Pneumatics Technology

Lucina Stowe

First Edition, 2012

ISBN 978-81-323-4530-5

Published by:
The English Press
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

Table of Contents

Chapter 1

Pneumatics

Preserved Porter Locomotive Company No. 3290 of 1923.

Pneumatics is a branch of technology, which deals with the study and application of use of pressurized gas to affect mechanical motion.

Pneumatic systems are extensively used in industry, where factories are commonly plumbed with compressed air or other compressed inert gases. This is because a centrally-located and electrically-powered compressor that powers cylinders and other pneumatic devices through solenoid valves is often able to provide motive power in a cheaper, safer, more flexible, and more reliable way than a large number of electric motors and actuators.

Pneumatics also has applications in dentistry, construction, mining, and other areas.

Examples of pneumatic systems and components

- Air brakes on buses and trucks
- Air brakes, on trains
- Air compressors
- Air engines for pneumatically powered vehicles
- Barostat systems used in Neurogastroenterology and for researching electricity
- Cable jetting, a way to install cables in ducts
- Compressed-air engine and compressed-air vehicles
- Gas-operated reloading
- Holman Projector, a pneumatic anti-aircraft weapon
- Lego pneumatics can be used to build pneumatic models

- Pipe organs:
  - Electro-pneumatic action
  - Tubular-pneumatic action

- Pneumatic actuator
- Pneumatic air guns
- Pneumatic cylinder
- Pneumatic Launchers, a type of spud gun
- Pneumatic mail systems
- Pneumatic motor
- Pneumatic tire

- Pneumatic tools:
  - Jackhammer used by road workers
  - Pneumatic nailgun

- Pressure regulator
- Pressure sensor
- Pressure switch

- Vacuum pump

Gases used in pneumatic systems

Pneumatic systems in fixed installations such as factories use compressed air because a sustainable supply can be made by compressing atmospheric air. The air usually has moisture removed and a small quantity of oil added at the compressor, to avoid corrosion of mechanical components and to lubricate them.

Factory-plumbed, pneumatic-power users need not worry about poisonous leakages as the gas is commonly just air. Smaller or stand-alone systems can use other compressed gases which are an asphyxiation hazard, such as nitrogen - often referred to as OFN (oxygen-free nitrogen), when supplied in cylinders.

Any compressed gas other than air is an asphyxiation hazard - including nitrogen, which makes up 77% of air. Compressed oxygen (approx. 23% of air) would not asphyxiate, but it would be an extreme fire hazard, so is never used in pneumatically powered devices.

Portable pneumatic tools and small vehicles such as Robot Wars machines and other hobbyist applications are often powered by compressed carbon dioxide because containers designed to hold it such as soda stream canisters and fire extinguishers are readily available, and the phase change between liquid and gas makes it possible to obtain a larger volume of compressed gas from a lighter container than compressed air would allow. Carbon dioxide is an asphyxiant and can also be a freezing hazard when vented inappropriately.

Comparison to hydraulics

Both pneumatics and hydraulics are applications of fluid power. Pneumatics uses an easily compressible gas such as air or a suitable pure gas, while hydraulics uses relatively incompressible liquid media such as oil. Most industrial pneumatic applications use pressures of about 80 to 100 pounds per square inch (550 to 690 kPa). Hydraulics applications commonly use from 1,000 to 5,000 psi (6.9 to 34 MPa), but specialized applications may exceed 10,000 psi (69 MPa).

Advantages of pneumatics

- **Simplicity of Design And Control**
  - Machines are easily designed using standard cylinders & other components. Control is as easy as it is simple ON - OFF type control.
- **Reliability**
  - Pneumatic systems tend to have long operating lives and require very little maintenance.
  - Because gas is compressible, the equipment is less likely to be damaged by shock. The gas in pneumatics absorbs excessive force, whereas the fluid of hydraulics directly transfers force.
- **Storage**
  - Compressed Gas can be stored, allowing the use of machines when electrical power is lost.
- **Safety**
  - Very low chance of fire (compared to hydraulic oil).
  - Machines can be designed to be overload safe.

Advantages of hydraulics

- Liquid (as a gas is also a 'fluid') does not absorb any of the supplied energy.
- Capable of moving much higher loads and providing much higher forces due to the incompressibility.
- The hydraulic working fluid is basically incompressible, leading to a minimum of spring action. When hydraulic fluid flow is stopped, the slightest motion of the load releases the pressure on the load; there is no need to "bleed off" pressurized air to release the pressure on the load.

Pneumatic logic

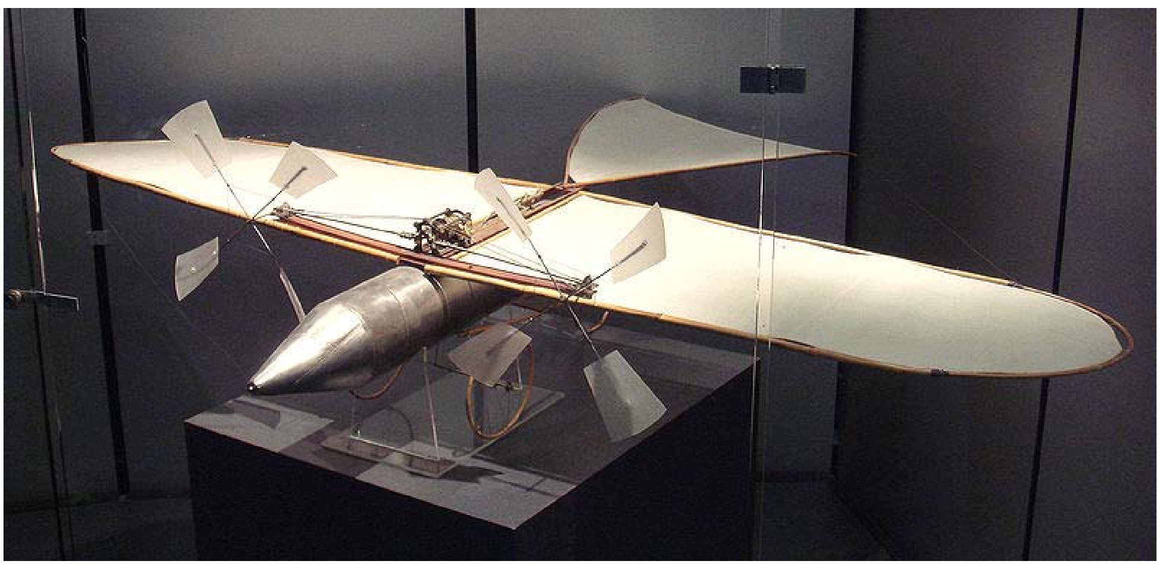
Pneumatic logic systems (sometimes called **air logic control**) are often used to control industrial processes, consisting of primary logic units such as:

- And Units
- Or Units
- 'Relay or Booster' Units
- Latching Units
- 'Timer' Units
- Sorteberg relay
- fluidics amplifiers with no moving parts other than the air itself

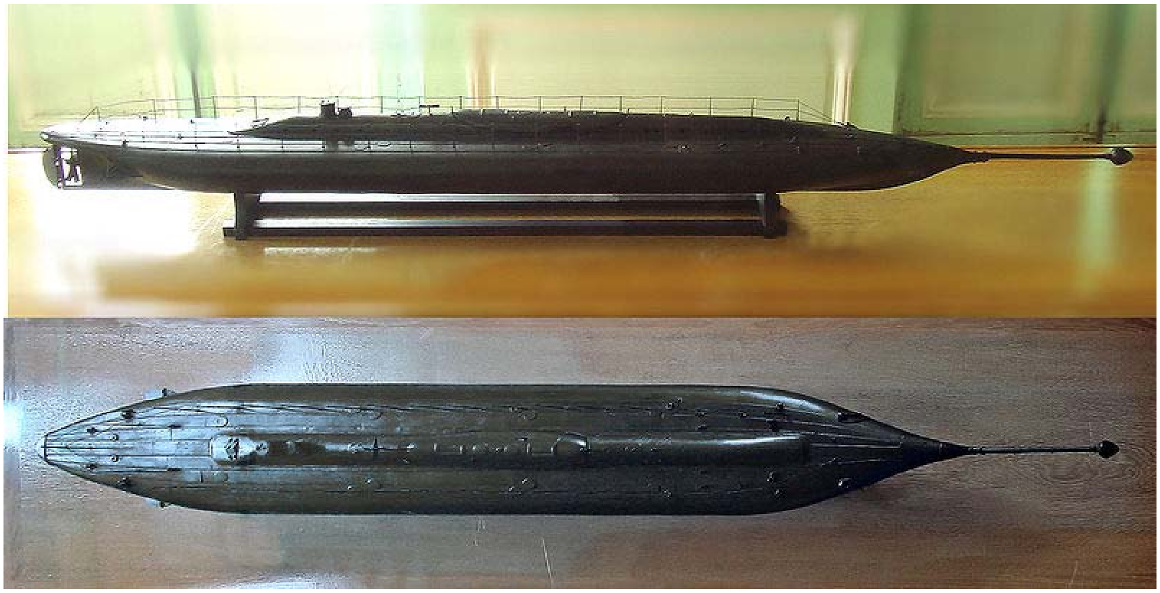
Pneumatic logic is a reliable and functional control method for industrial processes. In recent years, these systems have largely been replaced by electrical control systems, due to the smaller size and lower cost of electrical components. Pneumatic devices are still used in processes where compressed air is the only energy source available or upgrade cost, safety, and other considerations outweigh the advantage of modern digital control.

Chapter 2

Pneumatic Motor



The Victor Tatin airplane of 1879 used a compressed-air engine for propulsion. Original craft, at Musée de l'Air et de l'Espace.



The first mechanically-powered submarine, the 1863 *Plongeur*, used a compressed-air engine. Musée de la Marine (Rochefort).

A **pneumatic motor** or **compressed air engine** is a type of motor which does mechanical work by expanding compressed air. Pneumatic motors generally convert the compressed air to mechanical work through either linear or rotary motion. Linear motion can come from either a diaphragm or piston actuator, while rotary motion is supplied by either a vane type air motor or piston air motor.

Pneumatic motors have existed in many forms over the past two centuries, ranging in size from hand held turbines to engines of up to several hundred horsepower. Some types rely on pistons and cylinders, others use turbines. Many compressed air engines improve their performance by heating the incoming air, or the engine itself. Pneumatic motors have found widespread success in the hand-held tool industry and continual attempts are being made to expand their use to the transportation industry. However, pneumatic motors must overcome inefficiencies before being seen as a viable option in the transportation industry.

Classification

Linear

In order to achieve linear motion from compressed air, a system of pistons is most commonly used. The compressed air is pumped into an air-tight chamber that houses the shaft of the piston. Also inside this chamber a spring is coiled around the shaft of the piston in order to hold the chamber completely open when air is not being pumped into the chamber. As air is pumped into the chamber the force on the piston shaft begins to overcome the force being exerted on the spring. As more air is pumped into the chamber, the pressure increases and the piston begins to move down the chamber. When it reaches its maximum length the air pressure is released from the chamber and the spring completes the cycle by closing off the chamber to return to its original position.

Piston motors are the most commonly used in hydraulic systems. Essentially, piston motors are the same as hydraulic pumps except they are used to convert hydraulic energy into mechanical energy. Piston motors are often used in series of two, three, four, five, or six cylinders that are enclosed in a housing. This allows for more power to be delivered by the pistons because several motors are in sync with each other at certain times of their cycle.

Rotary

Another type of pneumatic motor, known as a rotary vane motor, uses air to produce rotational motion to a shaft. The rotating element is a slotted rotor which is mounted on a drive shaft. Each slot of the rotor is fitted with a freely sliding rectangular vane. The vanes are extended to the housing walls using springs, cam action, or air pressure, depending on the motor design. Air is pumped through the motor input which pushes on the vanes creating the rotational motion of the central shaft. Rotation speeds can vary between 100 and 25,000 rpm depending on several factors which including the amount of air pressure at the motor inlet and the diameter of the housing.

Rotary motion vane-type air motors are used to start large industrial diesel or natural gas engines. Stored energy in the form of compressed air, nitrogen or natural gas enters the sealed motor chamber and exerts pressure against the vanes of a rotor. Much like a windmill, this causes the rotor to turn at high speed. Because the engine flywheel requires a great deal of torque to start the engine, reduction gears are used. Reduction gears to create high torque levels with the lower amounts of energy input. These reduction gears allow for sufficient torque to be generated by the engine flywheel while it is engaged by the pinion gear of the air motor or air starter.

Application

A widespread application of small pneumatic motors is in hand-held tools, power ratchet wrenches, drills, sanders, grinders, cutters, and so on. Though overall energy efficiency of pneumatics tools is low and they require access to a compressed-air source, there are several advantages over electric tools. They offer greater power density (a smaller pneumatic motor can provide the same amount of power as a larger electric motor), do not require an axillary speed controller (adding to its compactness), generate less heat, and can be used in more volatile atmospheres as they do not require electric power.

Historically, many individuals have tried to apply pneumatic motors to the transportation industry. Guy Negre, CEO and founder of Zero Pollution Motors, has pioneered this field since the late 1980s. Recently Engineair has also developed a rotary motor for use in automobiles. Engineair places the motor immediately beside the wheel of the vehicle and uses no intermediate parts to transmit motion which means almost all of the motor's energy is used to rotate the wheel.

History in transportation

The pneumatic motor was first applied to the field of transportation in the mid-19th century. Though little is known about the first recorded compressed-air vehicle, it is said that the Frenchmen Andraud and Tessie of Motay ran a car powered by a pneumatic motor on a test track in Chaillot, France, on July 9, 1840. Although the car test was reported to have been successful, the pair didn't explore further expansion of the design.

The first successful application of the pneumatic motor in transportation was the Mekarski system air engine used in locomotives. Mekarski's innovative engine overcame cooling that accompanies air compression by heating air in a small boiler prior to use. The Tramway de Nantes, located in Nantes, France, was noted for being the first to use Mekarski engines to power their fleet of locomotives. The tramway began operation on December 13, 1879, and continues to operate today, although the pneumatic trams were replaced in 1917 by more efficient and modern electrical trams.

American Charles Hodges also found success with pneumatic motors in the locomotive industry. In 1911 he designed a pneumatic locomotive and sold the patent to the H. K. Porter Company in Pittsburgh for use in coal mines. Because pneumatic motors do not use combustion they were a much safer option in the coal industry.

Many companies claim to be developing Compressed air cars, but none are actually available for purchase or even independent testing.

Tools

Impact wrenches, drills, firearms, die grinders, dental drills and other pneumatic tools use a variety of air engines or motors. These include vane type pumps, turbines and pistons.

Torpedoes

Most successful early forms of self propelled torpedoes used high pressure compressed air, although this was superseded by internal or external combustion engines, steam engines, or electric motors.

Railways

Pneumatic Locomotive with attached pressure container used during the construction of the Gotthard Rail Tunnel 1872-1880.

A compressed air locomotive by H. K. Porter, Inc., in use at the Homestake Mine, South Dakota, between 1928 and 1961

Compressed air engines were used in trams and shunters, and eventually found a successful niche in mining locomotives, although eventually they were replaced by electric trains, underground. Over the years designs increased in complexity, resulting in a triple expansion engine with air-to-air reheaters between each stage.

Aircraft

Transport category airplanes, such as commercial airliners, use compressed air starters to start the main engines. The air is supplied by the load compressor of the aircraft's auxiliary power unit, or by ground equipment.

Automotive

There is currently some interest in developing air cars. Several engines have been proposed for these, although none have demonstrated the performance and long life needed for personal transport.

Energine

The Energine Corporation is a South Korean company that delivers fully-assembled cars running on a hybrid compressed air and electric engine. The compressed-air engine is used to activate an alternator, which extends the autonomous operating capacity of the car.

EngineAir

EngineAir, an Australian company, is making a rotary engine powered by compressed air, called The Di Pietro motor. The Di Pietro motor concept is based on a rotary piston. Different from existing rotary engines, the Di Pietro motor uses a simple cylindrical rotary piston (shaft driver) which rolls, with little friction, inside the cylindrical stator.

It can be used in boat, cars, carriers and other vehicles. Only 1 psi (≈ 6,8 kPa) of pressure is needed to overcome the friction. The engine was also featured on the ABC's New Inventors program in Australia on the 24th March, 2004.

K'Airmobiles

K'Airmobiles vehicles were intended to be commercialized from a project developed in France in 2006-2007 by a small group of researchers. However, the project has not been able to gather the necessary funds.

People should note that, meantime, the team has recognized the physical impossibility to use on-board stored compressed air due to its poor energy capacity and the thermal losses resulting from the expansion of the gas.

These days, using the patent pending 'K'Air Generator', converted to work as a compressed-gas motor, the project should be launched in 2010, thanks to a North

American group of investors, but for the purpose of developing first a green energy power system.

MDI

In the original Nègre air engine, one piston compresses air from the atmosphere to mix with the stored compressed air (which will cool drastically as it expands). This mixture drives the second piston, providing the actual engine power. MDI's engine works with constant torque, and the only way to change the torque to the wheels is to use a pulley transmission of constant variation, losing some efficiency. When vehicle is stopped, MDI's engine had to be on and working, losing energy. In 2001-2004 MDI switched to a design similar to that described in Regusci's patents, which date back to 1990.

It has been reported in 2008 that Indian car manufacturer Tata was looking at an MDI compressed air engine as an option on its low priced Nano automobiles. Tata announced in 2009 that the compressed air car was proving difficult to develop due to its low range and problems with low engine temperatures.

Quasiturbine

The **Pneumatic Quasiturbine** engine is a compressed air pistonless rotary engine using a rhomboidal-shaped rotor whose sides are hinged at the vertices.

The Quasiturbine has demonstrated as a pneumatic engine using stored compressed air

It can also take advantage of the energy amplification possible from using available external heat, such as solar energy.

The Quasiturbine rotates from pressure as low as 0.1 atm (1.47psi).

Since the Quasiturbine is a pure expansion engine, while the Wankel and most other rotary engines are not, it is well-suited as a compressed fluid engine, air engine or air motor.

Regusci

Armando Regusci's version of the air engine couples the transmission system directly to the wheel, and has variable torque from zero to the maximum, enhancing efficiency. Regusci's patents date from 1990.

Team Psycho-Active

Psycho-Active is developing a multi-fuel/air-hybrid chassis which is intended to serve as the foundation for a line of automobiles. Claimed performance is 50 hp/litre.

Defunct Air Engine Designs

Conger Motor

Milton M. Conger in 1881 patented and supposedly built a motor that ran off compressed air or steam that using a **flexible tubing** which will form a wedge-shaped or inclined wall or abutment in the rear of the tangential bearing of the wheel, and propel it with greater or less speed according to the pressure of the propelling medium.

Chapter 3

Lego Pneumatics

Lego Pneumatics	
Parent theme	Lego Technic
Availability	1984–
Total sets	Pneumatics Add-On Set (W979641) & Pneumatics Extension Pack (W991462)

Lego Pneumatic Components

Lego pneumatics is a variety of Lego bricks which use air pressure and specialised components to perform various actions using the principles of pneumatics.

History

The LEGO pneumatics components were first introduced as part of the LEGO Technic range in 1984. Since their introduction, LEGO pneumatics have featured in a variety of LEGO Technic and LEGO Educational (DACTA) products.

Generation 1

The first generation of LEGO Pneumatics ran from 1984 through 1988. This generation was simple compared to the later generations. The pneumatic cylinders, for example, only had one input valve. This meant that in a simple pump->switch->cylinder setup, the cylinder rod could only push outwards, requiring gravity to pull it back in.

A pneumatic distribution block piece was utilised (along with a switch) in order to enable pulling as well by creating vacuum instead of pressure in the cylinder, however, this had limitations and often made pneumatic circuits quite complex.

