(This page intentionally left blank)

22 Engine Types

22.1 Introduction

The steam engine was the first practical machine capable of converting heat energy into continuous mechanical power on a large scale. From the pumping engines of the eighteenth century to the great marine engines of the twentieth, steam engines powered mines, factories, railways, and ships throughout the industrialized world.

Although steam engines appeared in many forms, their operation was based on the same fundamental principle. Steam produced in a boiler enters a cylinder and exerts pressure on a piston. The piston's reciprocating motion is converted through a connecting rod and crank into rotary motion that can drive machinery, pumps, propellers, or locomotive wheels.

A simple explanation might suggest that steam should be admitted to the cylinder during the entire piston stroke. In practice, however, the most efficient engines admit steam for only part of the stroke. After the piston has traveled a fraction of its distance, typically between one-quarter and one-third of the stroke, the admission valve closes. The trapped steam continues to expand and pushes the piston to the end of the stroke without requiring additional steam from the boiler.

This process is known as **expansive working**. By allowing steam to expand after admission has stopped, the engine obtains more useful work from the same quantity of steam. Less steam is required for a given power output, reducing fuel and water consumption. Understanding expansive working is essential to understanding both simple and compound steam engines.

The operation of a steam engine can be studied using a **steam indicator**, an instrument that records cylinder pressure throughout the piston cycle. The resulting indicator diagram provides a graphical record of the engine's operation and identifies the principal events of the cycle:

- Steam admission
- Steam cut-off
- Expansion
- Exhaust release
- Compression

These events reveal how steam pressure changes during the stroke and how efficiently the engine uses the energy supplied by the boiler.

As engineers sought greater economy, they looked for ways to extract even more work from the steam before exhausting it. The solution was to divide the expansion process between two or more cylinders. Steam first expanded in a high-pressure cylinder and then passed through one or more larger cylinders, where additional expansion occurred. This development led to the compound, triple-expansion, and quadruple-expansion engines that became common in marine and stationary service during the late nineteenth and early twentieth centuries.

This chapter begins with the operation of the double-acting simple steam engine and the use of the steam indicator to study the events occurring within the cylinder. It then follows the development of compound, triple-expansion, and quadruple-expansion engines as engineers sought to improve the economy of steam power.

22.2 The Aeolipile

One of the earliest known steam-powered devices was the **Aeolipile**, described by Hero (Heron) of Alexandria during the first century AD. The device consisted of a hollow sphere mounted so that it could rotate freely. Steam produced in a boiler passed into the sphere and escaped through bent nozzles. The reaction force of the escaping steam caused the sphere to spin.

Fig. 1 Aeolipile

Although the Aeolipile demonstrated that steam could produce motion, it was not a practical engine. It could not perform useful work beyond its own rotation and was not connected to machinery. Nevertheless, it is historically significant because it illustrates an understanding of steam power nearly two thousand years before the Industrial Revolution.

The development of practical steam engines required a different approach. Instead of producing rotary motion directly from escaping steam, engineers learned to use steam pressure to move a piston within a cylinder. This arrangement made it possible to perform useful work and led to the development of the reciprocating steam engine.

22.3 Operation of a Double-Acting Simple Steam Engine

The double-acting simple steam engine is the basic form of reciprocating steam engine from which many later designs were developed. In a double-acting engine, steam acts alternately on both sides of the piston, producing power during both the outward and return strokes.

The principal components of the engine (Fig. 2) are the cylinder, piston, piston rod, connecting rod, crankshaft, flywheel, and steam valve. Steam from the boiler enters the cylinder through ports controlled by the valve mechanism. As steam pressure acts on one side of the piston, the piston moves through the cylinder and turns the crankshaft. At the same time, spent steam on the opposite side of the piston is released through the exhaust port.

