Principles of Energy Conversion

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Part 4. The Rise of Heat Engines

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**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 over the course of many centuries 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. The relevant discussion herein is on the historical development of modern thermal energy conversion systems.

Some description of ancient technology was 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 beginning in the late 1500’s, that resulted in the rapid advance of energy conversion technologies.

The history of discovery and subsequent engineering development 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]

~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 described many Roman technologies and included descriptions of the pneumatic and hydraulic work of Ctesibius.

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

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¹The 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.
The 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.

1550’s to 1600’s Ideas start 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 couple of thousand years.

~1600’s 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.

~1600’s 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.

~1647 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.

~1600’s to 1900’s Magdeburg Hemispheres are a popular demonstration of atmospheric force. 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.
Technologies Directly Affecting Thermal Energy Conversion

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

Hydraulis

"Ktesibios was fascinated by fluid flow – the movement of water and air. He revolutionized the measurement of time when he invented a new water clock. The flow of water into it was held steady by the first feedback-controlled water supply valve.

Ktesibios was also interested in music. Writer Thomas Levenson tells how Ktesibios solved the problem of supplying air to a set of pipes. He used his water-powered air-reservoir to fill a box that fed the pipes. He created a keyboard that let performers open individual pipes to the air box. In one stroke he’d given us the pipe organ, close to its modern form, over 2200 years ago.

The organ quickly took root. The Romans were quite taken with it. They called it the hydraulis. If Nero played anything while Rome burned, it wasn’t the fiddle. Nero was an organist.

But after Rome adopted Christianity, the organ died out. St. Augustine was troubled by music. It could, no doubt, provide us with a wink of Heaven, but it was too seductive – more likely to break our concentration on God than enhance it. And organs produced the most powerful musical sound available. In the end, the early Church of Rome came down against organs."
Only when the Church found a new home in medieval Europe did theologians once again take the view that the arts, including music, were acceptable aids to worship. The organ entered that world in AD 757 when the Byzantine court presented a Ktesibios type of water organ to Charlemagne’s father. From then on, organs became an integral part of Northern European culture.”

quoted from Liehhard [2]

Magdeburg Spheres

The German scientist Otto von Guericke [mayor of Magdeburg] (1602-1686), staged elaborate demonstrations of the force of atmospheric pressure by pulling a vacuum between two half spheres and showing the force holding the two halves together. Otto von Guericke performed a similar demonstration before a Reichstag at Regensburg on May 8, 1654.

Bone Digesters and the Safety Valve

The jump from elastic fluids (gases) and inelastic fluids (liquids) to vapors was not straightforward. However, there were a number of people who recognized that vapors could be generated from application of heat and that these 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 an engine designed by Marquis of Worcester is described in 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 (bone digesters), leading Papin to develop a safety valve that is essentially the same used today on 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 to create a vacuum and published his design in 1690.

Aeolipile

Papin’s engine condensed the steam in order to pull a vacuum relative to the atmosphere. The early development of steam power will follow this approach. There were attempts to convert the energy in steam directly into mechanical work via expansion. The earliest known example is the aeolipile.
The *aeolipile* is credited to Hero of Alexandria (c. 10-70 AD). 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. "Even today, the basic idea has remained the same: generate heat, transfer the heat to water, and produce steam." 

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. It is not known if this machine was built.

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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.

3 [5, Chapter 2. Introduction to Steam]
Plate 25 from *Le machine*, Giovanni Branca, 1629 [6]
Savory’s Engine - “The Miner’s Friend”

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

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’.

Steam enters one of the chambers then the steam valve is closed. Condensation is induced by pouring cold water onto the chamber. Water from the mine is drawn into vessel via the vacuum formed from the condensation of the steam. A check valve prevents water previously pumped from returning to the chamber. Then the steam valve is opened increasing the pressure in the vessel which pushes the condensate and mine water through the check valve into the delivery pipe. A check valve on the suction pipe prevents the water from returning to the mine. Some of the mine water is used to cool the chambers during the next cycle. Some water is 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 process 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-condensable gas) reduced the vacuum which could be generated.
Conceptual illustration of Savory's engine. [4]
Atmospheric Engines

Atmospheric engines generate work by the expansion of the atmosphere. The power and compression strokes are at constant pressure; \( \approx 14.7 \text{ psia}, 1 \text{ bar}, 101 \text{ kPa} \) less the internal pressure of the steam and air.

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 arrangement instead of a fixed volume chamber. He also incorporated the oscillating beam for transmitting the work of the piston to the water pump. He still created a vacuum by injecting cold water into the steam-filled cylinder. The work generated was due to the atmosphere expanding (pushing the piston) against the vacuum in the cylinder.

Operating principle of Newcomen’s engine from the Markham Grange Steam Museum [7].
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 are true atmospheric engines and 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 was far from negative atmospheric pressure. In addition, the piston-cylinder had to be warmed by the steam and then cooled during every cycle.
Illustration of a Newcomen steam engine from the Markham Grange Steam Museum [7].
Watt’s Engine

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. He recognized the loss of heat associated with condensing inside the cylinder. Watt designed a steam engine in which the condensing function were separated from the work producing function. Separation the condenser from the piston also allowed for a better vacuum to be maintained. The separate condenser reduced irreversibilities since piston-cylinder could stay hot. The engine work is still primarily from work by the expanding atmosphere, not by the internal steam. Later, Watt developed double acting cylinder and rotary motion output.
Watt’s refined engine with double-acting cylinder and rotary-motion output. [9, Track 9]

**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. 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 cycle. 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. The circulation of the working fluid also improved the vacuum achieved in the condenser since there was not the continuous introduction of air during condensation due the injection of new water into the cycle. Evan’s engine was possible by 1805 due to improvements in iron making which

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4There 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.
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), which he purportedly mounted on four wheels and drove from his engine works to the harbor.

![Illustration of the Oruktor Amphibolos from The Boston mechanic and journal of the useful arts and sciences. Boston: G.W. Light & Co., 1834 July, p. 17.](image)

**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.
Schematics of Major Advances

Newcomen’s Engine – 1707

Watt’s Engine – 1764

Evans’ Engine – 1805
References