Generation 2

In 1989, the LEGO pneumatic line was revamped, and a new cylinder and pump piece were introduced. The old cylinders and pumps were discontinued. The chief difference is that the new cylinder had two input valves now, which allowed both pushing and pulling without needing complex circuits involving the distribution block piece.

Over the years, several new pieces were introduced in this line as well. The new pump was spring based, and could only be operated by hand, which limited pneumatic power to how fast it could be manually pumped. This obviously limited the power of pneumatic circuits. So in 1992, LEGO introduced two new pieces; a small pump and a small cylinder. The small pump did not have a spring on it, and it was designed to be operated by a motor, which would allow for continuously-running pneumatic creations. As of 2011, the small pump has only appeared in two model sets — 8868 Air Tech Claw Rig (1992) and 8049 Tractor with Log Loader (2010) (both found on Peeron) — and a few parts sets (no longer available).

In 1997, LEGO introduced the Air Tank, which acts like a battery, storing compressed air so that even more powerful pneumatic circuits can be created. This piece is very popular with the enthusiast community, but many feel that it was underutilised by LEGO, as it only appeared in 3 model sets and a parts pack. This tank is now only available at the LEGO Education Store, along with a new manometer part.

In 2003, LEGO discontinued the old cylinder and switch parts, and made new "studless" versions to fit in with their transition towards removing studs from Technic sets.

Linear Actuator

Beginning 2008, LEGO has released several sets with mechanical linear actuators, which are used for the same purpose as the pneumatic cylinders, but the fact that they can easily be extended to intermediate points means that they approximate hydraulic cylinders more closely.

Lego pneumatics components

The key components of Lego pneumatics are:

Pneumatic pump

There are three versions of the pump. The old Generation 1 pump, the new Generation 2 pump (both of these are spring-loaded) and the small pump without a spring (designed for use with motors). The Gen. 1 pump is red, while the Gen. 2 pump is yellow and has a larger contact pad at the top of the pump.

Pumps are the primary source of air in a pneumatic circuit.

Pneumatic cylinder

Cylinders look like pumps, but they are the outputs of the energy, rather than the inputs. There are five versions of cylinders. The Generation 1 cylinders came in two lengths, only had one input and thus were limited in how they could be used. The Generation 2 cylinders have 2 inputs (and come in studded, studless, and small versions), and allow pushing and pulling, depending on which input air is pumped into.

Pneumatic switch

Switches have three ports on them, and a Lego axle which controls which of the ports are connected to each other.

Switch	Left Port	Middle Port	Right Port
Left position	Open	Connected to Right	Connected to Center
Middle Position	Closed	Closed	Closed
Right position	Connected to Center	Connected to Left	Open

When a port is "open", that means it is like an open tire valve; all the air will leak out as fast as it can. When a port is closed, no air can enter or leave that port. When ports are connected, air will freely travel through the switch between those two ports.

Pneumatic tubing

Tubing is simply the means by which air power is transferred through the circuit. Tubing can connect to a switch, air tank, T-junction, cylinder, pump, distribution block, or flex-hose.

Flex-hoses aren't actually considered pneumatic pieces; they were designed as part of the Technic system for a different purpose, but Lego fans have discovered that pneumatic tubing actually fits over flex hoses pretty well, so many people use them as tubing extenders whenever they are needed. Flex hoses are more rigid than tubing.

Lego pneumatic tubing almost always comes with sets in an uncut form, and are required to be cut into smaller pieces using scissors. On the new 8049 technic tractor and log loader, the tubes are already cut to size.

Pneumatic T-junction

A T-junction is a very small piece that allows three pieces of tubing to connect into one junction, essentially splitting (or joining) airflow from two hoses into one. These only allow 1:2 branching, but by combining T-junctions, any number of branches can be achieved (ie: one tube can branch into three by using two T-junctions).

Air tank

Air tanks are an important piece to most larger pneumatic designs, as they allow air power to be easily stored for later retrieval.

In 2006, Lego has discontinued this piece.

In 2008 Lego Education has re-released the tank in a new white color, as part of an add-on set (W979641)

Pneumatic distribution block

These pieces used a special kind of one-way valve inside of them, and three ports on the outside. The leftmost port could only have air going into it, no air would ever come out. The middle port could have air going in or out. The right port could only have air coming out of it, no air could go into it.

Using these, it was possible to make the Generation 1 cylinders pull down as well as push up, however the pulling wasn't as strong as the pushing, and this prompted Lego to redesign the pneumatics into an easier-to-use and stronger system.

These were discontinued when Lego switched to Generation 2, in 1988.

Pneumatic principles

Lego pneumatics offer the opportunity to learn and experiment with the principles of pneumatics and control circuits. Advanced use of Lego pneumatics has been made in various Lego Mindstorms creations.

Lego pneumatic projects usually include a compressor made from a combination of a lego electric motor and pneumatic pump, together with a pressure switch which will activate the motor when greater pressure is required.

Because a slight delay is involved between increased pressure and cylinder movement, various feedback loops can be used whereby one pneumatic component can activate another in a series of mechanical events.

Lego pneumatics can be configured in such a way that electronic circuits can be replicated. These circuits can then be combined to create digital computers.

Alternative pneumatic systems

Fischertechnik offers a similar pneumatics system for robotic and control technology hobbyists. The Fischertechnik system includes an electrically activated air solenoid, a feature not available in the Lego range.

A number of hobbyists have also constructed additional components such as larger air tanks and solenoids to complement the standard Lego pneumatic components.

Chapter 4

Electro-Pneumatic Action and Tubular-Pneumatic Action

Electro-pneumatic action

The **electro-pneumatic action** is a control system for pipe organs, whereby air pressure, controlled by an electric current and operated by the keys of an organ console, opens and closes valves within wind chests, allowing the pipes to speak. This system also allows the console to be physically detached from the organ itself. The only connection was via an electrical cable from the console to the relay, with some early organ consoles utilizing a separate wind supply to operate combination pistons.

Invention

Although early experiments with Barker lever, tubular-pneumatic and electro-pneumatic actions date as far back as the 1850s, credit for a feasible design is generally given to the English organist and inventor, Robert Hope-Jones. He overcame the difficulties inherent in earlier designs by including a rotating centrifugal air blower and replacing banks of batteries with a DC generator, which provided electrical power to the organ. This allowed the construction of new pipe organs without any physical linkages whatsoever. Previous organs used tracker action, which requires a mechanical linkage between the console and the organ windchests, or tubular-pneumatic action, which linked the console and windchests with a large bundle of lead tubing.

Operation

When an organ key is depressed, an electric circuit is completed by means of a switch connected to that key. This causes a low-voltage current to flow through a cable to the windchest, upon which a rank, or multiple ranks of pipes are set. Within the chest, a small electro-magnet associated with the key that is pressed becomes energized. This causes a very small valve to open. This, in turn, allows wind pressure to activate a bellows or "pneumatic" which operates a larger valve. This valve causes a change of air pressure within a channel that leads to all pipes of that note. A separate "stop action" system is used to control the admittance of air or "wind" into the pipes of the rank or ranks selected by the organist's selection of stops, while other ranks are "stopped" from playing. the stop action can also be an electro-pneumatic action, or may be another type of action

This pneumatically assisted valve action is in contrast to a direct electric action in which each pipe's valve is opened directly by an electric solenoid which is attached to the valve.

Advantages and Disadvantages

The console of an organ which uses either type of electric action is connected to the other mechanisms by an electrical cable. This makes it possible for the console to be placed in any desirable location. It also permits the console to be movable, or to be installed on a "lift", as was the practice with theater organs.

While many consider tracker action organs to be more sensitive to the player's control, others find some tracker organs heavy to play and tubular-pneumatic organs to be sluggish, and so prefer electro-pneumatic or direct electric actions.

An electro-pneumatic action requires less current or amperage to operate than a direct electric action. This causes less demand on switch contacts. An organ using electro-pneumatic action was more reliable in operation than early direct electric organs until improvements were made in direct electric components.

A disadvantage of an electro-pneumatic organ is its use of large quantities of thin perishable leather, usually lambskin. This requires an extensive "re-leathering" of the windchests every twenty-five to forty years depending upon the quality of the material used, the atmospheric conditions and the use of the organ.

Like tracker and tubular action, electro-pneumatic action is less flexible in operation than direct electric action, in which each rank operates independently, allowing "unification", where each individual rank on a windchest can be played at various octave ranges.

A drawback to older electric action organs was the large amount of wiring required for operation. With each stop tab and key being wired, the transmission cable could easily contain several hundred wires. The great number of wires required between the keyboards, the banks of relays and the organ itself, with each solenoid requiring its own signal wire, made the situation worse, especially if a wire was broken (this was particularly true with consoles located on lifts and/or turntables), which made tracing the break very difficult.

These problems increased with the size of the instrument, and it would not be unusual for a particular organ to contain over a hundred miles of wiring. The largest pipe organ in the world, the Boardwalk Hall Auditorium Organ, is said to contain more than 137,500 miles (221,300 km) of wire. Modern electronic switching has largely overcome these physical problems.

Modern methods

In the years after the advent of the transistor, and later, integrated circuits and microprocessors, miles of wiring and electro-pneumatic relays have given way to electronic and computerized control and relay systems, which have made the control of pipe organs much more efficient. But for its time, the electro-pneumatic action was considered a great success, and even today modernized versions of this action are used in many new pipe organs.

Tubular-pneumatic action

"Tubular-pneumatic action" refers to an apparatus used in many pipe organs built during the late 19th and early 20th centuries. The term "tubular" refers to the extensive use of lead tubing to connect the organ's console to the valves that control the delivery of "wind" (air under pressure) to the organ's pipes. Many such organs are extant 100 or more years after their construction.

Lead tubing of a 1910 Möller tubular-pneumatic pipe organ.

Description

In any organ, each pipe has a valve located at its foot which responds to the organist's commands from the console's keyboard, pedalboard and stop controls. These valves are contained in windchests upon which the organ's pipework is set. Any type of apparatus that connects an organ's console with its windchest is referred to as its "action". An organ that utilizes tubular-pneumatic action is commonly called a "tubular-pneumatic organ".

Invention

Until the advent of the tubular-pneumatic action, all organs used a system of levers and wooden rods called trackers to transmit the action of the keys and stops to the valves contained within the windchests. This necessitated a close proximity between the console and the chests. In 1845, Prosper-Antoine Moitessier, an organ-builder of Montpellier, France, patented the tubular-pneumatic system which allowed the console to be at a much greater distance from the organ pipes. Cavaillé-Coll, Henry Willis and Edwin Horsell Pulbrook were pioneers in perfecting and introducing the pneumatic action. The development of the tubular-pneumatic type of organ marked the first departure from the tracker organ style of construction that had been used for hundreds of years.

Operation

The operation of a tubular-pneumatic organ is accomplished by a change of air pressure within lead tubes of about $\frac{1}{4}$ in (0.6 cm) inside diameter that connect the organ's console to its windchest. A separate tube is needed for each manual key, pedal key and stop control on the console. A large four manual organ can require over 300 individual tubes.

Two basic types of tubular-pneumatic actions were used: the "pressure" system and the more popular "exhaust" system. Both use three major components for each key and stop: a valve (within the console), a pneumatic (within the windchest), and a lead tube that connects them.

In the pressure system, the air in the tube and the pneumatic are normally at atmospheric pressure. Depressing a key increases the pressure in the tube, inflating the pneumatic, which opens the pipe's valve.

In the exhaust system, the pneumatic and tube normally contain windchest pressure. Depressing a key lets this pressure exhaust, which collapses the pneumatic and opens the pipe's valve.

Advantages and Disadvantages

The advantages of the tubular-pneumatic action over the mechanical tracker action are a lightness of touch and the flexibility of console location. Although the latter was a great improvement over the tracker organ, the console location was still limited to around 50 ft (20 m) from the pipework.

While some considered the tubular-pneumatic action to be a great achievement in organ building, others thought just the opposite. Sir John Stainer, organist at St. Paul's, called it a "triumph of mechanical skill", while the eminent English organist W. T. Best called it "a complete failure; you cannot play a triplet on the Trumpet, and I consider it the most damnnable invention ever placed inside an organ".

The major disadvantage of tubular-pneumatic action is its sluggish response. This becomes more prevalent as the distance between the console and the pipework is increased. In organs whose divisions are located at various distances from the console, this slow response causes an undesirable time lag between the speech of the divisions.

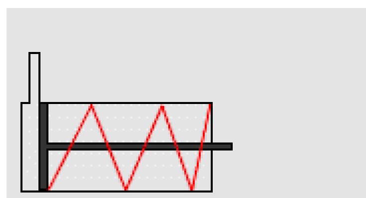
Another disadvantage over a tracker action organ is a lack of "feel" and control of attack by the organist, a trait that is present in all non-tracker action organs.

Decline of usage

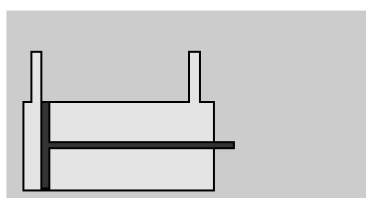
With the application of electric power to pipe organ action, the use of tubular-pneumatic action quickly declined. An organ with electro-pneumatic action or direct electric action has the lightness of touch of a tubular-pneumatic organ, but a faster response, and the console can be in any remote location. The console can also be movable, with only a cable connecting it to the rest of the organ.

Chapter 5

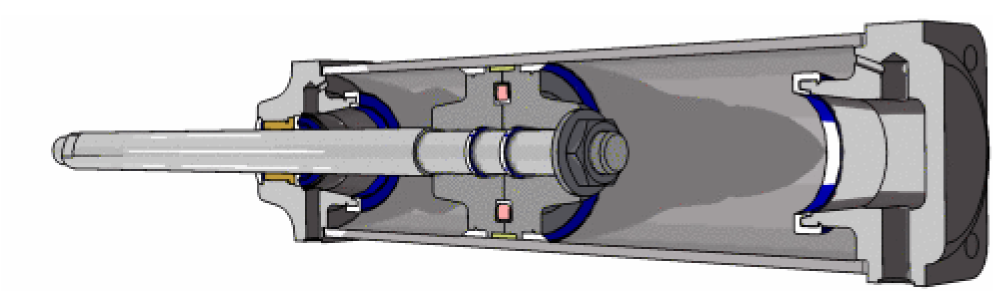
Pneumatic Cylinder



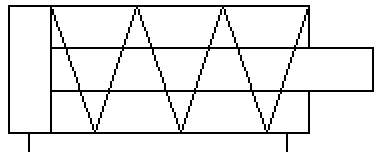
Operation diagram of a single acting cylinder. The spring (red) can also be outside the cylinder, attached to the item being moved.



Operation diagram of a double acting cylinder



Pneumatic cylinder (CAD)



Schematic symbol for pneumatic cylinder with spring return

Pneumatic cylinders (sometimes known as **air cylinders**) are mechanical devices which produce force, often in combination with movement, and are powered by compressed gas (typically air).

To perform their function, pneumatic cylinders impart a force by converting the potential energy of compressed gas into kinetic energy. This is achieved by the compressed gas being able to expand, without external energy input, which itself occurs due to the pressure gradient established by the compressed gas being at a greater pressure than the atmospheric pressure. This air expansion forces a piston to move in the desired direction. The piston is a disc or cylinder, and the piston rod transfers the force it develops to the object to be moved.

A note about popular terminology

At least in the USA, popular usage sometimes refers to the whole assembly of cylinder, piston, and piston rod (or more) collectively as a "piston", which is incorrect. See, for instance, "Hydraulic piston raises the table from 19 (in.) to 26 (in.)" Marine Tables, Inc. (Select item 3 of 8, near the bottom.)

Operation

General

Once actuated, compressed air enters into the tube at one end of the piston and, hence, imparts force on the piston. Consequently, the piston becomes displaced (moved) by the compressed air expanding in an attempt to reach atmospheric pressure.

Fail safe mechanisms

Pneumatic systems are often found in settings where even rare and brief system failure is unacceptable. In such situations locks can sometimes serve as a safety mechanism in case of loss of air supply (or its pressure falling) and, thus, remedy or abate any damage arising in such a situation. Due to the leakage of air from input or output reduces the pressure and so the desired output.

Types

Although pneumatic cylinders will vary in appearance, size and function, they generally fall into one of the specific categories shown below. However there are also numerous other types of pneumatic cylinder available, many of which are designed to fulfill specific and specialised functions.

Single acting cylinders

Single acting cylinders (SAC) use the pressure imparted by compressed air to create a driving force in one direction (usually out), and a spring to return to the "home" position.

Double acting cylinders

Double Acting Cylinders (DAC) use the force of air to move in both extend and retract strokes. They have two ports to allow air in, one for outstroke and one for instroke.

Other types

Although SACs and DACs are the most common types of pneumatic cylinder, the following types are not particularly rare:

- Rotary air cylinders: actuators that use air to impart a rotary motion
- Rodless air cylinders: These have no piston rod. They are actuators that use a mechanical or magnetic coupling to impart force, typically to a table or other body that moves along the length of the cylinder body, but does not extend beyond it.

Rodless cylinders

Some rodless types have a slot in the wall of the cylinder. That slot is closed off for much of its length by two flexible metal sealing bands. The inner one prevents air from escaping, while the outer one protects the slot and inner band. The piston is actually a pair of them, part of a comparatively long assembly. They seal to the bore and inner band at both ends of the assembly. Between the individual pistons, however, are camming surfaces that "peel off" the bands as the whole sliding assembly moves toward the sealed volume, and "replace" them as the assembly moves away from the other end. Between the camming surfaces is part of the moving assembly that protrudes through the slot to move the load. Of course, this means that the region where the sealing bands are not in contact is at atmospheric pressure.

Another type has cables (or a single cable) extending from both (or one) end[s] of the cylinder. The cables are jacketed in plastic (nylon, in those referred to), which provides a smooth surface that permits sealing the cables where they pass through the ends of the cylinder. Of course, a single cable has to be kept in tension. .

Still others have magnets inside the cylinder, part of the piston assembly, that pull along magnets outside the cylinder wall. The latter are carried by the actuator that moves the load. The cylinder wall is thin, to ensure that the inner and outer magnets are near each other. Multiple modern high-flux magnet groups transmit force without disengaging or excessive resilience.

Sizes

Air cylinders are available in a variety of sizes and can typically range from a small 2.5 mm air cylinder, which might be used for picking up a small transistor or other electronic component, to 400 mm diameter air cylinders which would impart enough force to lift a car. Some pneumatic cylinders reach 1000 mm in diameter, and are used in place of hydraulic cylinders for special circumstances where leaking hydraulic oil could impose an extreme hazard.

Pressure, radius, area and force relationships

Although the diameter of the piston and the force exerted by a cylinder are related, they are not directly proportional to one another. Additionally, the typical mathematical relationship between the two assumes that the air supply does not become saturated. Due to the effective cross sectional area reduced by the area of the piston rod, the instroke force is less than the outstroke force when both are powered pneumatically and by same supply of compressed gas.

The relationship, between force on outstroke, pressure and radius, is as follows:

$$F = p(\pi r^2)$$

Cord

This is derived from the relationship, between force, pressure and **effective** *cross-sectional area*, which is:

F = p A\,

With the same symbolic notation of variables as above, but also *A* represents the effective cross sectional area.

On instroke, the same relationship between force exerted, pressure and *effective cross sectional area* applies as discussed above for outstroke. However, since the cross sectional area is less than the piston area the relationship between force, pressure and *radius* is different. The calculation isn't more complicated though, since the effective cross sectional area is merely that of the piston less that of the piston rod.