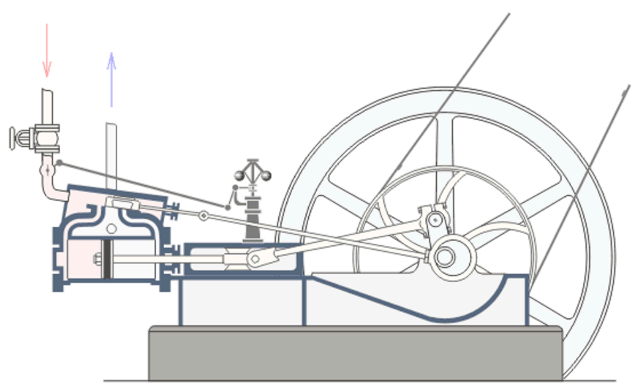

Fig. 2 Double Acting Simple

Near the end of the stroke, the valve mechanism changes position. Steam is then admitted to the opposite side of the piston while the first side is opened to exhaust. The piston reverses direction and the process repeats. As long as steam is supplied from the boiler, the engine continues to produce rotary motion.

Because power is developed during both strokes, a double-acting engine produces a smoother turning effort than a single-acting engine. The flywheel stores energy during the stronger portions of the cycle and releases it during the weaker portions, helping to maintain a more uniform rotational speed.

The pressure acting on the piston is not constant throughout the stroke. Steam is admitted, expanded, exhausted, and compressed in a carefully controlled sequence. These pressure changes determine both the power produced by the engine and its efficiency. To study these changes, engineers use an instrument known as a **steam indicator**, which produces a graphical record of cylinder pressure during each piston cycle.

22.3.1 Comparison with Internal-Combustion Engines

Students familiar with gasoline or diesel engines may find it useful to compare the frequency of power strokes in different engine types.

In a four-stroke (Otto-cycle) engine, each cylinder produces one power stroke for every two revolutions of the crankshaft. The remaining strokes are required for intake, compression, and exhaust.

A two-stroke engine produces one power stroke for every revolution of the crankshaft.

A double-acting steam engine is different. Steam pressure acts alternately on both sides of the piston, producing power during both the outward and return strokes. Since each piston stroke corresponds to one-half revolution of the crankshaft, the engine delivers a power stroke every half revolution.

For a single cylinder, the comparison is:

- Four-stroke internal-combustion engine: 1 power stroke per 2 revolutions
- Two-stroke internal-combustion engine: 1 power stroke per revolution
- Double-acting steam engine: 1 power stroke per 1/2 revolution

This frequent application of power helps explain the smooth operation of steam engines and reduces the size of the flywheel needed to carry the engine through non-power-producing portions of the cycle.

22.3.2 The Steam Indicator

The operation of a steam engine cannot be fully understood by observing the motion of the piston and valve gear alone. Engineers must also know how the steam pressure changes throughout the piston stroke. To measure these pressure changes, early engineers developed an instrument known as the **steam indicator**.

Instruments like these date back to the days of James Watt in the late 18th century. The illustration in Fig. 3 is of a steam indicator developed by Charles Richards a hundred years later.

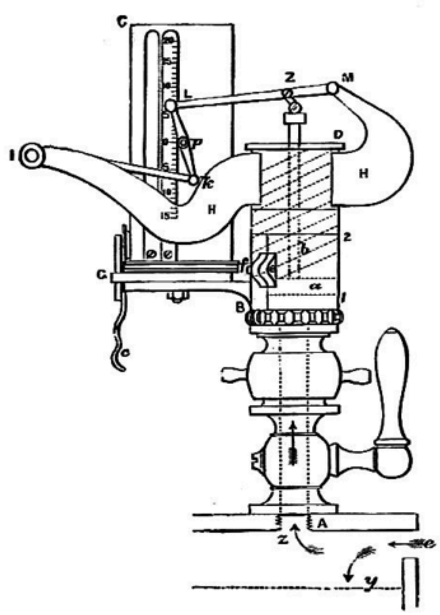

Fig. 3 Steam Indicator c. 1875

22.3.2.1 The Intuition

The purpose of a steam indicator is to record what is happening inside the cylinder while the engine is running. It produces a graphical record of cylinder pressure throughout the piston stroke.

A simple way to visualize the instrument is to imagine a sheet of paper wrapped around a tin can. The can oscillates back and forth in step with the engine piston. A pencil rests against the paper and moves up and down in response to the steam pressure inside the cylinder.

As the piston travels through its stroke, the paper moves horizontally. As the cylinder pressure rises and falls, the pencil moves vertically. The combined motions trace a closed loop on the paper known as an **indicator diagram** or **indicator card**.

