He recognized the enormous loss of heat associated with condensing steam inside the cylinder. On each cycle, the cylinder wall had to be heated and then cooled. He concluded that the engine could be improved by separating the work function (piston) and the condensing function. Separating the condenser from the piston also allowed for a better vacuum to be maintained. The engine work is still primarily from the atmosphere expanding against the vacuum created by condensation, though a small fraction was now being done by expansion of the steam.

Figure 11.7 is an illustration of his early experiment with separating the condenser. A vacuum pump in included in the experiment to draw out non-condensible gases and improve the vacuum created during condensation. His experiment also included a double-acting piston where work was performed during both the up and down strokes. Figure 11.8 is an illustration of a complete Watt engine with additional improvements – the double-acting cylinder and rotary-motion output. Watt also developed an early indicator of work to measure steam power in an engine.

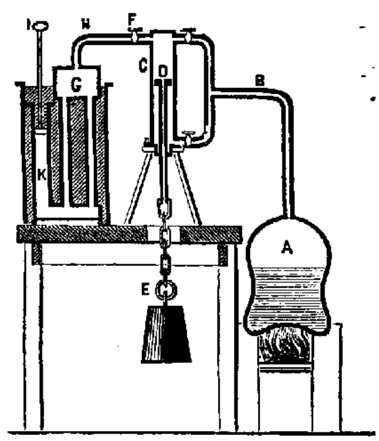


Figure 11.7: Watt's experiment with separation of the condenser. [8, Chapter 3]

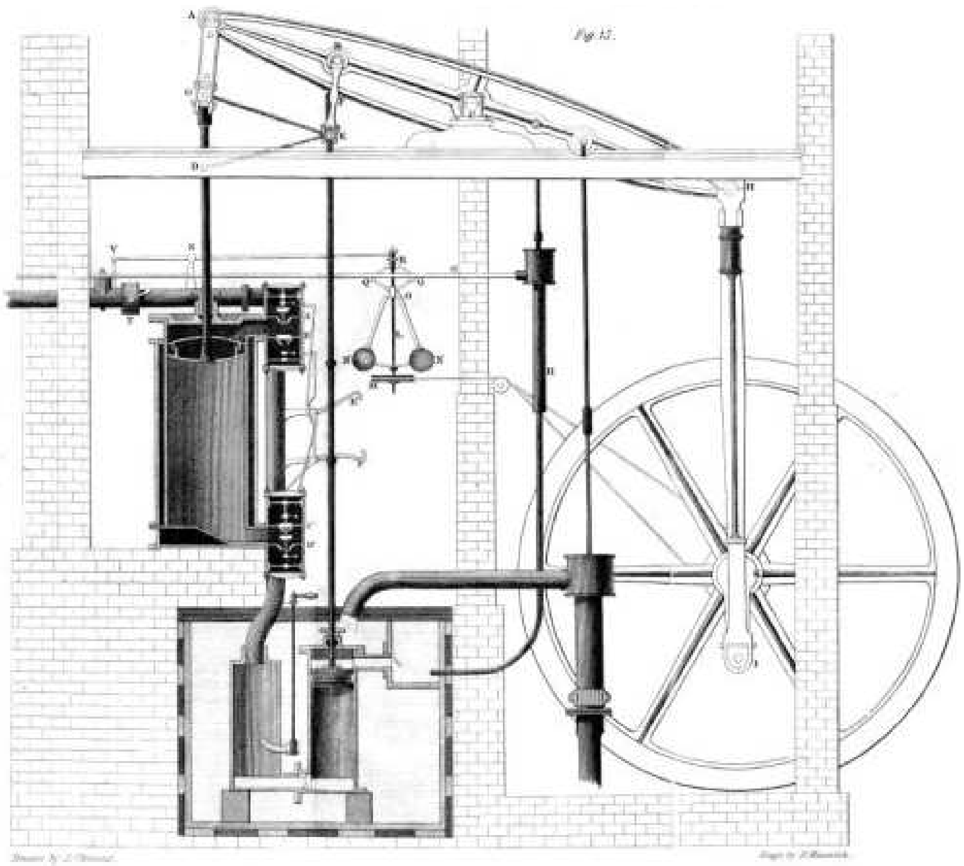


Figure 11.8: Watt engine with double-acting cylinder and rotary-motion output. [9]

11.4 Evan's Engine

In 1805 Oliver Evans demonstrated the use of expanding high pressure steam, or "live steam", to do work instead of atmospheric expansion. There were parallel developments in Europe.[1] Evan's dubbed his engine the "inexhaustible steam engine" because he circulated the working fluid from the condenser back to the boiler. This is the first steam engine operating as a closed cycle (illustrated in Figure 11.9). Evans also passed the feedwater (the water fed to the boiler) through a heat exchanger with the hot condensate from the cylinder. This preheating of the feedwater reduced the external irreversibilities of the cycle and improved the engine's efficiency. Circulation of the same

[1] There are competing claims that engineers in Russia, France, England, and Spain preceded Evans. The engine built by Richard Trevithick in England around 1799 is earlier, but the development by Evans and Trevithick appear to be independent. Evans' exposition "The Abortion of the Young Steam Engineer's Guide" published in 1805 definitely describes a complete Rankine cycle.