For instroke, therefore, the relationship between force exerted, pressure, radius of the piston, and radius of the piston rod, is as follows:

$$F = p(\pi r_1^2 - \pi r_2^2) = p\pi(r_1^2 - r_2^2)$$

Where:

F represents the force exerted
r_1 represents the radius of the piston
r_2 represents the radius of the piston rod
π is pi, approximately equal to 3.14159.

Materials

The pneumatic cylinders designed for educational use typically have transparent outer sleeves (often plexiglass), so students can see the piston moving inside.

The pnuematic cylinders designed for cleanroom applications often use lubricant-free Pyrex glass pistons sliding inside graphite sleeves.

Chapter 6

Spud Gun

A pneumatic potato cannon

A **potato cannon** (also known as a *spud gun*) is a pipe-based cannon which uses air pressure (*pneumatic*), or *combustion* of a gaseous fuel, to launch projectiles at high speeds. They are built to fire chunks of potato, as a hobby, or to fire other sorts of projectiles, for practical use. The projectile can be dangerous and result in life-threatening injuries, including cranial fractures, if a person is hit.

Launcher types

All spud guns propel projectiles down their barrels using pressurised gas in the same manner as a firearm (although at a much lower pressure). There are four basic ways that spud guns may achieve this:

- By the combustion of a gaseous fuel-air mixture; this is generally called a **combustion launcher**, and its pressure is limited primarily by the energy density of the fuel-air mixture (less than 100 psi (0.7 MPa) with all safe fuels).
- By the release of compressed gas (normally air) through a valve; such a launcher is typically referred to as a **pneumatic launcher**, and its power is limited primarily by the pressure of the air supply, be that from a compressor, manual pump or bottled gas.
- By the explosion of a dry ice bomb placed in the pipe before the projectile, generally referred to as a **dry ice bomb cannon**, these are limited in power by the materials and size of the dry ice bomb but firing pressures can be around 200–300 psi (1.4–2.1 MPa).
- By the combustion of a pre-pressurised fuel-air mixture; this is called a **hybrid launcher**, and yields higher pressures than that of a normal combustion spud gun, limited only by the construction of the launcher (generally a few hundred pounds-force per square inch).

Combustion launchers

Combustion powered spud guns typically have the least complex designs, the four basic elements of which are:

- A fuel system
- A combustion chamber
- An ignition source
- A barrel

In order to fire, the operator loads a projectile into the barrel, adds fuel to the combustion chamber (for example aerosols or propane), and triggers the ignition source (often using a piezoelectric BBQ igniter). The fuel then ignites, creating hot expanding gases, and forcing the projectile out of the barrel. Distances vary greatly depending on many factors, including the type of fuel used, the efficiency of the fuel/air ratio, the combustion chamber/barrel ratio, and the flight characteristics of the projectile. Common distances vary from 100 to 200 metres (110 to 220 yd), and there is a reported case of a cannon exceeding 500 metres (550 yd) of range.

Advanced combustion launchers may include metered propane injection to ensure proper fueling, chamber fans to mix the fuel with the air and accelerate venting of the chamber after firing, multiple spark gaps (spark strips) to decrease combustion time, and high-voltage ignition sources (flyback circuits, stun guns, camera flashes, etc.).

Combustion launchers are usually less powerful than their pneumatic or hybrid counterparts.

Pneumatic launchers

A large pneumatic design: The projectile is loaded in the muzzle (not pictured), which is then attached to the cannon (at 2). The air reservoir (3) is filled to 120 psi (0.83 MPa) using the Schrader valve (4). Upon opening the solenoid valve (1), the air from the reservoir is transferred to the projectile, which is fired out of the muzzle.

Pneumatic launchers are considered a little more difficult to build due to the need of a completely airtight construction. These cannons have four basic components:

- A filling valve
- An air chamber
- A pressure release valve
- A barrel

In a pneumatic spud gun, air is pumped into the pressure chamber. After the desired chamber pressure is reached, the pressure release valve is opened, allowing the gas to expand down the barrel, propelling the projectile forwards.

The filling valve is usually a commonly available type such as a Schrader or Presta valve but other assemblies to pressurise the cannon such as quick release connections with ball or check valves have been used.

The pressure release valve is often one of a variety of commercially available types such as a plumbing ball valve, an irrigation sprinkler valve or a quick exhaust valve. Experienced builders often make their own valves for this purpose to gain greater flow and faster actuation. The most common custom design used is the piston valve. Multiple valves arranged to be triggered together are occasionally used as an alternative to a single larger valve.

The range of pneumatic cannons is more variable than the range of combustion spud guns due to the increased variation possible in the components. Typical ranges are slightly higher because of the greater power, but the maximum range of some high power pneumatic cannons has been said to be over 1,000 metres (1,100 yd).

Pneumatic spud guns are generally more powerful than combustion spud guns. A typical combustion gun generates average chamber pressures of about 30 psi (210 kPa) with peaks of around 70–100 psi (500–700 kPa), while the average pneumatic gun can operate at pressures in the vicinity of 100 psi (700 kPa). In recent times, it has become increasingly common for metal pneumatic launchers to use even higher pressures, sometimes up to 500 psi (3.4 MPa) or higher

Dry ice launchers

PVC dry ice cannon in use, 1.5kg (3 pounds) of concrete is poured at the bottom to reinforce it, and plastic sleeves are used to stiffen the lower (highest pressure) part.

A dry ice cannon uses the sublimation of solid carbon dioxide to generate the gas pressure to propel a projectile.

The oldest examples simply involve dropping pieces of dry ice into a tube closed at one end and sealing the other end by jamming the projectile in. When the pressure of the carbon dioxide from the subliming dry ice builds high enough, the projectile will be blown out of the tube. The pressures of such devices are not very high as it only needs to build enough to overcome the friction of the projectile jammed in the barrel. Tens of psi is most likely.

A more modern example is the dry ice bomb launcher. A plastic bottle containing water has some dry ice added and is quickly sealed and dropped down a tube closed at one end. A projectile is inserted in after it. The water accelerates the sublimation of the dry ice and the pressure from the carbon dioxide gas produced eventually ruptures the plastic bottle and launches the projectile. The rupturing pressure of a standard plastic soda bottle is between 200 and 300 psi (1.4 and 2.1 MPa) in the open air but when confined in a pipe, it could be higher.

Due to the operation of a dry ice bomb cannon extra safety issues are present:

- The dry ice bomb used for propulsion can achieve bursting pressure in a matter of seconds to hours depending on the quantity of water and dry ice. If too little dry ice, it also may not achieve bursting pressure at all. These timing issues can cause belief that the cannon has failed to fire but attempting to unload the cannon may then provide the extra stress on the bottle needed for it to rupture.
- Piping and any reinforcement of such may be underestimating the high pressure spike when the dry ice bomb explodes and plastic tubing may rupture with such forces
- The recoil of such cannons can be very great due to the high pressure combined with the large internal diameter piping needed for the bottles (5–9 cm; 2–3½ in) resulting in them being ill-suited for hand held firing.

Compared to the operation of other spud guns, dry ice bomb cannons are similar in firing principle to a burst disk cannon of the pneumatic type; the plastic bottle performing the task of the burst disk albeit in a less controlled manner.

Another means of utilising dry ice in spud guns is to use the sublimation of dry ice to create substantial pressure behind a valve, and placing a barrel on the other side of that valve with a projectile loaded into it. Pressures behind the valve can reach upwards of 800 psi (5.5 MPa), and by quickly releasing the valve, the projectile can be launched. Whilst this method is more controllable and in many means safer than utilising a soda bottle as a burst disk (provided pressure rated valves and piping are used), it is limited in that quick release valves, such as ball valves, are generally not bigger in diameter than 1 or 2 inches. Additionally, they cannont be opened as rapidly as a soda bottle will rupture, and consequently there is less immediate airflow. However, this is offset by the fact that such a design can operate at more than double the pressure of a typical dry ice bomb launcher, as soda bottles will rupture at only 200–300 psi (1.4–2.1 MPa).

Hybrid launchers

A hybrid launcher consists of seven basic elements:

- A fuel system (usually metered propane)
- An air filling valve
- One or more pressure gauges
- A high pressure combustion chamber
- A pressure-triggered main valve (burst disk)
- A barrel
- An ignition source

A hybrid combines principles of the combustion and pneumatic spud gun. It uses a pre-pressurised mixture of fuel and air to get more power out of a given chamber volume.

In order to fire, the operator first readies the pressure-triggered valve then injects several times the normal amount of fuel and appropriately more air. When the ignition source is triggered, the pressure from the combustion causes the main valve to open and propels the projectile out of the barrel with the released combustion gases. The hybrid is capable of higher velocities than a combustion or pneumatic spud gun because the pressure generated is higher than that in a combustion gun (for most fuels), and the shock wave moves faster than it can in a pneumatic (for most gases), due to the higher temperature. Projectiles fired by a hybrid have broken the sound barrier.

A hybrid using a fuel and air mix at twice atmospheric pressure is said to be using a 2X mix. Higher mixtures can be used and will produce even higher pressures. The fuel and air needs to be measured and matched carefully to ensure reliable operation; hence the use of accurate air pressure gauges and fuel meters.

Primary materials

Plastics

- PVC-U (Polyvinyl chloride, unplasticized) - Highly popular due to its availability and relatively low cost. PVC pipes are available in a wide variety of sizes and pressure ratings. In industry, however, they are illegal for compressed air applications—if they are damaged under pressure the plastic can fail explosively.

- ABS (Acrylonitrile butadiene styrene) - Another popular plastic piping material, more expensive and less common than PVC but available in the same sizes and pressure ratings. Unlike PVC it is used in compressed air systems as it splits rather than shatters on failure. It also has a greater temperature tolerance (−40 °C to +80 °C, or −40 to 175 °F) compared to 0 °C to +60 °C or 30 to 140 °F for PVC).

Both PVC and ABS piping are also available in forms which are not pressure rated. Use of unrated plastic piping and fittings is a common source of cannon failure and poses a much greater risk to a cannon operator.

Metals

- Steel - The very high pressure rating of steel piping makes it a familiar sight on high-powered hybrid cannons. It is however much more expensive than any other common piping material. The extra weight and joining difficulties are also a consideration.
- Copper - As a common plumbing material, copper pipes and associated fittings are readily available. They have higher pressure ratings and flow compared to similar plastic piping. The drawbacks are that copper is heavier, and up to four times the cost of PVC or ABS pipes of similar external diameters.
- Aluminium - Aluminium is a lightweight metal with good corrosion resistance. Aluminium pipes are sometimes used as barrels on spud guns on their own and machined aluminium is a popular material for particularly unique designs.
- Brass - Often brass fittings are used on spud guns for small parts of the construction like fuel systems, because it is one of the most common materials for small pipe fittings. Occasionally large parts of spud guns are machined entirely out of brass.

Valve types

Manual

- Ball Valve - Made out of either plastic or metal, ball valves are considered inferior by many enthusiasts due to their slow opening times. For those on a tight budget or in low-power setups, ball valves are ideal. Some choose to modify their valves by attaching a pneumatic actuator or spring to achieve a faster opening speed.
- Blowgun - A blowgun is a small hand held device used to blow away debris from a work area and is designed to be used attached to a compressed air line. It uses a sprung poppet valve operated by a lever to allow air through its body and out through a specially shaped nozzle. In spudgunning it is used to pilot larger valves - releasing a small volume of air to allow a piston or diaphragm to fly back and release a much larger volume of air into the barrel. It is also used as the primary valve for small cannons which fire airsoft pellets and so do not require high air flow. Blowguns can be modified to increase airflow.

Electronic

- Sprinkler valve (otherwise known as a solenoid valve) - The use of irrigation sprinkler valves as pneumatic valves has become increasingly popular for spudgunning. These valves are intended to be electronically triggered causing a solenoid to depressurise a diaphragm and allow airflow through. It is also possible to remove the solenoid and, instead, to actuate the valve manually with a blowgun to depressurise the diaphragm. Such modifications allow the valve to open as much as 3 to 5 times faster.

Pneumatic

- Diaphragm valve - A diaphragm valve is used in pneumatic cannons where the barrel is within the air chamber. It is a disk of flexible material mounted directly behind the barrel that seals it when pressure is increased behind the disk. The design is such that air leaks past the diaphragm from behind it to the chamber around the barrel, sealing the soft rubber against the butt of the barrel. Once the chamber is fully pressurised the compressed air behind the diaphragm is quickly vented, causing the centre of the diaphragm to flex backwards, exposing the butt of the barrel to the compressed air inside the chamber, which rapidly exhausts through the barrel, launching the projectile.
- Piston valve - The gold standard of pneumatic spudgunning is the piston valve, due to its extremely high rate of flow and opening speed. It works in an almost identical fashion to a diaphragm valve but replaces the flexible diaphragm with a hard rubber-faced piston. The valve opening is generally as wide as or wider than the barrel diameter, so there is very little constriction of airflow. Piston valves also open much faster than either ball or solenoid valves. However, construction of this type of valve is inherently complex, and some choose to order pre-built valves through the internet.
- Quick Exhaust Valve (QEV) - a commercial piston or diaphragm valve in a metal body intended for the quick venting of pneumatic cylinders. In spudgunning they are ideal barrel sealing valves with faster opening times than custom piston valves and high flow rates. They can be commonly found in sizes from ⅛ inch to 1½ inches (3–40 mm) and sometimes even larger models. It provides an easy option for inexperienced spud-gun builders but the cost is usually greater than for any other valve type.
- Burst Disk Valve - Used in a few pneumatics but primarily in hybrid cannons, burst valves are considered the ideal pressure release mechanism as they allow an unobstructed flow of high pressure air. Burst disks have no moving parts, making them very reliable. They are very appealing for hybrid cannons because they can withstand the low pressure gas mix in the chamber before ignition, yet fail as planned upon successful ignition. The high pressure combustion gases are released into the barrel at a rate which generates greater velocities than a mechanical valve could allow. Pneumatic cannon burst discs work similarly. The disc and projectile are loaded, and the chamber is pressurised until the disc ruptures. Unfortunately, this usually does not give the operators much in the way

of control over timing, although a puncturing mechanism can be used. Burst disks are of no specific material and may consist of plastic or thin sheet metal or foil.

- The Quick Dump Valve is a recent addition to the choices of valves for spudding. A QDV is a spool valve that is balanced under pressure with one end of the spool oriented toward the barrel. The spool is manually unbalanced allowing pressure between the end of the spool and the projectile in the barrel. The air pressure then forces the spool back and the projectile forward. Since the valve is triggered with no pilot pressure, the valve snaps open with no pilot pressure to hinder it. Currently it is not commercially for sale and must be hand built by the hobbyist like most piston valves.

Connections

Welding, soldering and gluing

- Solvent welding - used for similar plastic connections using solvent fittings, the solvent temporarily dissolves the polymer chains of the plastic and the parts to be joined are brought together. On rehardening, the polymer chains from each part are entangled and so form a solid weld.
- Metal welding - used to form strong joints between similar metals by melting the points of connection together. It is an uncommon process in spudgun construction due to the equipment necessary to make the welds.
- Soldering - commonly used in the construction of copper pipe based spudguns, a solder with a lower melting point than the copper is melted and drawn into the gaps between pipe and fitting with capillary action, holding to pipe and fitting with a wetting action before hardening.
- Gluing - the use of epoxy resin in small designs is common for the making of custom parts but it is rare to see glues used for structural connections.
- Duct tape - sometimes used in simple cannons, is unsuitable for sealing any significant pneumatic pressure and if used on a combustion cannon the heat produced can soften the glue and melt the tape, greatly weakening any seal or join it creates.

Mechanical joints

- Compression Fittings - primarily seen on copper pipe spudguns, the compression fitting squeezes a metal ring against the pipe between a nut and the fitting body to form the connection. Easier than solder fittings and requiring only a spanner they are much more expensive and are of greater weight.
- Threaded Fittings - commonly available in BSP or NPT (not interchangeable) they generally require a fitting attached to a pipe by other means to allow screwing into another threaded fitting. The exception to this is steel pipe, the ends of which can have the appropriate thread cut into them.
- Flange joints - on large steel spudguns, pipe and fittings are sometimes bolted together by means of flanges with a gasket sandwiched between them to provide an airtight joint.

- Cam Locks - on spudguns with interchangeable barrels a cam lock is sometimes used to connect barrels to the cannon as it provides a quick and simple solution to switching barrels. Two levers either side of the socket side of the fitting rotate internal cams to lock in or release the plug side of the fitting to which a barrel is attached.

The sound barrier

It is rare for a spud gun to be powerful enough to break the sound barrier, although there are some cases of this happening using specialized designs. The spud guns used are typically hybrids; but some pneumatic cannons have achieved the feat, either by using a special low density gas, such as helium, or high pressures combined with a fast valve. There is also one reported case of a combustion design achieving super-sonic velocities.

The difficulty in breaking the barrier arises from the speed of the particles within the gas. If the projectile is travelling at, or near to that speed, then the gases simply cannot keep up with it to provide the accelerating force. The problem is solved by increasing the speed of the particles, either by:

- Using lighter molecules, as occurs when helium is used in a pneumatic.
- Heating the gases to far higher temperatures, and thus giving them more energy. This allows hybrids and combustions to achieve supersonic velocities.
- Using steel and much higher pressures of 800 psi (5.5 MPa) or more, but achieving these pressures is difficult. CO_2 gas, although it can reach these pressures, is not suitable due to its high density.

Supersonic velocities may theoretically be attained by pneumatics with a sufficiently large "dead space" between the main valve and projectile. The incoming air can raise the pressure rapidly in this dead space, creating high temperatures sometimes sufficient to achieve supersonic velocities. This particular effect has not yet been successfully used, but has been discussed, as both adiabatic and shock heating are documented phenomenons in gases.

The highest projectile speed recorded from a spud gun is 933.3 m/s (3,062 ft/s) (approximately 2.7 times the speed of sound) with a 16.6-gram (256 gr) 20 mm plastic slug from a hybrid using a 1 MPa (150 psi) pre-ignition mixture of air and propane. The highest velocity attained by a potato specifically is approximately 2,700 ft/s (820 m/s).

Practical uses

Although spudguns are created and used for the purpose of recreation there are other devices which work on identical principles in many other fields with more serious uses.

Entertainment

- Promotional sports cannons: Portable pneumatic cannons which run on bottled CO_2 are common at large sports games in the U.S. where they are used to project items such as T-shirts or wrapped food into the audience. They tend to be made of higher quality materials than an average pneumatic spudgun but they use the same methods of operation.
- Special effects cannons: In film and theatre productions pneumatic cannons are often used as a pyrotechnic-free method of material projection. These can vary from simple ball valve, manually operated models to electronically triggered designs operated from a remote control panel depending on the exact requirements.

Industry

A typical propane gun bird scarer.

- Hail cannons: these are very large devices which consist of a combustion chamber and a large funnel shape mounted on top of it. A gas mix is ignited in the combustion chamber and the funnel directs the blast wave upwards. They are intended to protect crops from hail damage by disrupting hail formation with the shock waves. There has however been no scientific proof of their effectiveness.
- Air cannons: This can mean:
    - A pneumatic spudgun

    - Air blaster, a compressed air device to unblock clogging in large storage containers (e.g. silos) for powdery material.
    - Air cannon (mechanics), a compressed air device for creating high pressure shock waves under water
- Bird scarers: these devices are essentially automatic combustion cannons. They require bottled propane gas and a lead-acid battery. At intervals they ignite a propane/air mix to produce a loud explosion (up to 150 decibels close to the device) to scare birds from crop fields or near airport runways.
- Chicken cannons: Many aircraft parts must be able to survive the impact of a bird in flight, known as a birdstrike. Pneumatic guns are used to project a bird, typically a dead chicken, into a product designed to mitigate a birdstrike. Aircraft canopies, engines, and critical flight control surfaces will normally undergo this type of stress testing to determine whether they are strong enough to withstand a birdstrike in flight.