The horizontal direction of the diagram represents piston position within the cylinder, while the vertical direction represents steam pressure. The shape of the loop reveals the events occurring during the piston cycle and provides valuable information about engine operation.

Engineers used indicator diagrams to evaluate performance, adjust valve settings, diagnose operating problems, and compare the efficiency of different engine designs. For the steam engineer, the indicator diagram became one of the most important tools for understanding what was happening inside the cylinder.

By examining the indicator diagram, it is possible to identify the principal events of the steam-engine cycle:

- Steam admission
- Steam cut-off
- Expansion
- Exhaust release
- Compression

These events explain how a steam engine obtains useful work from expanding steam and form the foundation for understanding compound and multiple-expansion engines.

22.3.3 The Implementation

A steam indicator is connected to the engine cylinder by a small pipe. Inside the instrument, a spring-loaded piston moves in response to changes in cylinder pressure. At the same time, a mechanism driven from the engine crosshead moves a pencil horizontally in proportion to piston position. The resulting diagram records cylinder pressure against piston travel.

The diagram produced by the instrument is known as an **indicator diagram** or **indicator card**. It provides a graphical record of the events occurring within the cylinder during each cycle.

For steam engineers, the indicator diagram serves much the same purpose that diagnostic instruments serve for modern internal-combustion engines. It reveals how effectively the engine is operating and can identify problems such as incorrect valve timing, excessive back pressure, steam leakage, or restricted exhaust flow.

The indicator was one of the most important tools available to steam engineers because it transformed the operation of the engine from guesswork into a measurable engineering process. By studying the indicator diagram, engineers could evaluate engine performance, adjust valve settings, and compare the effectiveness of different engine designs.

The indicator diagram also provides a convenient way to visualize the principal events of the steam-engine cycle. These events include steam admission, steam cut-off, expansion, exhaust release, and compression. Understanding these events is essential to understanding why compound and multiple-expansion engines achieve greater efficiency than simple engines.

22.3.4 Events of the Piston Cycle

The indicator diagram records the changing pressure within the cylinder as the piston moves through its stroke. By following the diagram clockwise, the principal events of the steam-engine cycle can be identified.

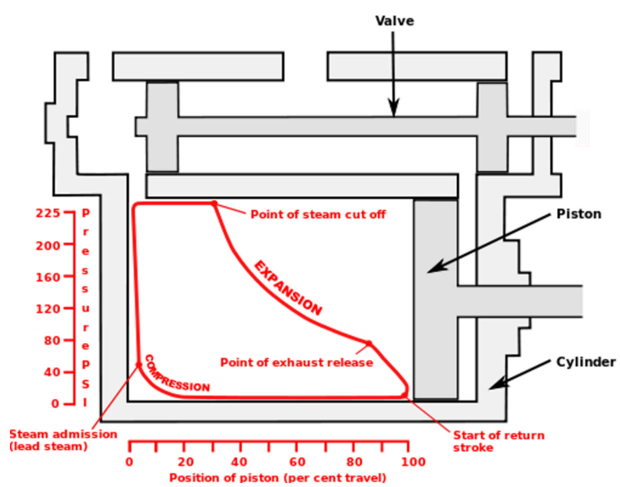

Fig. 4 Schematic Indicator Diagram

Unlike a stand-alone indicator card, Figure Fig. 4 places the indicator diagram directly on the engine cylinder. This allows the reader to associate events on the diagram with the physical position of the piston and the operation of the valves.

22.3.4.1 Steam Admission

At the beginning of the stroke, the admission valve opens and high-pressure steam enters the cylinder. Pressure rises rapidly and acts on the piston, producing the force required to move the piston and turn the crankshaft.

On the indicator diagram, steam admission appears as the near-vertical rise at the left side of the loop.

22.3.4.2 Steam Cut-Off

After the piston has traveled a portion of its stroke, the admission valve closes. No additional steam enters the cylinder.

Rather than ending the power stroke, the trapped steam continues to push on the piston. This is known as **cut-off**, and it marks the beginning of expansive working.

The position of cut-off is one of the most important adjustments affecting engine performance and economy.