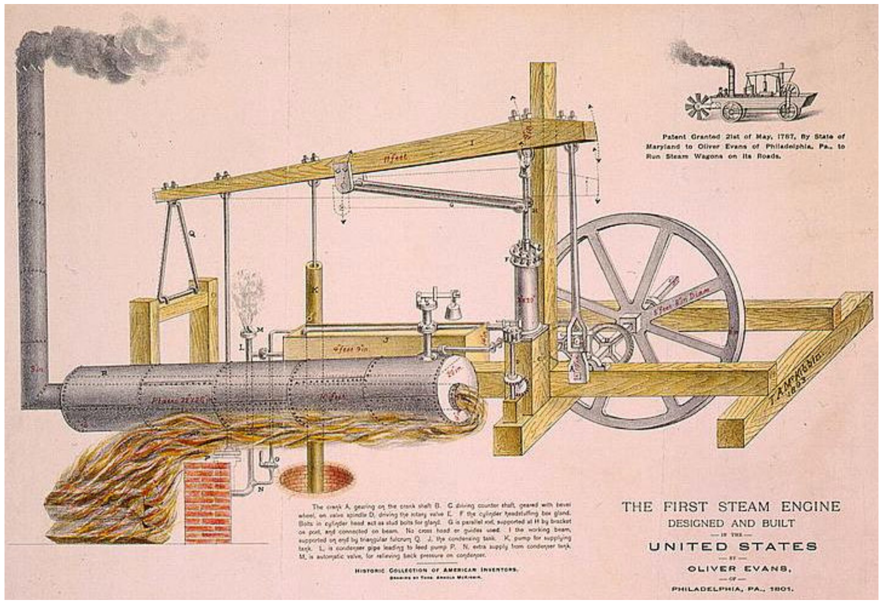


Figure 11.9: Oliver Evan's steam engine.

water (working fluid) also improved the vacuum achieved in the condenser since there was not the continuous introduction of air during injection of new water into the cycle. Evan's engine was possible by 1805 due to improvements in iron making which allowed for boilers and cylinders which would not burst at moderate steam pressures.

In 1805 Evans received a contract from the Philadelphia Board of Health to build a steam powered dredge for the harbor. He designed and built the *Oruktor Amphibolos* (Amphibious Digger, see Figure 11.10), which he purportedly mounted on four wheels and drove under steam power from his engine works to the harbor.

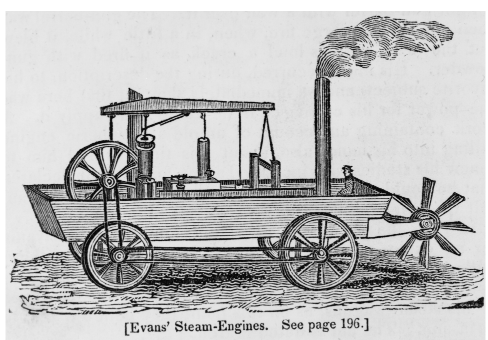


Figure 11.10: Oruktor Amphibolos from The Boston mechanic and journal of the useful arts and sciences. Boston: G.W. Light & Co., 1834 July, p. 17.

11.5 End of Early Steam Engine Development

In 1830, the Liverpool & Manchester Railway held a competitions for selecting a steam locomotive. The competition was called the 'Rainhill Tests' and an engine dubbed the 'Rocket' won. The 'Rocket' as well as several other competitors had incorporated all of the major advances in steam engines up to that point in time. The Rainhill Tests are considered to mark the end of early steam engine development. There continued to be advances in materials, boiler arrangements, combustion and engine configurations, but the basic steam engine design was complete.

11.6 Schematics of Major Advances in Atmospheric Engines

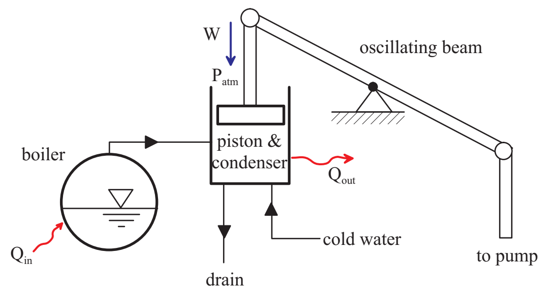


Figure 11.11: Newcomen's Engine – 1707

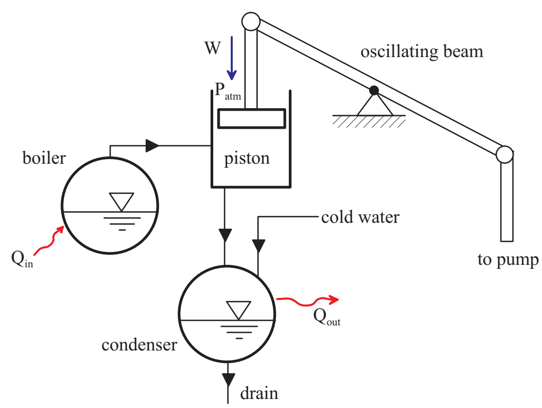


Figure 11.12: Watt's Engine – 1764

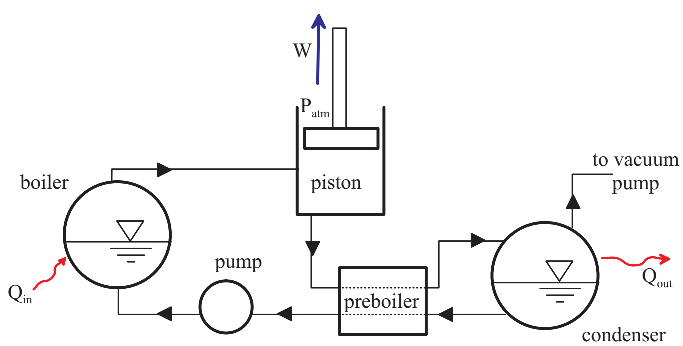


Figure 11.13: Evan's Engine – 1805

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