Military

- Combustion light gas guns are weaponised combustion cannons which burn a low molecular weight gas such as hydrogen to provide a higher specific impulse than relatively high molecular weight conventional solid propellants.

Safety

Spud guns by nature are hazardous and can present safety issues if poorly constructed or used.

Users should follow the same rules as if handling a conventional firearm, but given the frequently improvised materials and construction used in spudguns, it is particularly important for the user to use basic ear and eye protection when operating a spudgun.

Legal issues

In some jurisdictions spud guns are outlawed or have restrictions on their use and may require licenses and certification of the gun.

Chapter 7

Pneumatic Tube

Modern day Pneumatic tube terminal used in factories, supermarkets, banks/credit unions and medical facilities

Pneumatic tubes (or **capsule pipelines** or **Lamson tubes**; also known as **Pneumatic Tube Transport** or **PTT**) are systems in which cylindrical containers are propelled through a network of tubes by compressed air or by partial vacuum. They are used for transporting solid objects, as opposed to conventional pipelines, which transport fluids. Pneumatic tube networks gained great prominence in the late 19th and early 20th century for businesses or administrations that needed to transport small but urgent packages (such as mail or money) over relatively short distances (within a building, or, at most, within a city). Some of these systems grew to great complexity, but they were eventually superseded by more modern methods of communication and courier transport, and are now much rarer than before. However, in some settings, such as hospitals, they remain of great use, and have been extended and developed further technologically in recent decades.

A small number of pneumatic transportation systems were also built for larger cargo, to compete with more standard train and subway systems. However, these never gained as much popularity as practical systems.

History

Historical use

Pneumatics can be traced back to Hero of Alexandria in the 1st century AD, though there was apparently no thought of using them to move objects through pipes.

Pneumatic capsule transportation was originally invented by William Murdoch. Though a marvel of the time, and a successful sideshow, it was considered little more than a novelty until the invention of the capsule in 1836. The Victorians were the first to use *capsule pipelines* to transmit telegraph messages, or telegrams, to nearby buildings from telegraph stations.

While they are commonly used for small parcels and documents — now most often used as cash carriers at banks or supermarkets — they were originally proposed in the early 19th century for transport of heavy freight. It was once envisioned that networks of these massive tubes might be used to transport people.

Current use

NASA Mission Control Center during the Apollo 13 mission. Note pneumatic tube canisters in console to the right.

Pneumatic tubes in use at a drive-through bank.

The technology is still used on a smaller scale. While its use for communicating information has been completely superseded by electronic systems, pneumatic tubes are still widely used for transporting small valuable objects, or where convenience and speed in a local environment is useful.

In the United States, a large number of drive-up banks use pneumatic tubes to transport cash and documents between cars and tellers. Most hospitals have a computer-controlled pneumatic tube system to deliver drugs, documents and specimens to and from laboratories and nurses' stations. Many factories use them to deliver parts quickly across large campuses. Many larger stores use systems to securely transport excess cash from checkout stands to back offices, and to send change back to cashiers. NASA's original

Mission Control Center in Houston, Texas had pneumatic tubes connecting controller consoles with staff support rooms. Denver International Airport is noteworthy for the large number of pneumatic tube systems, including a 25 cm diameter system for moving aircraft parts to remote concourses, a 10 cm system for United Airlines ticketing, and a robust system in the parking toll collection system with an outlet at every booth.

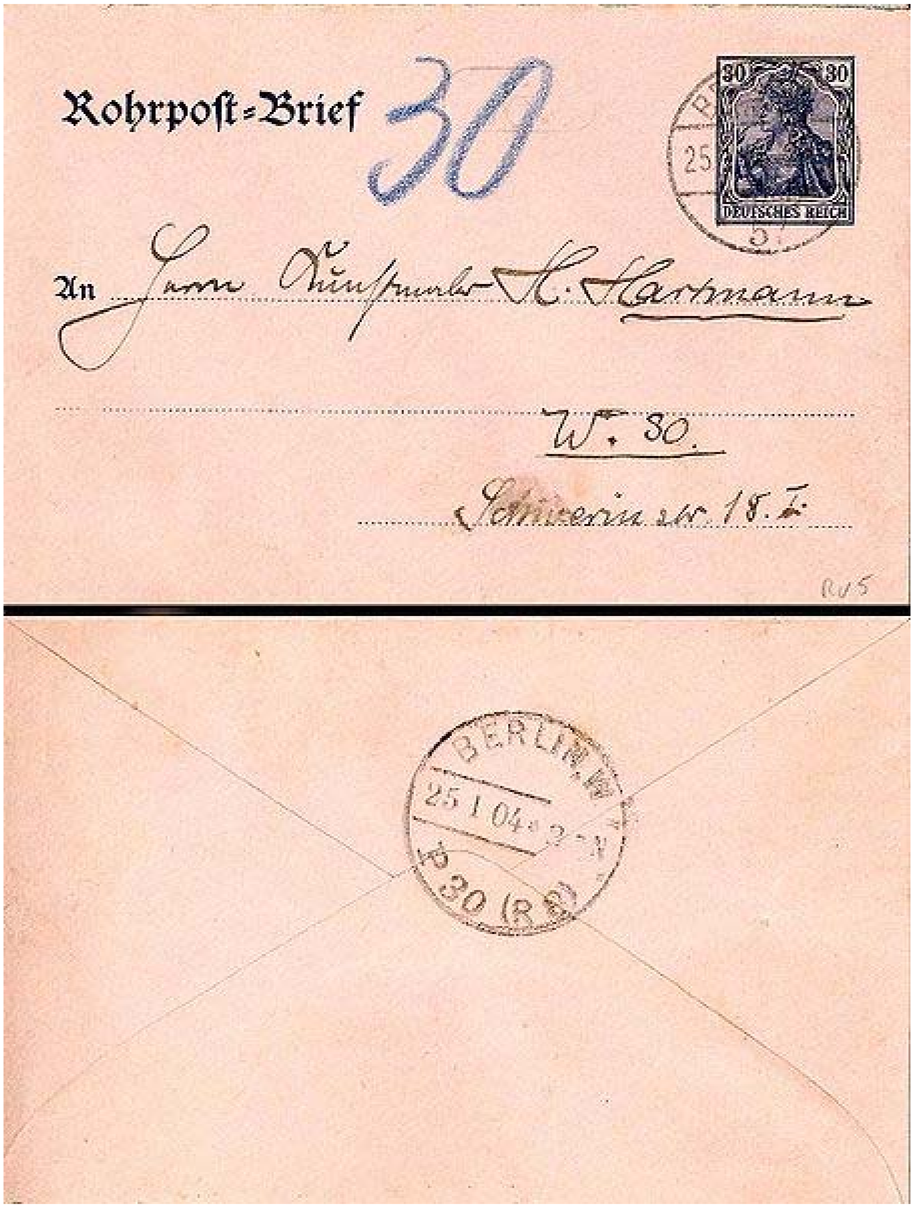
Pneumatic tube systems are used in science, to transport samples during neutron activation analysis. Samples must be moved from the nuclear reactor core, in which they are bombarded with neutrons, to the instrument that records the resulting radiation. As some of the radioactive isotopes in the sample can have very short half-lives, speed is important. These systems may be automated, with a magazine of sample tubes that are moved into the reactor core in turn for a predetermined time, before being moved to the instrument station and finally to a container for storage and disposal.

Until it closed in early 2011, a McDonald's in Edina, MN claimed on its receipts to be the "World's Only Pneumatic Air Drive-Thru," sending food from their strip-mall location to a drive-through in the middle of a parking lot.

In Britain, the House of Commons telephone and computer exchange also has a pneumatic tube system in place.

Usages

In postal service



Pneumatic tube letter from Berlin, Germany, 1904

Pneumatic post or **pneumatic mail** is a system to deliver letters through pressurized air tubes. It was invented by the Scottish engineer William Murdoch in the 19th century and was later developed by the London Pneumatic Despatch Company. Pneumatic post systems were used in several large cities starting in the second half of the 19th century (including an 1866 London system powerful and large enough to transport humans during trial runs - though not intended for the purpose), but were largely abandoned during the 20th century.

It was also speculated that a system of tubes might deliver mail to every home in the US. A major network of tubes in Paris was in use until 1984, when it was finally abandoned in favor of computers and fax machines. In Prague, in the Czech Republic, a network of tubes extending approximately 60 kilometres in length still exists for delivering mail and parcels. Following the 2002 European floods, the Prague system sustained damage, and operation was mothballed indefinitely.

Pneumatic post stations usually connected post offices, stock exchanges, banks and ministries. Italy was the only country to issue postage stamps (between 1913 and 1966) specifically for pneumatic post. Austria, France, and Germany issued postal stationery for pneumatic use.

Typical current applications are in banks and hospitals. Many large retailers use pneumatic tubes to transport cheques or other documents from cashiers to the accounting office.

Historical use

- 1853: linking the London Stock Exchange to the city's main telegraph station (a distance of 220 yards)
- 1861: in London with the London Pneumatic Despatch Company providing services from Euston railway station to the General Post Office and Holborn
- 1865: in Berlin (until 1976), the *Rohrpost*, a system 400 kilometers in total length at its peak in 1940
- 1866: in Paris (until 1984, 467 kilometers in total length from 1934)
- 1875: in Vienna (until 1956)
- 1887: in Prague (until 2002 due to flooding), the Prague pneumatic post
- 1897: in New York City (until 1953)
- other cities: Munich, Rio de Janeiro, Buenos Aires, Hamburg, Rome, Naples, Milan, Marseilles, Melbourne, Boston, Philadelphia, Chicago, St. Louis

In public transportation

19th century

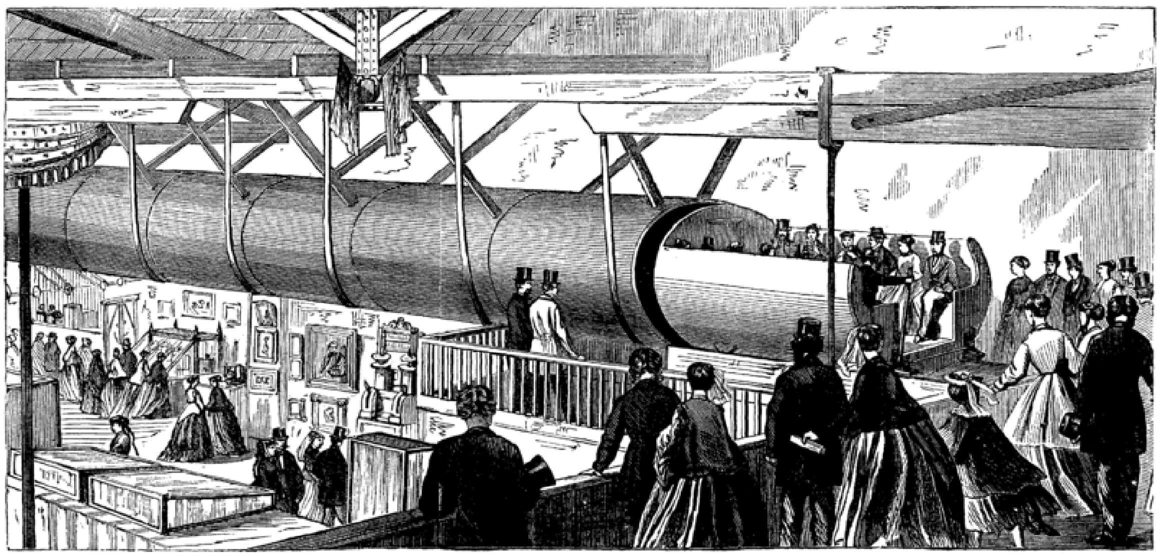
In 1812, George Medhurst first proposed, but never implemented, blowing passenger carriages through a tunnel. Precursors of pneumatic tube systems for passenger transport, the atmospheric railway (for which the tube was laid between the rails, with a piston running in it suspended from the train through a sealable slot in the top of the tube) were operated as follows:

- 1844–54: Dublin and Kingstown Railway's Dalkey Atmospheric Railway between Kingstown (Dún Laoghaire) and Dalkey, Ireland (1.75 mi (3 km))
- 1846–47: London and Croydon Railway between Croydon and New Cross, London, England (7.5 mi (12 km))
- 1847–48: Isambard Kingdom Brunel's South Devon Railway between Exeter and Newton Abbot, England (20 mi (32 km))

- 1847–60: Paris–Saint-Germain railway between Bois de Vésinet and Saint-Germain-en-Laye, France (2 km (1 mi))

In 1861, the **London Pneumatic Despatch Company** built a system large enough to move a person, although it was intended for parcels. The inauguration of the new Holborn Station on 10 October 1865 was marked by having the Duke of Buckingham, the chairman, and some of the directors of the company blown through the tube to Euston (a five minute trip).

The 550-meter Crystal Palace pneumatic railway was exhibited at the Crystal Palace in 1864. This was a prototype for a proposed *Waterloo and Whitehall Railway* that would have run under the River Thames linking Waterloo and Charing Cross. Digging commenced in 1865 but was halted in 1868 due to financial problems.



Alfred Ely Beach's experimental pneumatic elevated subway on display in 1867

In 1867 at the American Institute Fair in New York, Alfred Ely Beach demonstrated a 32.6 m long, 1.8 m diameter pipe that was capable of moving 12 passengers plus a conductor. In 1869, the Beach Pneumatic Transit Company of New York secretly constructed a 95 m long, 2.7 m diameter pneumatic subway line under Broadway, to demonstrate the possibilities of the new transport mode. The line only operated for a few months, closing after Beach was unsuccessful in getting permission to extend it – Boss Tweed, an immensely powerful local politician, did not want it to go ahead as he was intending to personally invest into competing schemes for an elevated rail line.

20th century

In the 1960s, Lockheed and MIT with the United States Department of Commerce conducted feasibility studies on a vactrain system powered by ambient atmospheric pressure and "gravitational pendulum assist" to connect cities on the East Coast of the US. They calculated that the run between Philadelphia and New York City would average

174 meters per second, that is 626 km/h (388 mph). When those plans were abandoned as too expensive, Lockheed engineer L.K. Edwards founded Tube Transit, Inc. to develop technology based on "gravity-vacuum transportation". In 1967 he proposed a **Bay Area Gravity-Vacuum Transit** for California that would run alongside the then-under construction BART system. It was never built.

21st century

Research into trains running in partially-evacuated tubes is continuing.

Technical characteristics

Modern systems (for smaller, i.e. "normal" tube diameters as used in the transport of small capsules) reach speeds of around 7.5 m (25 ft) per second, though some historical systems already achieved speeds of 10 m (33 ft) per second. Further, modern systems can also be computer-controlled, allowing, among other things, the tracking of any specific capsule. Varying air pressures also allow capsules to brake slowly, removing the jarring arrival that used to characterise earlier systems and make them unsuitable for fragile contents.

Chapter 8

Pneumatic Tool and Nail Gun

Pneumatic tool

Pneumatic tools' or **air tools** are tools driven by gas, usually compressed air supplied by a gas compressor. Pneumatic tools can also be driven by compressed carbon dioxide (CO_2) stored in small cylinders allowing for portability. Pneumatic tools are commonly cheaper and safer to run and maintain than their electric power tool counterparts, as well as having a higher power to weight ratio, allowing a smaller, lighter tool to accomplish the same task.

Air tools were formerly unpopular in the DIY market, but are becoming increasingly popular, and have always been ubiquitous in industrial and manufacturing settings.

Flow represents the quantity of compressed air that passes through a section over a unit of time. It is represented in l/min, m3, at the equivalent value in free air in conditions of standard reference atmosphere (SRA), i.e. +20 c, 65% of relative humidity, 1013 mbar, in accordance with norms NFE

Some common pneumatic tools

- Air impact wrench
- Air ratchet
- Airbrush
- Jackhammer
- pneumatic grinder
- pneumatic sander
- Pneumatic drill
- pneumatic screwdriver
- pneumatic tapping machine

- pneumatic hack saw
- Pneumatic Hammers (Stone Sculpting)
- pneumatic trimmer
- pneumatic paint gun
- pneumatic tacker
- pneumatic polisher
- pneumatic nail gun
- sandblaster
- Paint sprayer

Some common brand names

- Cuturi Martelli Pneumatici
- Bavaria Lufthammer
- Milani (Toncani) Martelli Pneumatici / Utensili
- RAD Torque Systems
- RAD Torque Systems
- RAD Torque Systems
- Fuji Air Tools Co.,LTD
- Dynabrade
- Ober Spa
- 3M
- Atlas Copco
- Compair Broomwade Ltd
- Ingersoll-Rand
- Snap-on
- Chicago Pneumatic
- Master Air Tool
- ELGI
- Bostich
- KAESER

In addition, many house brands exist, such as those carried at Princess Auto, Summit Tools or Harbor Freight Tools.

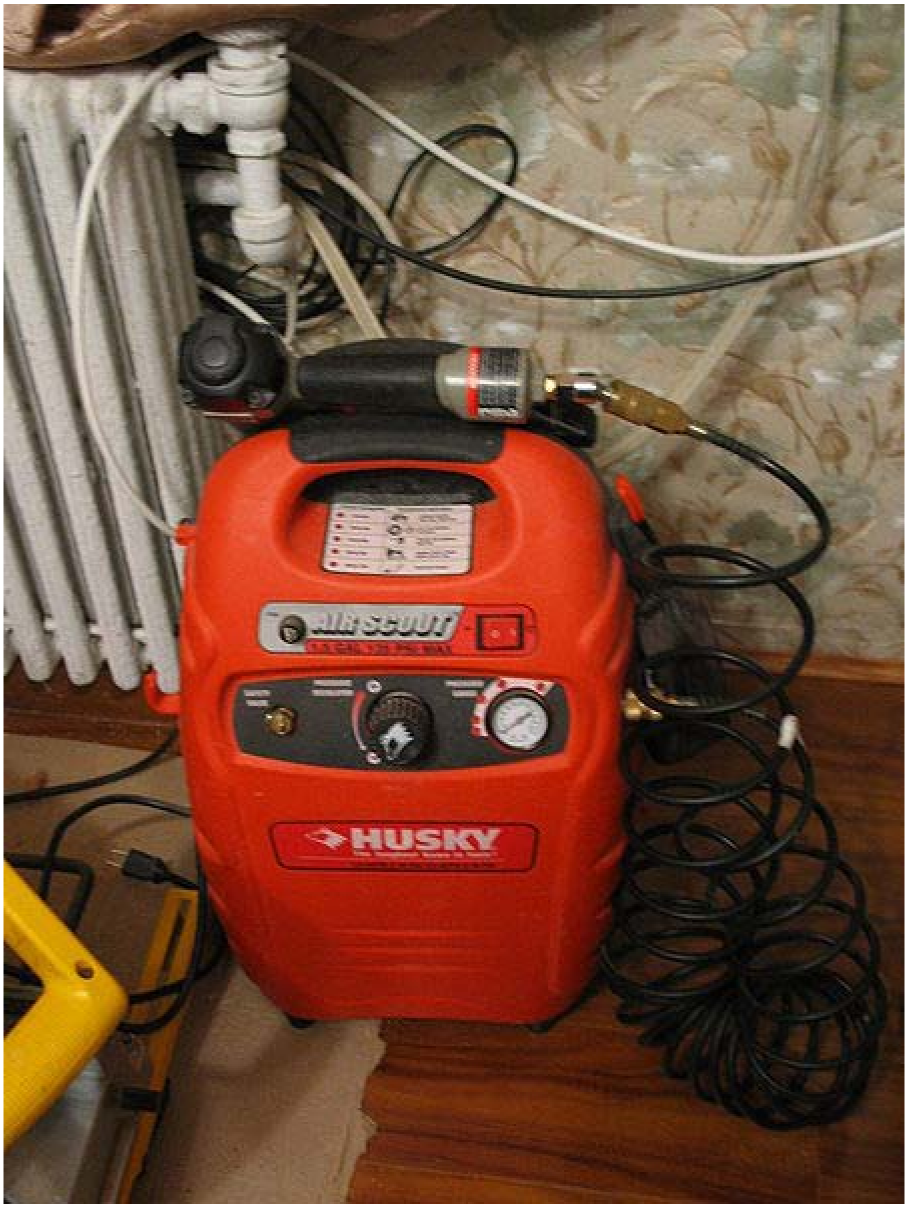
Nail gun

Pneumatic nail gun in use

A **nail gun**, **nailgun** or **nailer** is a type of tool used to drive nails into wood or some other kind of material. It is usually driven by electromagnetism, compressed air (pneumatic), highly flammable gases such as butane or propane, or, for powder-actuated tools, a small explosive charge. Nail guns have in many ways replaced hammers as tools of choice among builders.