22.3.4.3 Expansion

Following cut-off, the steam expands as the piston continues its travel toward the end of the cylinder. As the steam expands, both pressure and temperature decrease. Even though the pressure falls, the steam continues to exert force on the piston and produce useful work.

The curved upper portion of the indicator diagram represents the expansion of the steam.

The ability of expanding steam to continue performing work after admission has stopped is the key to the efficiency of the steam engine.

22.3.4.4 Exhaust Release

Near the end of the stroke, the exhaust valve opens. The remaining steam is released from the cylinder, causing a sudden drop in pressure.

This event is known as **release**. By opening slightly before the piston reaches the end of the stroke, the engine reduces the pressure that would otherwise oppose the return movement of the piston.

On the indicator diagram, release appears as the steep drop on the right side of the loop.

22.3.4.5 Compression

As the piston begins its return stroke, the exhaust valve closes before the piston reaches the end of its travel. A small quantity of steam remains trapped within the cylinder.

This trapped steam is compressed during the final portion of the return stroke, causing cylinder pressure to rise again before fresh steam is admitted.

Compression cushions the motion of the piston, reduces mechanical shock, and prepares the cylinder for the next admission of steam.

The lower portion of the indicator diagram represents this compression process.

22.3.4.6 The Complete Cycle

Together, steam admission, cut-off, expansion, release, and compression form a complete piston cycle. The indicator diagram provides a convenient way to visualize these events and to understand how the engine converts the energy contained in steam into useful mechanical work.

Of these events, cut-off and expansion are particularly important. They allow the engine to continue producing work after steam admission has stopped, reducing steam consumption and improving operating economy.

22.4 Expansion and Thermal Efficiency

One of the most important questions in steam-engine design is why steam admission is cut off before the piston reaches the end of its stroke.

A simple solution would be to keep the admission valve open throughout the entire stroke. While this would produce a large force on the piston, it would also consume a large quantity of steam. Steam engineers discovered that a more economical approach was possible.

High-pressure steam enters the cylinder through the admission valve and begins pushing the piston. After the piston has travelled approximately 25% to 33% of its stroke, the valve closes. No additional steam enters the cylinder, but the trapped steam continues to expand as the piston moves toward the end of its stroke.

Although the pressure of the steam falls during expansion, it continues to exert force on the piston and perform useful work. In this way, the engine extracts additional work from steam that has already been admitted to the cylinder.

Near the end of the stroke, the exhaust valve opens and the remaining steam is released. Depending on the type of engine, the exhaust steam may be discharged directly to the atmosphere or passed into a condenser.

The ability of expanding steam to continue performing work after admission has stopped is known as **expansive working**. This is one of the fundamental principles of efficient steam-engine operation.

22.4.1 Temperature Changes During Expansion

As steam expands in the cylinder, its pressure decreases. Its temperature also decreases as energy is transferred to the piston in the form of mechanical work.

Ideally, very little heat is exchanged between the steam and its surroundings during the brief period of expansion. Engineers describe this process as **adiabatic expansion**, meaning that the steam performs work while losing little or no heat to the outside environment.

As a result, steam enters the cylinder at a relatively high temperature and leaves at a lower temperature after expansion.

22.4.2 A Source of Inefficiency

The changing temperature of the steam creates a problem. During admission, the hot incoming steam heats the cylinder walls. During expansion and exhaust, the cooler steam allows those same walls to cool.

This continual cycle of heating and cooling occurs with every stroke of the engine. Energy is repeatedly transferred into and out of the metal cylinder rather than being converted into useful work.

The heating and cooling of the cylinder is one of the principal sources of inefficiency in a simple steam engine.

22.4.3 The Trade-Off

Early cut-off improves economy because more work is obtained from each pound of steam admitted to the cylinder. However, there is a disadvantage.

Because steam pressure falls during expansion, the force acting on the piston becomes progressively smaller during the stroke. The turning moment, or torque, applied to the crankshaft therefore becomes less uniform.

To smooth out these variations, steam engines rely on a flywheel. The flywheel stores energy during the stronger portions of the cycle and releases it during the weaker portions. Engines employing very early cut-off generally require larger flywheels to maintain a steady speed.

Steam engineers therefore faced a compromise. Early cut-off improved economy by reducing steam consumption, but it also increased the variation in turning effort. Much of the history of steam-engine development can be viewed as an attempt to achieve both good economy and smooth operation.

22.5 The Uniflow Engine

The compound and multiple-expansion engines improved efficiency by dividing the expansion of steam among several cylinders. This reduced the temperature range experienced by any one cylinder and allowed more work to be extracted from the steam before it was exhausted.

Engineers eventually recognized another source of inefficiency. In conventional steam engines, steam enters and leaves through ports located at the ends of the cylinder. Hot incoming steam and cooler exhaust steam therefore pass through the same regions of the cylinder. As a result, the cylinder walls are repeatedly heated and cooled during each cycle.

This continual temperature cycling wastes energy and promotes condensation of steam within the cylinder.

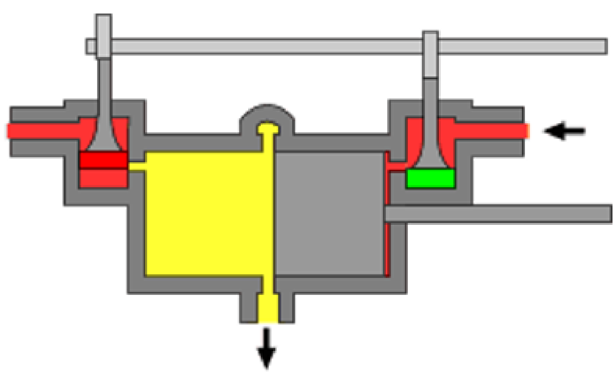

Fig. 5 Uniflow Engine

The **uniflow engine** was developed to reduce this problem. A useful way to visualize a uniflow engine is as two half-cylinders sharing a common exhaust region at the center of the cylinder. Steam enters through inlet valves located near the ends of the cylinder but exhausts through ports near the center. Near the end of the stroke, the piston uncovers exhaust ports located close to the center of the cylinder, allowing the steam to escape.

Unlike a conventional double-acting engine, where admission and exhaust occur alternately at both ends of the cylinder, steam in a uniflow engine always travels in the same general direction: from the hot ends of the cylinder toward the cooler central exhaust ports.

Because the ends of the cylinder remain relatively hot while the central exhaust region remains relatively cool, temperature variations within the cylinder are reduced. This decreases condensation losses and improves thermal efficiency.

The uniflow engine represented one of the final major developments in reciprocating steam-engine design. Although it arrived after compound and triple-expansion engines had become well established, it demonstrated that significant improvements in efficiency were still possible through careful management of heat flow within the cylinder.

The history of steam-engine development can be viewed as a continual effort to extract more useful work from each pound of steam. Early cut-off, expansive working, compound expansion, and the uniflow principle were all important steps toward that goal.

22.5.1 Historical Note: Steam-Engine Catechisms

Many nineteenth- and early twentieth-century engineering manuals were written in the form of a catechism: a series of questions and answers intended for memorization and discussion. This format reflected the apprenticeship system through which many engineers, mechanics, and engine operators learned their trade.

The goal was not merely to provide information but to establish a shared technical vocabulary. By repeatedly reviewing questions and answers, apprentices learned both the terminology and the principles needed to operate and maintain steam machinery.

Nehemiah Hawkins's *Steam Engine Catechism* and *Steam Indicator Catechism* were among the best-known examples of this style of technical instruction.

22.6 Engine Configurations

The double-acting simple engine uses a single cylinder in which steam is admitted, expanded, and exhausted. While this arrangement is mechanically simple and reliable, engineers soon recognized that additional work could be obtained from the steam before it was exhausted.

As steam expands, its pressure and temperature decrease. In a simple engine, a large temperature range exists between admission and exhaust, causing repeated heating and cooling of the cylinder walls. Steam engineers therefore sought methods of dividing the expansion process into stages.

The solution was the **compound engine**. Instead of exhausting steam after a single expansion, the steam is passed from one cylinder to another, expanding progressively as its pressure decreases. Each cylinder handles only a portion of the total expansion.

In a compound engine, high-pressure steam first enters a relatively small **high-pressure (HP) cylinder**. After doing work there, the partially expanded steam passes to a larger **low-pressure (LP) cylinder**, where additional expansion takes place before the steam is exhausted to the atmosphere or to a condenser.