Usage

Nail guns do not use individual fasteners. Instead, the fasteners are mounted in long strips (similar to a stick of staples) or collated in a paper or plastic carrier, depending on the design of the nailgun. Some full head nail guns, especially those used for pallet making and roofing, use long plastic or wire collated coils. Some strip nailers use a clipped head so the nails can be placed closer together, which necessitates less frequent reloading. Industrial nailers designed for use against steel or concrete may have a self-loading action for the explosive caps, but most require nails to be loaded by hand. Nail guns vary in the length and gauge (thickness) of nails they can drive.



Air compressor supplies air into a nail gun

The smallest size of fasteners are normally 24 to 22 gauge (0.60 to 0.71 mm diameter) and generally have no head. They are used for attaching beadings, mouldings and so forth to furniture, etc. Lengths are normally in the range ⅜ to 1¼ in. (10 to 32 mm) although some specialist manufacturers supply up to 2 in. (50 mm)

The next size up is the 18 gauge (1.22 mm diameter) fixing, often referred to as a "brad nail". These fastenings are also used to fix mouldings but can be used in the same way as the smaller 22 to 24 gauge fastenings. Their greater strength leads to their use in trim carpentry on hardwoods where some hole filling is acceptable. Whilst most 18 gauge brads have heads, some manufacturers do offer headless fastenings. Lengths range from ⅝ in to 2 in. (16 mm to 50 mm)

Going up from 18 gauge fastenings the next sizes are 16 and 15 gauge (1.63 and 1.83 mm diameter). These are generally referred to a "finish nails". They come in lengths between ⅝ and 2½ in. (16 to 64 mm) and are used in the general fixing of much softwood and MDF trim work (such as baseboard/skirtings, architraves, etc.) where the holes will be filled and the work painted afterwards.

The largest sizes of conventional collated fastenings are the clipped head and full head nails which are used in framing, fencing and other forms of structural and exterior work. These nails generally have a shank diameter of 0.11 to 0.13 in. (2.9 to 3.1 mm) although some manufacturers offer smaller diameter nails as well. General lengths are in the range 2 in to 3 ⅓ in (50 to 90 mm). Shank styles include plain, ring annular, twisted, etc. and a variety of materials and finishes are offered including plain steel, galvanised steel, sherardised steel, stainless steel, etc. depending on the pull-out resistance, corrosion resistance, etc. required for the given application. These sizes of fastenings are available in stick collated form (often 20° to 21° for full head, 28° to 34° for clipped head) or coil form (for use in pallet/roofing nailers) depending on the application. Full-head nails have greater pull-out resistance than clipped head nails and are mandated by code in many hurricane zones for structural framing.

Another type of fastening commonly found in construction is the strap fastening which is roughly analogous to the large head clout nail. These are used in conjunction with a strap shot nailer (or positive placement nailer *UK*) to fix metalwork such as joist hangers, corner plates, strengthening straps, etc. to timber structures. They differ from conventional nailers in that the point of the fastening is not sheathed so it can be exactly positioned before firing the nail gun.

Other specialist nailers are also available which can drive spikes up to 6¼ inches long, fix wood to steel, etc.

A variation on the nail gun is the palm nailer which is a lightweight handheld pneumatic nailer that straps to the hand. It is convenient for working in tight spaces where a conventional nailer will not fit and is flexible enough to drive either short nails into metal straps or six inch nails into timber. By repeated hammer action (of around 40 hits per second) the fastener is driven into the material by a more constant palm pressure (as opposed to a conventional nailgun which drives the nail against the inertia of the nailgun itself).

Safety

In the United States, about 37,000 people every year go to emergency rooms with injuries from nail guns, according to the U.S. Centers for Disease Control (CDC). Forty percent of those injuries occur to consumers. Nail gun injuries tripled between 1991 to 2005. Foot and hand injuries are among the most common. The U.S. Consumer Product Safety Commission estimates that treating nail gun wounds costs at least $338 million per year nationally in emergency medical care, rehabilitation, and workers' compensation.

All kinds of nail guns can be dangerous, so safety precautions similar to those for a firearm are usually recommended for their use. For safety, nail guns are designed to be used with the muzzle touching the target. Unless specifically modified for the purpose, they are not effective as projectile weapons.

The most common firing mechanism is the dual-action contact-trip trigger, which requires that the manual trigger and nose contact element both be depressed for a nail to be discharged. The sequential-trip trigger, which is safer, requires the nose contact to be depressed before the manual trigger, rather than simultaneously with the trigger. Approximately 65% to 69% of injuries from contact-trip tools could be prevented through the use of a sequential-trip trigger, according to the CDC.

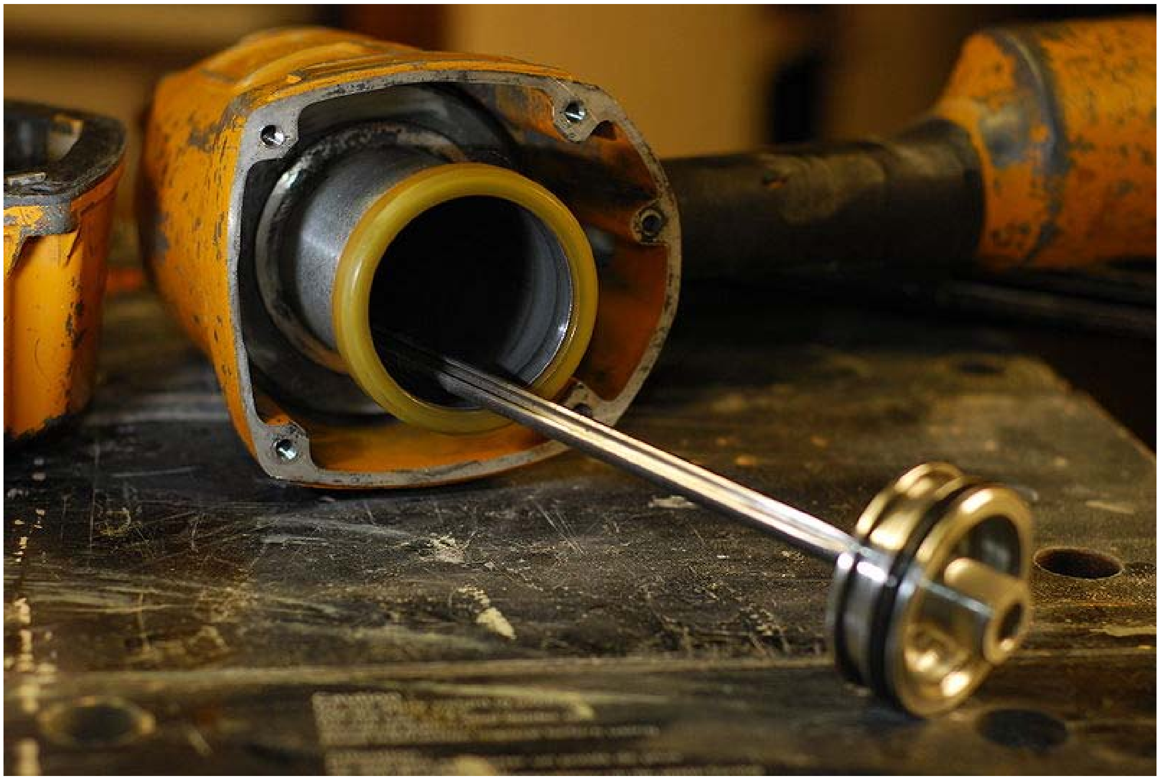
Powder actuation

Explosive-powered ("powder actuated") nailguns fall into two broad categories:

- Direct drive or high velocity devices. This uses gas pressure acting directly on the nail to drive it.
- Indirect drive or low velocity devices. This uses gas pressure acting on a heavy piston which drives the nail. Indirect drive nailers are safer because they cannot launch a free-flying projectile even if tampered with or misused, and the lower velocity of the nails is less likely to cause explosive shattering of the work substrate.

Either type can, with the right cartridge loads, be very powerful, driving a nail or other fastener into hard concrete, stone, rolled steelwork, etc., with ease.

Pneumatic nail guns require air hoses to fire



In the nailgun's head, the inner chamber contains the piston assembly which drives the nail.

Nails come in clips for use in nail guns

Cartridges, used in powder actuated nail guns

Chapter 9

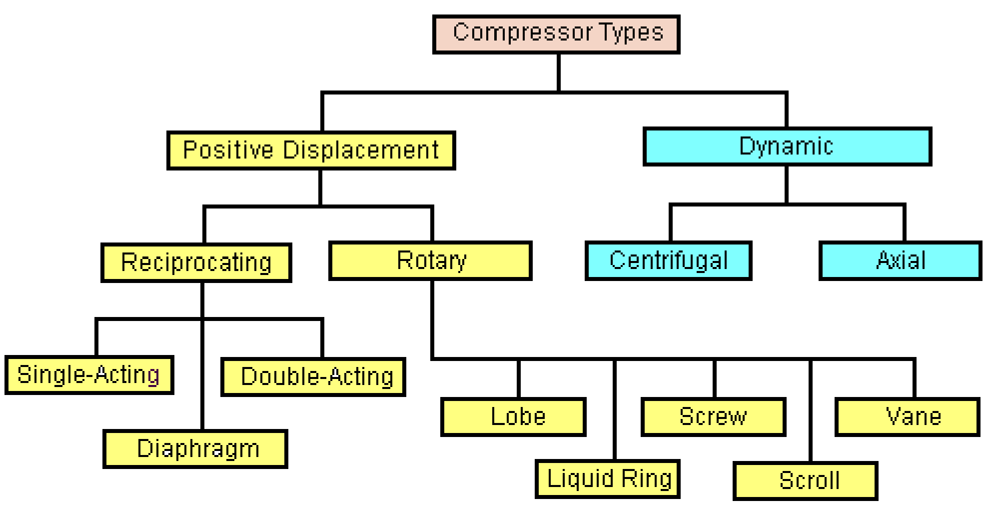
Gas Compressor

A **gas compressor** is a mechanical device that increases the pressure of a gas by reducing its volume.

Compressors are similar to pumps: both increase the pressure on a fluid and both can transport the fluid through a pipe. As gases are compressible, the compressor also reduces the volume of a gas. Liquids are relatively incompressible, while some can be compressed, the main action of a pump is to pressurize and transport liquids.

Types of compressors

The main types of gas compressors are illustrated and discussed below:



Hermetically-Sealed, Open, or Semi-

A small hermetically sealed compressor in a common consumer refrigerator or freezer; it typically has a rounded steel outer shell that is permanently welded shut, and which seals operating gases inside the system. There is no route for gases to leak, such as around motor shaft seals. On this model, the plastic top section is part of an auto-defrost system which use motor heat to evaporate the water.

Compressors are often described as being either open, hermetic, or semi-hermetic, to describe how the compressor and motor drive is situated in relation to the gas or vapour being compressed. The industry name for a hermetic is **hermetically sealed compressor**, while a semi- is commonly called a **semi hermetic compressor**.

In hermetic and most semi-hermetic compressors, the compressor and motor driving the compressor are integrated, and operate within the pressurized gas envelope of the system. The motor is designed to operate and be cooled by the gas or vapour being compressed.

The difference between the hermetic and semi-hermetic, is that the hermetic uses a one-piece welded steel casing that cannot be opened for repair; if the hermetic fails it is simply replaced with an entire new unit. A semi-hermetic uses a large cast metal shell with gasketed covers that can be opened to replace motor and pump components.

The primary advantage of a hermetic and semi-hermetic is that there is no route for the gas to leak out of the system. Open compressors rely on either natural leather or synthetic rubber seals to retain the internal pressure, and these seals require a lubricant such as oil to retain their sealing properties.

An open pressurized system such as an automobile air conditioner can leak its operating gases, if it is not operated frequently enough. Open systems rely on lubricant in the system to splash on pump components and seals. If it is not operated frequently enough, the lubricant on the seals slowly evaporates, and then the seals begin to leak until the system is no longer functional and must be recharged. By comparison, a hermetic system can sit unused for years, and can usually be started up again at any time without requiring maintenance or experiencing any loss of system pressure.

The disadvantage of hermetic compressors is that the motor drive cannot be repaired or maintained, and the entire compressor must be removed if a motor fails. A further disadvantage is that burnt out windings can contaminate whole systems requiring the system to be entirely pumped down and the gas replaced. Typically hermetic compressors are used in low-cost factory-assembled consumer goods where the cost of repair is high compared to the value of the device, and it would be more economical to just purchase a new device.

An advantage of open compressors is that they can be driven by non-electric power sources, such as an internal combustion engine or turbine. However, open compressors that drive refrigeration systems are generally not totally *maintenance free* throughout the life of the system, since some gas leakage will occur over time.

Centrifugal compressors

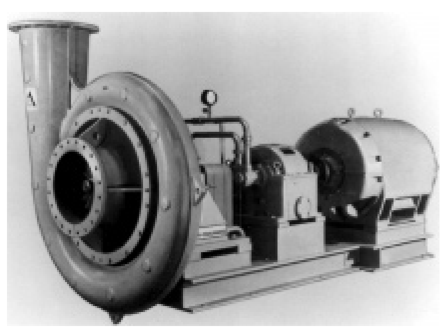


Figure 1: A single stage centrifugal compressor

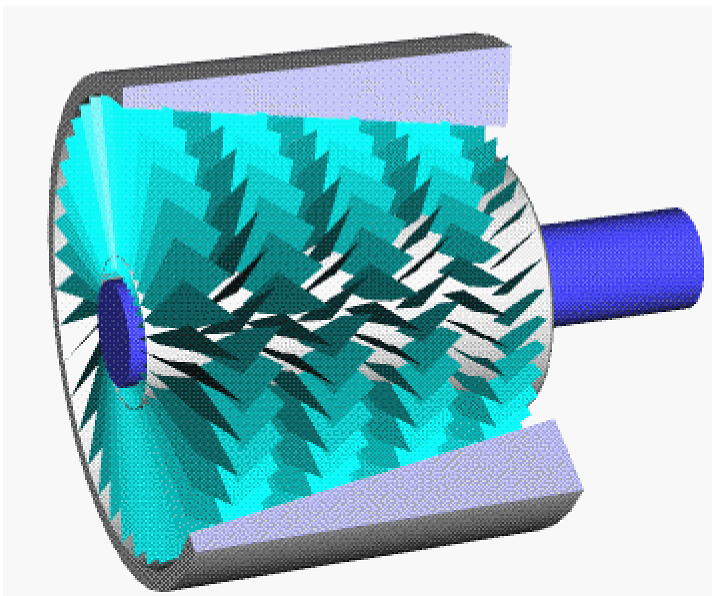
Centrifugal compressors use a rotating disk or impeller in a shaped housing to force the gas to the rim of the impeller, increasing the velocity of the gas. A diffuser (divergent duct) section converts the velocity energy to pressure energy. They are primarily used for continuous, stationary service in industries such as oil refineries, chemical and petrochemical plants and natural gas processing plants. Their application can be from 100 horsepower (75 kW) to thousands of horsepower. With multiple staging, they can achieve extremely high output pressures greater than 10,000 psi (69 MPa).

Many large snowmaking operations (like ski resorts) use this type of compressor. They are also used in internal combustion engines as superchargers and turbochargers. Centrifugal compressors are used in small gas turbine engines or as the final compression stage of medium sized gas turbines. Sometimes the capacity of the compressors is written in NM3/hr. Here 'N' stands for normal temperature pressure (20°C and 1 atm) for example 5500 NM3/hr.

Diagonal or mixed-flow compressors

Diagonal or **mixed-flow compressors** are similar to centrifugal compressors, but have a radial and axial velocity component at the exit from the rotor. The diffuser is often used to turn diagonal flow to an axial rather than radial direction.

Axial-flow compressors



Axial compressor.

Axial-flow compressors are dynamic rotating compressors that use arrays of fan-like airfoils to progressively compress the working fluid. They are used where there is a requirement for a high flow rate or a compact design.

The arrays of airfoils are set in rows, usually as pairs: one rotating and one stationary. The rotating airfoils, also known as blades or *rotors*, accelerate the fluid. The stationary airfoils, also known as *stators* or vanes, decelerate and redirect the flow direction of the fluid, preparing it for the rotor blades of the next stage. Axial compressors are almost always multi-staged, with the cross-sectional area of the gas passage diminishing along the compressor to maintain an optimum axial Mach number. Beyond about 5 stages or a 4:1 design pressure ratio, variable geometry is normally used to improve operation.

Axial compressors can have high efficiencies; around 90% polytropic at their design conditions. However, they are relatively expensive, requiring a large number of components, tight tolerances and high quality materials. Axial-flow compressors can be found in medium to large gas turbine engines, in natural gas pumping stations, and within certain chemical plants.

Reciprocating compressors

A motor-driven six-cylinder reciprocating compressor that can operate with two, four or six cylinders.

Reciprocating compressors use pistons driven by a crankshaft. They can be either stationary or portable, can be single or multi-staged, and can be driven by electric motors or internal combustion engines. Small reciprocating compressors from 5 to 30 horsepower (hp) are commonly seen in automotive applications and are typically for intermittent duty. Larger reciprocating compressors well over 1,000 hp (750 kW) are commonly found in large industrial and petroleum applications. Discharge pressures can range from low pressure to very high pressure (>18000 psi or 180 MPa). In certain applications, such as air compression, multi-stage double-acting compressors are said to be the most efficient compressors available, and are typically larger, and more costly than comparable rotary units. Another type of reciprocating compressor is the swash plate compressor, which uses pistons which are moved by a swash plate mounted on a shaft - see Axial Piston Pump.

Household, home workshop, and smaller job site compressors are typically reciprocating compressors 1½ hp or less with an attached receiver tank.

Rotary screw compressors

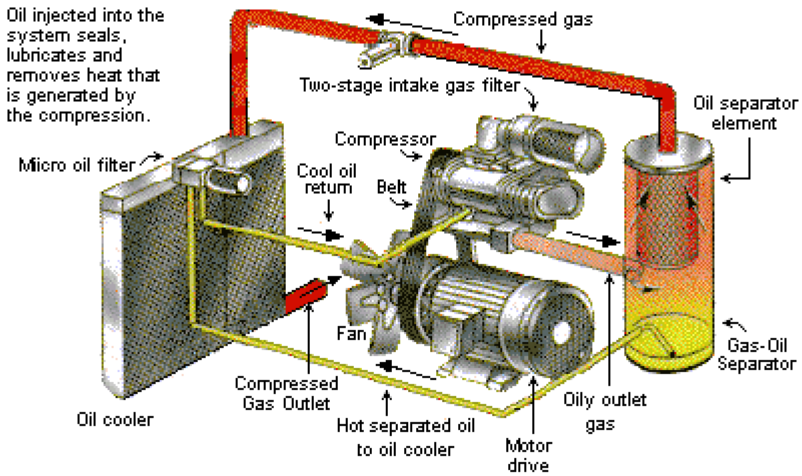


Diagram of a rotary screw compressor

Rotary screw compressors use two meshed rotating positive-displacement helical screws to force the gas into a smaller space. These are usually used for continuous operation in commercial and industrial applications and may be either stationary or portable. Their application can be from 3 horsepower (2.2 kW) to over 1,200 horsepower (890 kW) and from low pressure to moderately high pressure (>1,200 psi or 8.3 MPa).