The purpose of compounding is not simply to add cylinders. The purpose is to obtain more useful work from the steam, reduce cylinder temperature variations, and improve the overall economy of the engine.

Several arrangements were developed to achieve these goals. The principal configurations are described in the following sections.

22.6.1 Cross Compound

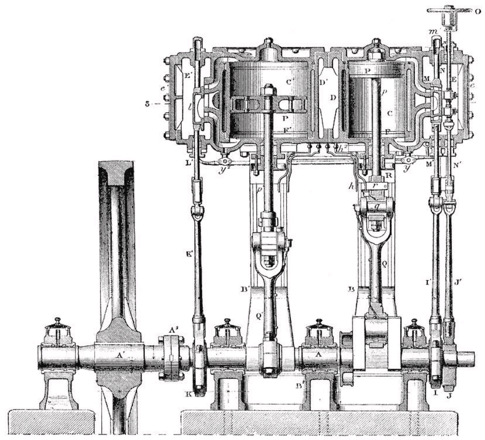

Fig. 6 Cross Compound

In the cross-compound arrangement, the high-pressure and low-pressure cylinders are mounted side by side and drive separate crank throws on a common crankshaft. Steam first enters the smaller high-pressure cylinder and performs part of its expansion. It then passes to the larger low-pressure cylinder, where expansion continues before the steam is exhausted.

The low-pressure cylinder must be larger than the high-pressure cylinder because the steam occupies a greater volume after it has expanded.

A cross-compound engine can be recognized by its two separate cylinders and connecting rods acting on different crank throws. This arrangement distributes the turning effort more evenly around the crankshaft and provides smoother operation than would be obtained from a single-cylinder engine.

The steam follows the path:

Boiler → High-Pressure Cylinder → Low-Pressure Cylinder → Exhaust

The cross-compound engine became a popular arrangement for stationary and marine service because it combined improved economy with relatively straightforward mechanical construction.

22.6.2 Triple-Expansion Engine

As boiler pressures increased during the nineteenth century, engineers found that even greater economy could be achieved by expanding steam in three stages instead of two. This led to the development of the **triple-expansion engine**, one of the most successful steam-engine designs ever built.

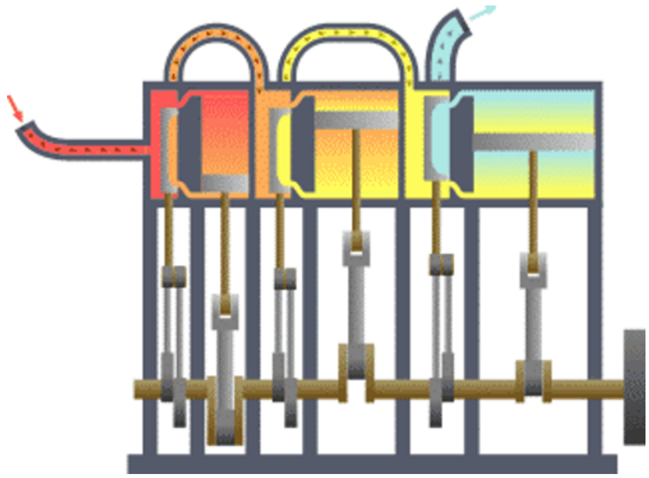

Fig. 7 Triple-expansion Engine

In a triple-expansion engine, steam passes through three cylinders of progressively increasing size:

- High-Pressure (HP) Cylinder
- Intermediate-Pressure (IP) Cylinder
- Low-Pressure (LP) Cylinder

High-pressure steam from the boiler first enters the HP cylinder, where it performs part of its work. The partially expanded steam then passes to the IP cylinder, where further expansion occurs. Finally, the steam enters the LP cylinder, where the last stage of expansion takes place before the steam is exhausted to a condenser or, in some cases, directly to the atmosphere.

The steam path is therefore:

Boiler → HP Cylinder → IP Cylinder → LP Cylinder → Exhaust

Because steam expands as its pressure falls, each successive cylinder must be larger than the one before it. The low-pressure cylinder is often several times larger than the high-pressure cylinder.

Dividing the expansion process among three cylinders reduces the temperature range experienced by each cylinder. This decreases condensation losses and allows more useful work to be extracted from the steam before it is exhausted.

Triple-expansion engines became the preferred choice for many marine applications during the late nineteenth and early twentieth centuries. Their improved economy allowed ships to travel greater distances while carrying less coal, increasing both operating range and cargo capacity.

The triple-expansion engine represents the logical extension of the compound principle. Rather than extracting energy from the steam in one or two stages, the process is divided into three successive expansions, allowing the engine to make more complete use of the energy supplied by the boiler.

22.6.3 Tandem Compound

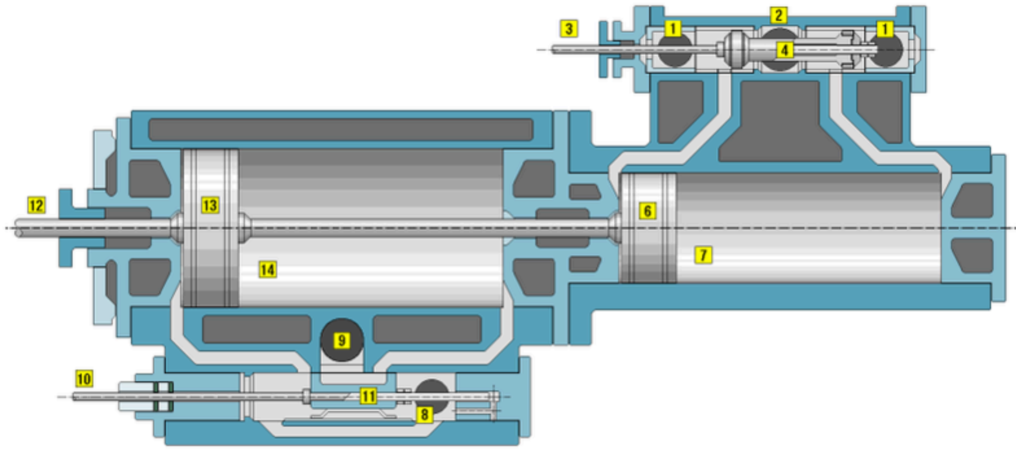

Fig. 8 Tandem Compound

In a tandem compound engine, the high-pressure (HP) and low-pressure (LP) cylinders are arranged in line and share a common piston rod. Both pistons drive the same connecting rod and crankshaft.

High-pressure steam first enters the smaller HP cylinder, where it performs part of its work. The partially expanded steam then passes directly into the larger LP cylinder, where expansion continues before the steam is exhausted.

The steam path is:

Boiler → HP Cylinder → LP Cylinder → Exhaust

Unlike the cross-compound engine, which uses separate connecting rods and crank throws, the tandem compound places both cylinders on the same centerline. This results in a more compact engine with fewer moving parts.

Because both cylinders act on a common piston rod, the forces produced by the HP and LP pistons combine before reaching the crankshaft. This simplifies the mechanical arrangement while retaining the economic advantages of compounding.

The tandem arrangement was widely used on stationary engines, traction engines, and other applications where a compact layout was desirable. Many agricultural and portable steam engines employed tandem compounds to obtain improved fuel economy without greatly increasing the overall size of the machine.

The tandem compound demonstrates that steam engineers could achieve the benefits of compound expansion through different mechanical arrangements. While the cross-compound and tandem-compound engines operate on the same thermodynamic principle, they differ significantly in the way their cylinders are connected to the crankshaft.

22.6.4 Vauclain Compound

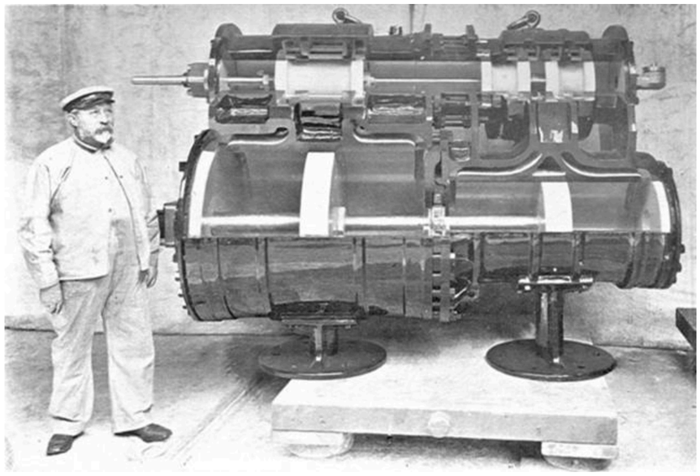

Fig. 9 Vauclain Compound

The Vauclain compound was developed by the Baldwin Locomotive Works as a compact method of applying compound expansion to railway locomotives.