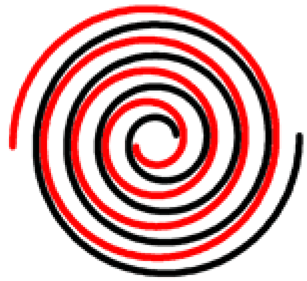
Rotary vane compressors

Rotary vane compressors consist of a rotor with a number of blades inserted in radial slots in the rotor. The rotor is mounted offset in a larger housing which can be circular or a more complex shape. As the rotor turns, blades slide in and out of the slots keeping contact with the outer wall of the housing. Thus, a series of decreasing volumes is created by the rotating blades. Rotary Vane compressors are, with piston compressors one of the oldest of compressor technologies.

With suitable port connections, the devices may be either a compressor or a vacuum pump. They can be either stationary or portable, can be single or multi-staged, and can be driven by electric motors or internal combustion engines. Dry vane machines are used at relatively low pressures (e.g., 2 bar or 200 kPa; 29 psi) for bulk material movement while oil-injected machines have the necessary volumetric efficiency to achieve pressures up to about 13 bar (1,300 kPa; 190 psi) in a single stage. A rotary vane compressor is well suited to electric motor drive and is significantly quieter in operation than the equivalent piston compressor.

Rotary vane compressors can have mechanical efficiencies of about 90%.

Scroll compressors



Mechanism of a scroll pump

A **scroll compressor**, also known as **scroll pump** and **scroll vacuum pump**, uses two interleaved spiral-like vanes to pump or compress fluids such as liquids and gases. The vane geometry may be involute, archimedean spiral, or hybrid curves. They operate more smoothly, quietly, and reliably than other types of compressors in the lower volume range

Often, one of the scrolls is fixed, while the other orbits eccentrically without rotating, thereby trapping and pumping or compressing pockets of fluid or gas between the scrolls.

This type of compressor was used as the supercharger on Volkswagen G60 and G40 engines in the early 1990s.

Diaphragm compressors

A **diaphragm compressor** (also known as a **membrane compressor**) is a variant of the conventional reciprocating compressor. The compression of gas occurs by the movement of a flexible membrane, instead of an intake element. The back and forth movement of the membrane is driven by a rod and a crankshaft mechanism. Only the membrane and the compressor box come in contact with the gas being compressed.

Diaphragm compressors are used for hydrogen and compressed natural gas (CNG) as well as in a number of other applications.

A three-stage diaphragm compressor

The photograph included in this section depicts a three-stage diaphragm compressor used to compress hydrogen gas to 6,000 psi (41 MPa) for use in a prototype compressed hydrogen and compressed natural gas (CNG) fueling station built in downtown Phoenix, Arizona by the Arizona Public Service company (an electric utilities company). Reciprocating compressors were used to compress the natural gas.

The prototype alternative fueling station was built in compliance with all of the prevailing safety, environmental and building codes in Phoenix to demonstrate that such fueling stations could be built in urban areas.

Air bubble compressor

A mixture of air and water generated through turbulence is allowed to fall into a subterranean chamber where the air separates from the water. The weight of falling water compresses the air in the top of the chamber. A submerged outlet from the chamber allows water to flow to the surface at a lower height than the intake. An outlet in the roof of the chamber supplies the compressed air to the surface. A facility on this principal was built on the Montreal River at Ragged Shutes neary Cobalt, Ontario in 1910 and supplied 5,000 horsepower to nearby mines.

Temperature

Compression of a gas naturally increases its temperature, often referred to as the *heat of compression*. $W = \int_{V_1}^{V_2} P dV = P_1 V_1^n \int_{V_1}^{V_2} V^{-n} dV$ where

$$\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^n$$

so

$$W = \frac{P_1 V_1^n}{1-n} \left(V_2^{1-n} - V_1^{1-n}\right)$$

with n taking different values for different compression processes.

- Adiabatic - This model assumes that no energy (heat) is transferred to or from the gas during the compression, and all supplied work is added to the internal energy of the gas, resulting in increases of temperature and pressure. Theoretical temperature rise is:

$T_2 = T_1 . {R_c}^{(k-1)/k}$ with T_1 and T_2 in degrees Rankine or kelvins, and k = ratio of specific heats (approximately 1.4 for air). R_c is the compression ratio; being the absolute outlet pressure divided by the absolute inlet pressure. The rise in air and temperature ratio means compression does not follow a simple pressure to volume ratio. This is less efficient, but quick. Adiabatic compression or expansion more closely model real life when a compressor has good insulation, a large gas volume, or a short time scale (i.e., a high power level). In practice there will always be a certain amount of heat flow out of the compressed gas. Thus, making a perfect adiabatic compressor would require perfect heat insulation of all parts of the machine. For example, even a bicycle tire pump's metal tube becomes hot as you compress the air to fill a tire. The relation between temperature and compression ratio described above means that the value of n for an adiabatic process is k (the ratio of specific heats).

- Isothermal - This model assumes that the compressed gas remains at a constant temperature throughout the compression or expansion process. In this cycle, internal energy is removed from the system as heat at the same rate that it is added by the mechanical work of compression. Isothermal compression or expansion more closely models real life when the compressor has a large heat exchanging surface, a small gas volume, or a long time scale (i.e., a small power level). Compressors that utilize inter-stage cooling between compression stages come closest to achieving perfect isothermal compression. However, with practical devices perfect isothermal compression is not attainable. For example, unless you have an infinite number of compression stages with corresponding intercoolers, you will never achieve perfect isothermal compression.

For an isothermal process, n is 1, so the value of the work integral for an isothermal process is:

$$W = -P_1 v_1 \ln\left(\frac{P_2}{P_1}\right)$$

When evaluated, the isothermal work is found to be lower than the adiabatic work.

- Polytropic - This model takes into account both a rise in temperature in the gas as well as some loss of energy (heat) to the compressor's components. This assumes that heat may enter or leave the system, and that input shaft work can appear as both increased pressure (usually useful work) and increased temperature above adiabatic (usually losses due to cycle efficiency). Compression efficiency is then the ratio of temperature rise at theoretical 100 percent (adiabatic) vs. actual (polytropic). Polytropic compression will use a value of n between 0 (a constant-pressure process) and infinity (a constant volume process). For the typical case where an effort is made to cool the gas compressed by an approximately adiabatic process, the value of n will be between 1 and k.

Staged compression

In the case of centrifugal compressors, commercial designs currently do not exceed a compression ratio of more than a 3.5 to 1 in any one stage (for a typical gas). Since compression generates heat, the compressed gas is to be cooled between stages making the compression less adiabatic and more isothermal. The inter-stage coolers typically result in some partial condensation that is removed in vapor-liquid separators.

In the case of small reciprocating compressors, the compressor flywheel may drive a cooling fan that directs ambient air across the intercooler of a two or more stage compressor.

Because rotary screw compressors can make use of cooling lubricant to remove the heat of compression, they very often exceed a 9 to 1 compression ratio. For instance, in a typical diving compressor the air is compressed in three stages. If each stage has a compression ratio of 7 to 1, the compressor can output 343 times atmospheric pressure ($7 \times 7 \times 7 = 343$ atmospheres). (343 atm/34.8 MPa; 5.04 ksi)

Prime movers

There are many options for the "prime mover" or motor which powers the compressor:

- gas turbines power the axial and centrifugal flow compressors that are part of jet engines
- steam turbines or water turbines are possible for large compressors
- electric motors are cheap and quiet for static compressors. Small motors suitable for domestic electrical supplies use single phase alternating current. Larger motors can only be used where an industrial electrical three phase alternating current supply is available.
- diesel engines or petrol engines are suitable for portable compressors and support compressors. Common in automobiles and other types of vehicles (including piston-powered airplanes, boats, trucks, etc.), diesel or gasoline engines can power compressors using their own crankshaft power (this setup known as a supercharger), or, using their waste exhaust gas to spin a turbine connected to the the compressor (this setup known as a turbocharger).

Multiple compressor configurations

It is possible to connect two or more compressors in tandem, effectivly doubling their CFM output and air storage capacity. The advantages of such a configuration are portability and cost savings. It is significantly less expensive to purchase smaller compressors and rig them together than it would be to purchase one large compressor with the same output.

Applications

Gas compressors are used in various applications where either higher pressures or lower volumes of gas are needed:

- in pipeline transport of purified natural gas to move the gas from the production site to the consumer. Often, the compressor in this application is driven by a gas turbine which is fueled by gas bled from the pipeline. Thus, no external power source is necessary.
- in petroleum refineries, natural gas processing plants, petrochemical and chemical plants, and similar large industrial plants for compressing intermediate and end product gases.
- in refrigeration and air conditioner equipment to move heat from one place to another in refrigerant cycles.
- in gas turbine systems to compress the intake combustion air
- in storing purified or manufactured gases in a small volume, high pressure cylinders for medical, welding and other uses.
- in many various industrial, manufacturing and building processes to power all types of pneumatic tools.
- as a medium for transferring energy, such as to power pneumatic equipment.
- in pressurised aircraft to provide a breathable atmosphere of higher than ambient pressure.
- in some types of jet engines (such as turbojets and turbofans) to provide the air required for combustion of the engine fuel. The power to drive the combustion air compressor comes from the jet's own turbines.
- in SCUBA diving, hyperbaric oxygen therapy and other life support devices to store breathing gas in a small volume such as in diving cylinders.
- in submarines, to store air for later use in displacing water from buoyancy chambers, for adjustment of depth.
- in turbochargers and superchargers to increase the performance of internal combustion engines by increasing mass flow.
- in rail and heavy road transport to provide compressed air for operation of rail vehicle brakes or road vehicle brakes and various other systems (doors, windscreen wipers, engine/gearbox control, etc.).
- in miscellaneous uses such as providing compressed air for filling pneumatic tires.
- in the case of the fire piston and the heat pump, the desired outcome is the temperature rise of the gas, and compressing the gas is only a means to that end.

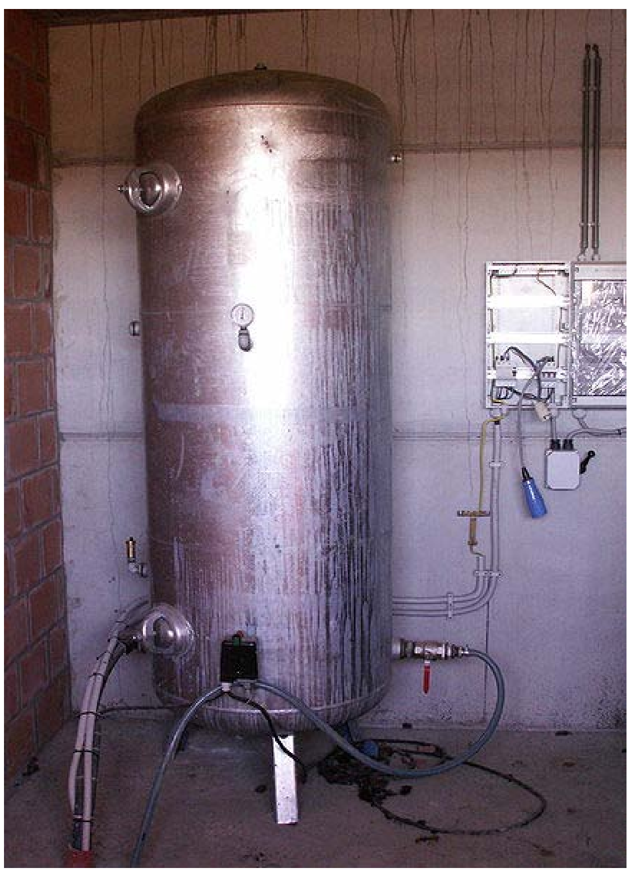
Chapter 10

Pressure Vessel

A **pressure vessel** is a closed container designed to hold gases or liquids at a pressure substantially different from the ambient pressure.

The pressure differential is dangerous and many fatal accidents have occurred in the history of their development and operation. Consequently, their design, manufacture, and operation are regulated by engineering authorities backed up by laws. For these reasons, the definition of a pressure vessel varies from country to country, but involves parameters such as maximum safe operating pressure and temperature.

Uses



A pressure tank connected to a water well and domestic hot water system

A few pressure tanks, here used to hold propane

Pressure vessels are used in a variety of applications in both industry and the private sector. They appear in these sectors as industrial compressed air receivers and domestic hot water storage tanks. Other examples of pressure vessels are diving cylinder, recompression chamber, distillation towers, autoclaves, and many other vessels in mining or oil refineries and petrochemical plants, nuclear reactor vessel, habitat of a space ship, habitat of a submarine, pneumatic reservoir, hydraulic reservoir under pressure, rail vehicle airbrake reservoir, road vehicle airbrake reservoir and storage vessels for liquified gases such as ammonia, chlorine, propane, butane, and LPG.

Shape of a pressure vessel

Pressure vessels may theoretically be almost any shape, but shapes made of sections of spheres, cylinders, and cones are usually employed. A common design is a cylinder with end caps called heads. Head shapes are frequently either hemispherical or dished (torispherical). More complicated shapes have historically been much harder to analyze for safe operation and are usually far tougher to construct.

Theoretically, a sphere would be the best shape of a pressure vessel. Unhappily, a spherical shape is tough to manufacture, therefore more expensive, so most pressure vessels are cylindrical with 2:1 semi-elliptical heads or end caps on each end. Smaller pressure vessels are assembled from a pipe and two covers. A disadvantage of these vessels is that greater breadths are more expensive, so that for example the most economic shape of a 1,000 litres (35 cu ft), 250 bars (3,600 psi) pressure vessel might be a breadth of 914.4 millimetres (36 in) and a width of 1,701.8 millimetres (67 in) including the 2:1 semi-elliptical domed end caps.

Construction materials

Steel Pressure Vessel

Theoretically almost any material with good tensile properties that is chemically stable in the chosen application could be employed. However, pressure vessel design codes and application standards (ASME BPVC Section II, EN 13445-2 etc.) contain long lists of approved materials with associated limitations in temperature range.

Many pressure vessels are made of steel. To manufacture a cylindrical or spherical pressure vessel, rolled and possibly forged parts would have to be welded together. Some mechanical properties of steel, achieved by rolling or forging, could be adversely affected by welding, unless special precautions are taken. In addition to adequate mechanical strength, current standards dictate the use of steel with a high impact resistance, especially for vessels used in low temperatures. In applications where carbon steel would suffer corrosion, special corrosion resistant material should also be used.

Some pressure vessels are made of composite materials, such as filament wound composite using carbon fibre held in place with a polymer. Due to the very high tensile strength of carbon fibre these vessels can be very light, but are much more difficult to manufacture. The composite material may be wound around a metal liner, forming a composite overwrapped pressure vessel.

Other very common materials include polymers such as PET in carbonated beverage containers and copper in plumbing.

Pressure vessels may be lined with various metals, ceramics, or polymers to prevent leaking and protect the structure of the vessel from the contained medium. This liner may also carry a significant portion of the pressure load.

Scaling

No matter what shape it takes, the minimum mass of a pressure vessel scales with the pressure and volume it contains and is inversely proportional to the strength to weight ratio of the construction material (minimum mass decreases as strength increases).

Scaling of stress in walls of vessel

Pressure vessels are held together against the gas pressure due to tensile forces within the walls of the container. The normal (tensile) stress in the walls of the container is proportional to the pressure and radius of the vessel and inversely proportional to the thickness of the walls. Therefore pressure vessels are designed to have a thickness proportional to the radius of tank and the pressure of the tank and inversely proportional to the maximum allowed normal stress of the particular material used in the walls of the container.

Because (for a given pressure) the thickness of the walls scales with the radius of the tank, the mass of a tank (which scales as the length times radius times thickness of the wall for a cylindrical tank) scales with the volume of the gas held (which scales as length times radius squared). The exact formula varies with the tank shape but depends on the density, ρ, and maximum allowable stress σ of the material in addition to the pressure P and volume V of the vessel.

Spherical vessel

For a sphere, the mass of a pressure vessel is

$$M = \frac{3}{2} PV \frac{\rho}{\sigma},$$

where

M is mass,
P is the pressure difference from ambient (the gauge pressure),
V is volume,
ρ is the density of the pressure vessel material,
σ is the maximum working stress that material can tolerate.

Other shapes besides a sphere have constants larger than 3/2 (infinite cylinders take 2), although some tanks, such as non-spherical wound composite tanks can approach this.

Cylindrical vessel with hemispherical ends

This is sometimes called a "bullet" for its shape.

For a cylinder with hemispherical ends,

$$M = 2\pi R^2 (R + W) P \frac{\rho}{\sigma},$$

where

- R is the radius
- W is the middle cylinder width only, and the overall width is W + 2R

2:1 Cylindrical vessel with semi-elliptical ends

In a vessel with a 2:1 aspect ratio,

$$M = 6\pi R^3 P \frac{\rho}{\sigma}.$$

Gas storage

In looking at the first equation, the factor PV, in SI units, is in units of (pressurization) energy. For a stored gas, PV is proportional to the mass of gas at a given temperature, thus

$$M = \frac{3}{2} nRT \frac{\rho}{\sigma}.$$

The other factors are constant for a given vessel shape and material. So we can see that there is no theoretical "efficiency of scale", in terms of the ratio of pressure vessel mass to pressurization energy, or of pressure vessel mass to stored gas mass. For storing gases, "tankage efficiency" is independent of pressure, at least for the same temperature.

So, for example, a typical design for a minimum mass tank to hold helium (as a pressurant gas) on a rocket would use a spherical chamber for a minimum shape constant, carbon fiber for best possible ρ / σ, and very cold helium for best possible M / pV.

Stress in thin-walled pressure vessels

Stress in a shallow-walled pressure vessel in the shape of a sphere is

$$\sigma_\theta = \frac{pr}{2d},$$

where σ_θ is hoop stress, or stress in the circumferential direction, p is internal gauge pressure, r is the inner radius of the sphere, and d is depth. A vessel can be considered "shallow-walled" if the diameter is at least 10 times (sometimes cited as 20 times) greater than the wall depth.

Stress in a shallow-walled pressure vessel in the shape of a cylinder is

$$\sigma_\theta = \frac{pr}{d},$$
$$\sigma_{\text{long}} = \frac{pr}{2d},$$

where σ_θ is hoop stress, or stress in the circumferential direction, σ_{long} is stress in the longitudinal direction, p is internal gauge pressure, r is the inner radius of the cylinder, and d is wall depth.

Almost all pressure vessel design standards contain variations of these two formulas with additional empirical terms to account for wall thickness, quality control of welds and in-service corrosion allowances.

Winding angle of carbon fibre vessels

Wound infinite cylindrical shapes optimally take a winding angle of 54.7 degrees, as this gives the necessary twice the strength in the circumferential direction to the longitudinal.

Design and operation standards

Pressure vessels are designed to operate safely at a specific pressure and temperature, technically referred to as the "Design Pressure" and "Design Temperature". A vessel that is inadequately designed to handle a high pressure constitutes a very significant safety hazard. Because of that, the design and certification of pressure vessels is governed by design codes such as the ASME Boiler and Pressure Vessel Code in North America, the Pressure Equipment Directive of the EU (PED), Japanese Industrial Standard (JIS), CSA B51 in Canada, AS1210 in Australia and other international standards like Lloyd's, Germanischer Lloyd, Det Norske Veritas, Société Générale de Surveillance (SGS S.A.), Stoomwezen etc.