Unlike a conventional cross-compound engine, the Vauclain arrangement places the high-pressure (HP) and low-pressure (LP) cylinders above one another on each side of the locomotive. The two pistons share a common crosshead and drive a single connecting rod.

High-pressure steam first enters the smaller HP cylinder. After partially expanding, the steam is directed to the larger LP cylinder where additional expansion takes place before exhaust.

The steam path is:

Boiler → HP Cylinder → LP Cylinder → Exhaust

The arrangement combines some of the advantages of both tandem and cross-compound engines. The cylinders are closely grouped, producing a compact installation suitable for locomotive service where space between the frame rails is limited.

The Vauclain compound was widely used during the late nineteenth century, particularly by railways seeking improved fuel economy. Although mechanically ingenious, the design was eventually displaced by simpler locomotive arrangements that were easier to maintain.

The Vauclain compound demonstrates how steam engineers adapted the compound principle to the unique requirements of locomotive operation.

22.6.5 Quadruple-Expansion Engine

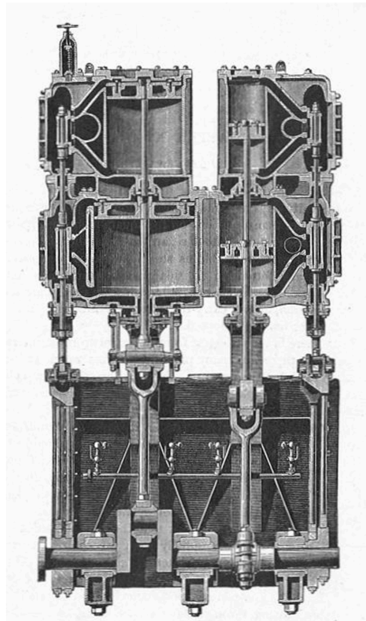

Fig. 10 Quadruple-Expansion Engine

As steam pressures continued to increase, some engineers sought even greater economy by dividing the expansion process into four stages. The result was the **quadruple-expansion engine**, the most highly developed form of the reciprocating compound steam engine.

Steam passes successively through four cylinders:

- High-Pressure (HP)
- First Intermediate-Pressure (IP)
- Second Intermediate-Pressure (IP)
- Low-Pressure (LP)

The steam path is therefore:

Boiler → HP → IP → IP → LP → Exhaust

Each cylinder is larger than the one before it because the steam occupies an increasingly greater volume as its pressure decreases.

The engine shown in Figure Fig. 10 was built by Fleming & Ferguson of Paisley and illustrates a typical quadruple-expansion arrangement. The cylinder diameters are:

- HP: 10¼ in.
- 1st IP: 14 in.
- 2nd IP: 20 in.
- LP: 28 in.

with a common stroke of 20 inches.

Operating with a boiler pressure of 200 psi, the engine developed approximately 360 indicated horsepower.

By dividing expansion among four cylinders, the temperature range within each cylinder is reduced even further than in a triple-expansion engine. This minimizes condensation losses and extracts more useful work from the steam before it reaches the condenser.

Quadruple-expansion engines represented the pinnacle of marine reciprocating steam-engine development. While the gain in efficiency over a triple-expansion engine was relatively modest, the arrangement could be justified in applications where fuel economy was of great importance, particularly in long-distance marine service.

22.7 Summary

From the Aeolipile of Hero to the highly refined uniflow engine, the history of the steam engine is largely the history of improving the use of steam expansion. Engineers progressively learned how to obtain more work from each pound of steam while reducing fuel consumption and mechanical losses.

Although steam engines appeared in many configurations, the underlying objective remained the same: to convert as much of the steam's heat energy as possible into useful mechanical work before the steam was exhausted.