Note that where the pressure-volume product is part of a safety standard, any incompressible liquid in the vessel can be excluded as it does not contribute to the potential energy stored in the vessel, so only the volume of the compressible part such as gas is used.

List of standards

- EN 13445: The current European Standard, harmonized with the Pressure Equipment Directive (97/23/EC). Extensively used in Europe.
- ASME Code Section VIII, in addition supported by Sections II (materials), V (NDT/NDE) and IX (welding). Published by the American Society of Mechanical Engineers.
    - ASME Code Section VIII Division 1: US standard, design by formula. Almost exclusively used in North America, widely used worldwide.
    - ASME Code Section VIII Division 2: Alternative Rules, design by analysis.
    - ASME Code Section VIII Division 3: Alternative Rules for Construction of High Pressure Vessel
- BS 5500: Former British Standard, replaced in the UK by EN 13445 but retained under the name PD 5500 for the design and construction of export equipment.
- AD Merkblätter: German standard, harmonized with the Pressure Equipment Directive.
- EN 286 (Parts 1 to 4): European standard for simple pressure vessels (air tanks), harmonized with Council Directive 87/404/EEC.
- BS 4994: Specification for design and construction of vessels and tanks in reinforced plastics.
- ASME PVHO: US standard for Pressure Vessels for Human Occupancy
- CODAP
- AS 1210
- API 510
- ISO 11439
- IS 2825-1969 (RE1977)_code_unfired_Pressure_vessels
- FRP tanks and vessels
- AIAA S-080-1998: AIAA Standard for Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
- AIAA S-081A-2006: AIAA Standard for Space Systems - Composite Overwrapped Pressure Vessels (COPVs)
- B51-09 Canadian Boiler, pressure vessel, and pressure piping code
- Stoomwezen: Former pressure vessels code in the Netherlands

Leak Before Burst

Leak before burst describes a pressure vessel designed such that a crack in the vessel will grow through the wall, allowing the contained fluid to escape and reducing the pressure, prior to growing so large as to cause fracture at the operating pressure.

Many pressure vessel standards, including the ASME Boiler and Pressure Vessel Code and the AIAA metallic pressure vessel standard, either require pressure vessel designs to be leak before burst, or require pressure vessels to meet more stringent requirements for fatigue and fracture if they are not shown to be leak before burst.

Alternatives to pressure vessels

Depending on the application and local circumstances, alternatives to pressure vessels exist. Examples can be seen in domestic water collection systems, where the following may be used:

- Gravity controlled systems which typically consist of an unpressurized water tank at an elevation higher than the point of use. Pressure at the point of use is the result of the hydrostatic pressure caused by the elevation difference. Gravity systems produce 0.43 pounds per square inch (3.0 kPa) per foot of water head (elevation difference). A municipal water supply or pumped water is typically around 90 pounds per square inch (620 kPa).
- Inline pump controllers or pressure-sensitive pumps.

History of pressure vessels

A 10,000 psi (69 MPa) pressure vessel from 1919, wrapped with high tensile steel banding and steel rods to secure the end caps.

Large pressure vessels were invented during the industrial revolution, particularly in Great Britain, to be used as boilers for making steam to drive steam engines.

Design and testing standards and a system of certification came about as the result of fatal boiler explosions.

In an early effort to design a tank capable of withstanding pressures up to 10,000 psi (69 MPa), a 6-inch (150 mm) diameter tank was developed in 1919 that was spirally-wound with two layers of high tensile strength steel wire to prevent sidewall rupture, and the end caps longitudinally reinforced with lengthwise high-tensile rods.

Chapter 11

Pneumatics Automation

Fluid is a substance that deforms continuously on the application of shear stress, no matter how much small is it. Fluid comprises both gases and liquid. The technique of using liquid for power transmission is called as hydraulics while which uses gases for power transmission is called Pneumatics.In most hydraulics system mineral oils will be used while in most pneumatic system atmospheric air will be used.

Principle behind fluid power

The basic principle which governs any fluid system is the pascal law. The law applies to fluid power transmission. The other laws which will be used in the analysis, design and manufacturing of any fluid system are Boyle's law, Charles's law and Bernoulli theorem.

Property of fluid

For reliable and proper working of hydraulic system the fluid used should have the following certain qualiteies. Some of them are

- Viscosity The fluid used should have its viscosity in the specified range. Higher viscosity will lead to higher friction and wear while lower viscosity will lead to leakage problems
- Viscosity Index This determines the change of viscosity with respect to temperature. Oil with High VI is prferrable
- Oxidation resistance The continuous use of oil will promote oxidation. So the oil should be able to resist oxidation
- Pour and Cloud point These determines the lowest range of temperature below which the fluid willnot transmit power

- Flash and fire point These determines the highest range of temperature above which fluid will catch fire and will cease to transmit power.
- Lubrication The fluid should be able to lubricate the moving parts in the system.
- Heat generation and transmission The amount of heat generated should be less. The fluid should have capacity to transmit the heat generated
- Corrosion resistance The fluid should not corrode the parts of the system.

Some of the most commonly used fluid for power transmission are water,emulsions,Water glycol, Synthetics, air and compressed gases

Parts of fluid system

The most of fluid system will employ some or all of the following parts

- Pump or Compressor: This gives the motion to the fluid which is used to perform useful work
- Control Valves: These are used to regulate and control the flow of the fluid
- Tubes, pipes and Hoses: These carry the fluid from the pump/compressor to the actuator
- Actuator: The actual work is performed by the actuators.
- Discharge Tank: The liquid after performing work will be discharged into a tank in case of liquids /gases or will let into the atmosphere in case of air
- Seals: These prevent the leakage of fluid into the atmosphere or surroundings
- Filter, Lubricator and Regulator Circuit (FRL UNIT):These circuit are used to remove dirt present in the fluid. They will also lubricate and regulate the flow of fluid
- Accumulator: These are used to produce head which can be converted into useful work

Cylinders

Cylinders are primary type of actuators used in fluid cicuit. The cylinder used in fluid circuit will consist the following parts

- Cylinder barrel
- Piston
- Ports
- Piston rod
- Cylinder Head
- Valves
- Seals

Whenever fluid is supplied to the cylinder the piston will move. This movement of piston is called as stroke. The piston can move in forward or reverse direction. The cylinders can be classified as double acting or single acting. In single acting cylinder work will be performed only in the forward stroke. The fluid will be supplied to the cylinder only during the forward stroke. The return stroke is achieved by the spring mounted in the cylinder. In double acting cylinder there will be two ports for the supply of fluid. Work can be obtained both at forward and reverse strokes. Directional control valves required for the easy operation of double acting cylinder.

Advantages of using Fluid Power

The transmission of power through fluid has following advantages compared to the other modes

- Power transmission requires less mechanical parts. The problem of breakage of parts like gears, cams, belts and chains is not involved.
- Lesser noise and less vibration can be ensured from the system by proper installation of fluid system
- Forces can be conveyed up and down with less loss in efficiency
- System overloading can be prevented by use of automatic relief valves
- Economical compared to other modes

Use of fluid power

The hydraulic press, invented by Englishman John Brahmah, was one of the first workable pieces of machinery developed that used hydraulics in its operation. Today, hydraulic power is used to operate many different tools and mechanisms. some of the devices which uses hydraulic power are

- Hydraulic jack
- Hydraulic doorstops
- Hydraulic brakes
- Power steering
- Tractors
- Various construction vehicles and equipments

Some devices which uses Pneumatics are

- Pneumatic drillers used in mining
- Air looms used in textile industries
- Air motors

Difference between Hydraulics and Pneumatics

Precise control of velocity is achievable in hydraulics while due to compressible nature of gas Pneumatics cannot have precise control over velocity. In Hydraulics, self regulation action of oil can be used while in pneumatics oil mist has to be used for lubrication. The pressure range for hydraulics is 500-5000 psi while the pressure range for pneumatics is below 100 psi The air after performing work can be sent in to atmosphere whereas oil has to be discharged into a tank.

Chapter 12

Atmospheric Railway

An **atmospheric railway** uses air pressure to provide power for propulsion. In one plan a pneumatic tube is laid between the rails, with a piston running in it suspended from the train through a sealable slot in the top of the tube. Alternately, the whole tunnel may be the pneumatic tube with the car being the piston with a seal to the walls. By means of stationary pumping engines along the route, air is exhausted from the tube leaving a partial vacuum in advance of the piston or car, and air is admitted to the tube behind the piston or car so that atmospheric pressure propels the train. In some plans, air pressure is applied behind the piston/car.

Historical applications

In 1799 George Medhurst of London discussed the idea of moving goods pneumatically through cast iron pipes, and in 1812 he proposed, but never implemented, blowing passenger carriages through a tunnel.

In 1835 Henry Pinkus launched a prospectus for the National Pneumatic Railway Association. It was in 1838, when the gas engineer Samuel Clegg and the marine engineers Jacob and Joseph Samuda jointly took out a patent “for a new improvement in valves” that atmospheric propulsion became possible. The partnership set up a working model at the Samuda Brothers’ workshop in Southwark in 1839, and a 0.5-mile (0.8 km) demonstration track of the Birmingham, Bristol & Thames Junction Railway at Wormwood Scrubs between 1840 and 1843. In 1841 Joseph d'Aguilar Samuda published *A Treatise on the Adaptation of Atmospheric Pressure to the Purposes of Locomotion on Railways* The Clegg-Samuda system attracted the attention and support of some of the foremost railway engineers of the day, notably William Cubitt, Charles Vignoles and Isambard Kingdom Brunel, each of whom was engaged on the construction of new railway lines. It was also severely criticised by other engineers and railway commentators, notably Robert Stephenson and John Herapath.

Dalkey Atmospheric Railway

The first practical use of the system was on the Dublin and Kingstown Railway's Dalkey Atmospheric Railway between Kingstown (Dún Laoghaire) and Dalkey, Ireland, This 1.75-mile (2.82 km) line was built by Vignoles and operated between 1844 and 1854.

London and Croydon Railway

Cubbit recommended the system for the 7.5-mile (12.1 km) London and Croydon Railway between London Bridge station and Croydon. Clegg and Samuda were invited by the directors to supply equipment to operate their trains between London Bridge and Epsom. The first stage of this project (between Croydon and Forest Hill) opened in January 1846, but many problems with both the pumping equipment and in maintaining air-tight seals in the delivery pipes were encountered. The London and Croydon Railway became a part of the London Brighton and South Coast Railway in July 1846 and the new board of directors invited Samuda to operate the new atmospheric railway on their behalf in return for a fixed fee. Once further propulsion problems became apparent in the second section of line to be equipped, between Forest Hill and New Cross, during 1847 the atmospheric method of propulsion was abandoned and the equipment sold.

One part of the pneumatic infrastructure was the viaduct from Sydenham to Crystal Palace, crossing the main lines. The pneumatic pipe could not cross the metals, so it was necessary to build a fly-over. This is reputed to be the first of its kind and is still in use today.

South Devon Railway

The remains of the SDR's atmospheric railway pipe at Didcot

The extension of Brunel's broad gauge railway westward from Exeter towards Plymouth by the South Devon Railway Company (SDR) involved one of his most interesting uses of technical innovation. Brunel and others from the GWR travelled to Ireland to view the atmospheric system at Dalkey first hand. Afterwards Brunel's engineer of locomotives for the GWR, Daniel Gooch, calculated that conventional locomotives could work the proposed Plymouth line at lower cost, but Brunel's concerns with the heavy grades led him to try the atmospheric system regardless.

The 20-mile (32 km) section from Exeter to Newton (now Newton Abbot) was completed on the principle, with stationary engines at around 3 mi (5 km) intervals. Trains ran at speeds of up to 70 miles per hour (113 km/h), but service speeds were usually around 40 mph (64 km/h). The level portions used 15-inch (38 cm) pipes and the steeper gradients west of Newton were to have used 22 in (56 cm) pipes. It is not clear how the change between the two pipe sizes would have been achieved unless the piston carriages were changed at Newton. It is also unclear how the level crossing at Turf was operated as the pipe projected above the rails.

The harsh environment of the line, which runs next to the sea and is soaked with salt spray in even moderate winds, presented difficulties in maintaining the leather flaps provided to seal the vacuum pipes, which had to be kept supple by being greased with tallow; even so, air leaked in, destroying the vacuum.

Pumping House at Torquay, Devon

Starcross pumping house.

Atmospheric-powered service lasted less than a year, from 1847 (experimental services began in September; operationally from February 1848) to 9 September 1848. The accounts of the SDR for 1848 suggest that the atmospheric traction cost 3s 1d per mile (£0.10/km) compared to 1s 4d (£0.04/km) for conventional steam power. Part of the problem was that the engines had to be run for longer than expected, as they were not initially connected to the telegraph and so had to pump according to the railway timetable until the train passed, which increased pumping costs.

Despite the building of several engine houses, the system never expanded beyond Newton. The proposal to use the same system on the Cornwall Railway was not pursued.

There are remains of several South Devon Railway engine houses, including one at Starcross, on the estuary of the River Exe. It is a striking landmark and a reminder of the atmospheric railway, commemorated by the name of the village pub, the 'Atmospheric Railway'. A section of the pipe, without the leather covers, is preserved in Didcot Railway Centre.

Other early applications

- The Paris–Saint-Germain railway between Bois de Vésinet and Saint-Germain-en-Laye, France (8.5 km, 5.3 mi) 1847–60
- Beach Pneumatic Transit One city block long subway beneath Broadway in New York City,1870–73.
- The Crystal Palace atmospheric railway of 1864 had seals around the carriage, so (like Rammell's similar GPO Railway) the whole carriage fits in a tube tunnel and was propelled by the large fixed fan.

Recent applications

The Aeromovel Corporation markets an automated people mover that is air driven. The elevated lightweight trains ride on a concrete box girder containing electric motors that drive air inside the girder, creating a constant airflow. Each car has a square plate protruding into the box girder. The plate is rotated into the airflow to catch the wind and accelerate the car.

Systems have been built in Porto Alegre, Brazil (a two-station demonstration line) and in Taman Mini Indonesia Indah, Jakarta, Indonesia (a 2-mile (3 km) six-station loop serving a theme park).

A web page describing a system called 'Whoosh' was available for a time. The system is a single monorail track of the vacuum tube with a track either side. The piston in the tube is connected to the carriage below which is supported by wheels running on the tracks each side of the tube.

Technical considerations

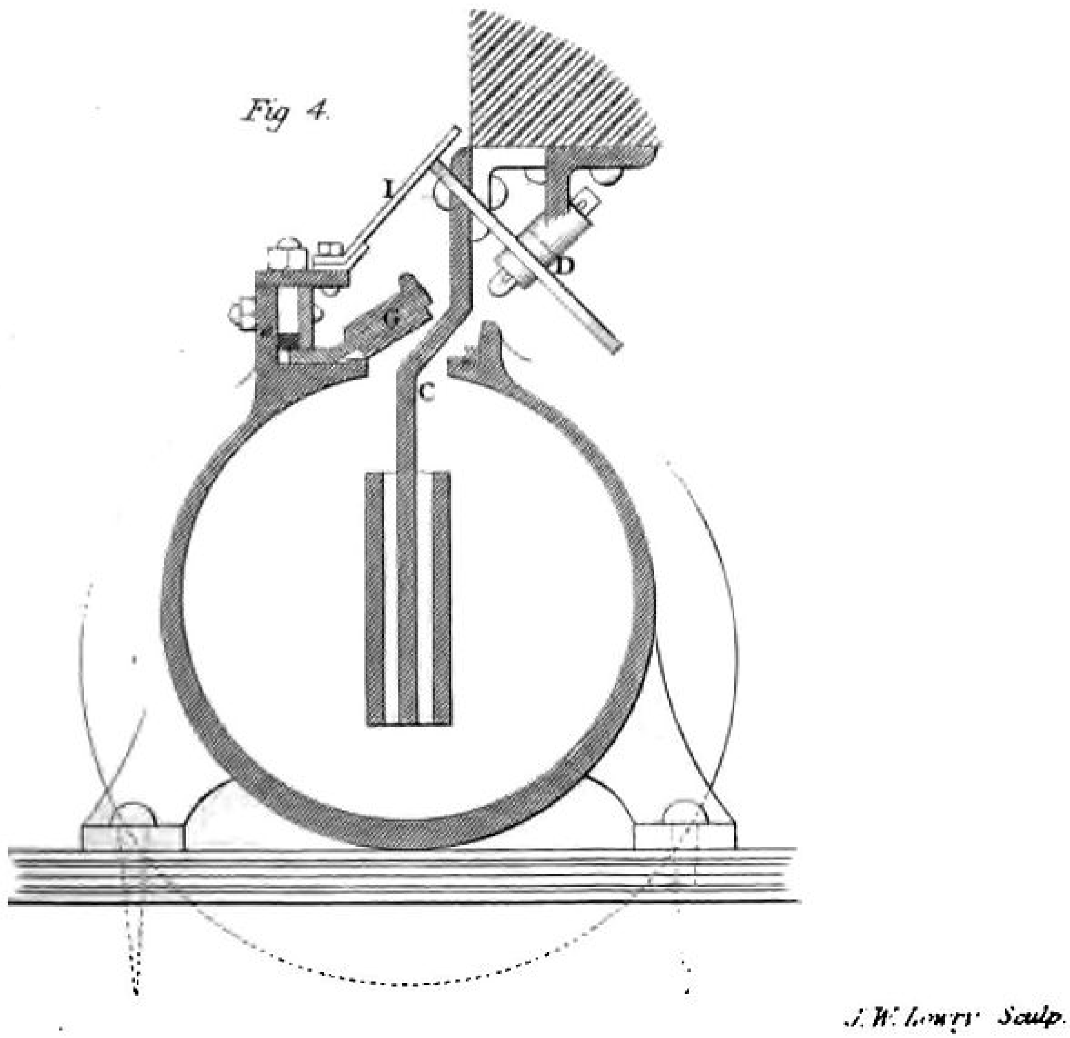


Illustration from *A Treatise on the Adaptation of Atmospheric Pressure to the Purposes of Locomotion on Railways*, Samuda

Advantages

The supporters of the atmospheric system claimed it had several advantages over traditional motive power by steam locomotive.

- Hillclimbing ability. On the two longest-lived applications, at Dalkey and Saint-Germain, this seems to have been vindicated: the system was used on uphill journeys and gravity in the other direction. Brunel assumed that the system would work on the very challenging gradients of up to 1 in 38 on the Plymouth main line if the South Devon application had been extended beyond Newton, probably by increasing the diameter of the tube on the gradients (although this would have involved a complex expanding piston arrangement); however here it was tested only on a relatively flat section.

- Operating efficiencies. Atmospheric railways could be operated on cheaper and lighter tracks which did not have to carry the weight of a locomotive, and could take advantage of sharper curves.
- Fuel efficiency. It was far cheaper to maintain and operate a few large pumping engines than a large number of individual locomotives.
- Cleanliness. The smoke and dirt from the steam engines was kept away from the passengers.
- Safety. The system could achieve higher speeds, but it would be impossible to operate two trains on the same stretch of track simultaneously and so collisions would be avoided.

Disadvantages

The failure of the system was due to technical problems with the stationary engines and the leather seals on the vacuum pipes. The former were suffered by the London and Croydon Railway but would have been overcome with more experience by the manufacturers and operators. The difficulty of maintaining an air-tight seal in the vacuum pipes was a serious problem, particularly for the South Devon Railway Company, which was never satisfactorily solved using the materials and technology of the 1840s.

The atmospheric system also suffered from a number of operating problems.

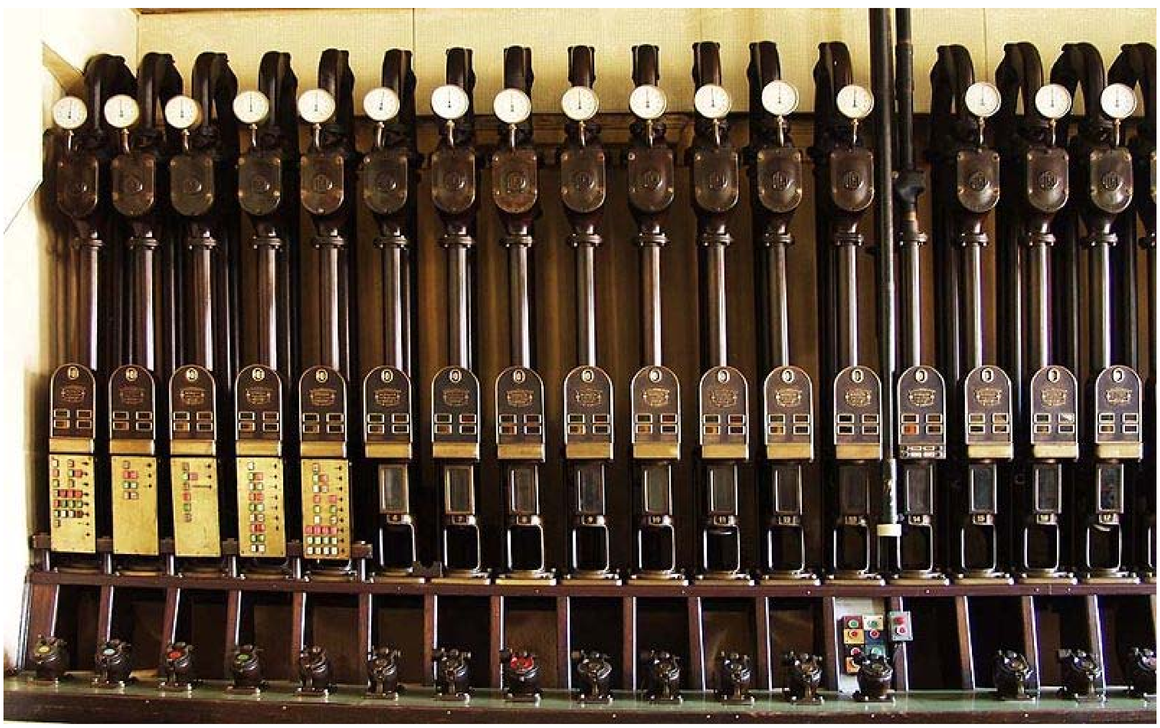
- Shunting the trains into atmospheric formation was difficult or cumbersome (although this would have seemed less of a problem in an era when much shunting was carried out by horse- or man-power).
- A change in traction, with consequent delays, would be necessary if an atmospheric line became part of a through route.
- There had to be gaps in the atmospheric tubes at points, with flyovers or similar arrangements at junctions; and special arrangements would have been needed at level crossings.

Overall assessment

The atmospheric system foresaw the inherent efficiencies of delivering centrally generated power to the line side rather than generating it on individual locomotives, as would ultimately become the normal practice with electrification systems. The use of modern materials and technology would overcome many of the problems of the original systems, but atmospheric railways were ultimately too inflexible for widespread use.

Chapter 13

Prague Pneumatic Post



Main control panel, showing the inlets, outlets and lane controllers

The **Prague pneumatic post** (Czech: Pražská potrubní pošta) is the world's last preserved municipal pneumatic post system. It is an underground system of metal tubes under the wider centre of Prague, totalling about 55 kilometres (34 mi) in length. Known as the Old Lady of Czech telecommunications, the system started service in 1889 and remained in use by the government, banks and the media until it was rendered inoperative by the August 2002 European floods. The current owner, Telefónica O2 Czech Republic gradually is repairing and conserving the system; due to limited funding the system remained inoperative as of March 2007.

History

The Prague pneumatic post entered public service on March 4, 1889. The first lane had been constructed as early as 1887, but at first it only served internal purposes. It ran from the main post office in Jindřišská st. (next to the Wenceslas Square) to the post bureau at Malé náměstí square (next to the Old Town Square) in the Old Town. (This bureau was situated in a corner house with Linhartská st., belonging to the V. J. Rott company, next to a house that is called 'U Rotta' today.) The first lane was later extended as far as the Prague Castle, making it over 5 km long. Prague was the fifth city in the world to receive a pneumatic post system after London, Vienna, Berlin, and Paris, which was considered a major achievement for Prague.

The system initially was employed mainly for sending telegrams. Only three stations had been connected between the Prague post and the telegraph office as of 1901.

The system was established for those desiring to send a document fast. The document would be taken to the post office and rolled up into a metal capsule. The clerk would then drop the metal capsule down a hatch leading to a predestined location. After the clerk pressed a button, the capsule would be moved by compressed air along a network of tubes beneath the pavement.

The main growth of the network dates to the economically prosperous era of 1927–1932. In those years, new lanes were constructed and tens of thousands of capsules transported per month. During the Prague Uprising the pneumatic post played a role in supplying the besieged building of the Czech radio.

In the late 1990s, the system was used by over 20 subscribers and operating at a loss, so kept rather for prestigious reasons. The traffic weakened gradually and the 2002 floods seriously damaged it, flooding 5 of the 11 underground engine rooms.

Air-pump control panel, with an ammeter and a manometer set in a marble slab

Pipes

The lanes consist of steel pipes of 65 mm bore and wall thickness of 2.5–3 mm. The pipes are connected with tight couplers 14 cm long to ensure perfect coaxial alignment and then welded together, ensuring air-tightness. To prevent dispersion current from causing excess corrosion, ceramic insulators are inserted between the pipe segments at some places. Pipes buried underground are protected from the outside by a layer of fiberglass, wound around at increased temperature and coated with hot asphalt. The pipeline is typically buried under the Prague sidewalks 80–120 cm deep. Inside buildings and in the Prague trunk conduit network the pipes simply are coated with anti-corrosive paint.

The minimum bend radius is 250 cm for underground pipes, but 300 cm is the most commonly used radius. Inside buildings a bend radius as low as 200 cm is allowed. The bends are made of special annealed pipes at normal temperature, using a custom-made bender.

A signaling cable is laid along with the pipe, enabling communication with the track components.

The lane segments are equipped with dumb wells, where the pipeline can be opened and inspected, or a stuck capsule removed. For this purpose a heavier capsule can be sent at a pressure of up to 30 atm, knocking the stuck capsule out.

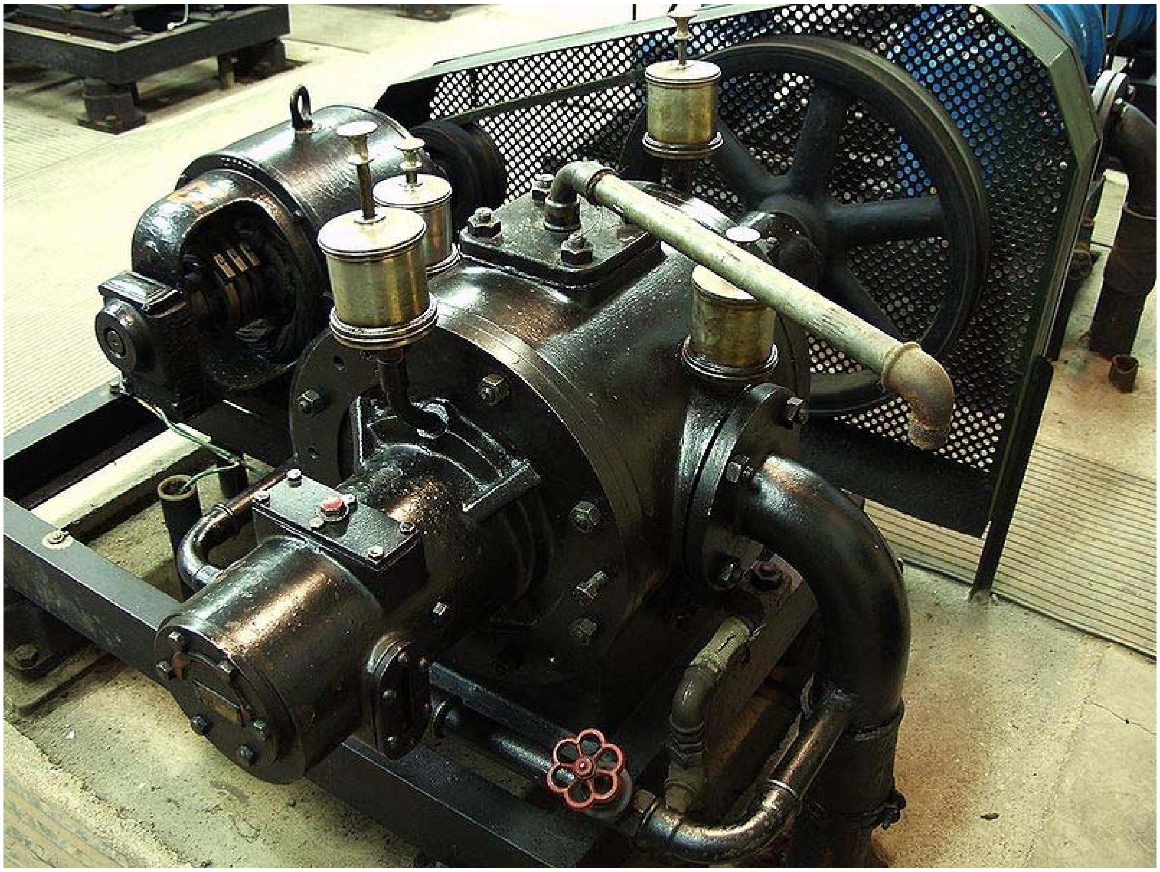
Transport capsule

A capsule for transporting packages using the Prague pneumatic post network

The system uses aluminium capsules measuring 48 mm in outer-diameter and 200 mm in length. On the rear end they are fitted with a plastic circlet, preventing friction against walls of the pipe and a soft plastic skirt, sealing air behind the capsule. The diameter of the rear circlet is 57 mm. The remaining 8 millimeters of the bore are sealed just by the skirt, allowing for excellent airtightness and low friction at the same time.

Propulsion units

Engine room in the main post office building in Jindřišská st. at 50°5′0.04″N 14°25′40.6″E / 50.0833444°N 14.427944°E



Original bladed air pump from the 1930s

Each lane is equipped with a dedicated propulsion unit, consisting of an electrically-powered air pump. One pump can service at most 3 kilometers of pipeline, so it's necessary to use several pumps on longer lanes.

The pumps must be reversible, creating either pressure or vacuum. The pumps are connected to the pipes with tee-fittings. On both sides of the tee the pipe is equipped with switches activated by a passing capsule.

At first the pump is set to intake mode, pulling the capsule towards the tee. Before reaching it, the capsule hits the first switch, causing the pump to start reversing. Meanwhile the capsule reaches the tee-fitting. As it passes the tee, the pump is already fully reversed and starts to push the capsule away.

The older pumps were bladed, having a single blade, mounted eccentrically inside a 300 mm high cylinder. More recent pumps employ a rotating piston instead.

Packages

The capsules can be loaded with packages up to 5 cm in diameter and 30 cm in length. Their weight can be up to 3 kg. Generally these were rolled-up telegrams, but any package within the set limits could be transported.

For obvious reasons, dangerous and corrosive substances, which could damage the pipeline, were banned. On the other hand, the travel speed could be adjusted, allowing for transporting fragile packages.

Lanes and stations

Lane input hatch, where the capsules were inserted

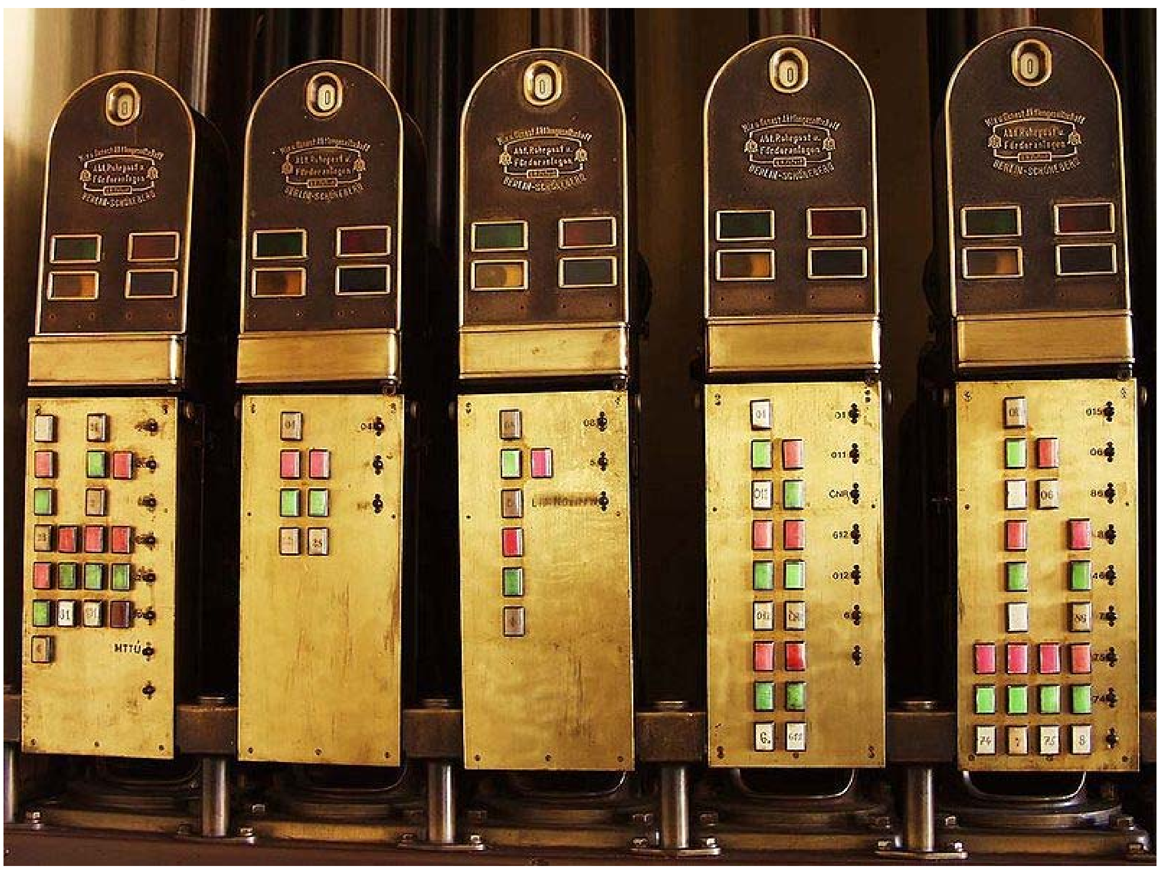
The Prague pneumatic post network consists of five main lanes arranged in a star topology, fitted with switches and concentrators, and of *subscriber's lines*. The total length of the lanes is about 55 kilometers. Some of the most frequented segments have two pipes (one for each direction), but the majority of the lanes use a single pipe and the direction is determined by setting up the pumps to run in the desired direction. The main lanes connect the following post offices and bureaus:

- Jindřišská st. – Prague 2, Prague 3, Prague 10
- Jindřišská st. – Prague 1, Prague 2
- Jindřišská st. – Prague 5
- Jindřišská st. – Prague 6
- Jindřišská st. – Prague 7

Originally there were 16 subscriber's lines, but only 7 have been preserved up till today. A total of 24 pneumatic post stations remain today.

The network crosses the river Vltava in three spots making use of bridges (Hlávkův most, Mánesův most, most Legií).

The headquarters/switchboard



Controllers of the five main lanes with counters, indicator lights and switch controls

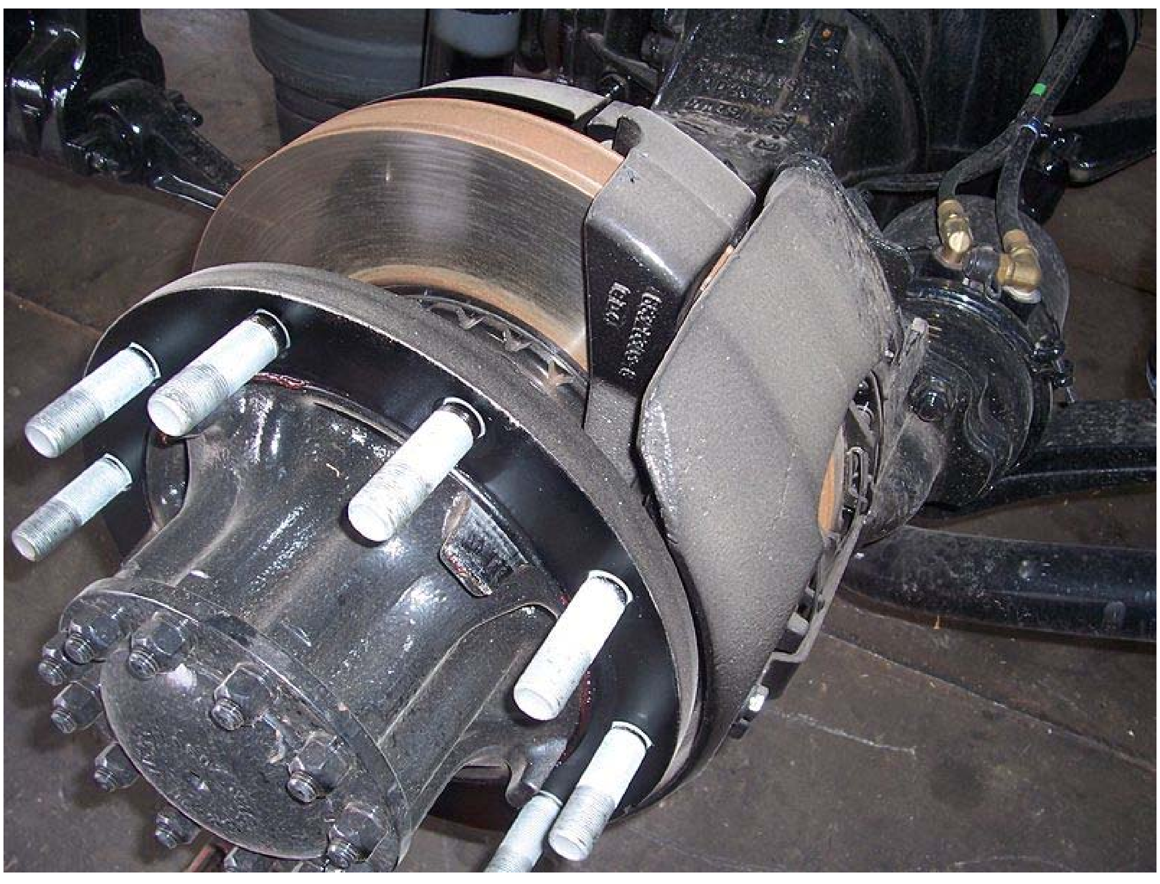
All the lanes converge to the *main post office* in Jindřišská st. Here all the packages were carefully recorded and from here the network was controlled and monitored. This is also the place where the packages were forwarded from one lane to another. The capsule was picked up from a receiving pocket by a member of the staff, recorded and inserted into the inlet of another lane.

The current lane state was indicated by indicator lights on the lane's controller. Up to 10 packages in 30-second intervals could be sent on the same lane at once, although this was rarely used in practice.

When sending capsules to **switched lanes**, the capsules had to be sent out in a predefined order, as the switches could only be activated before commencing the transfer. The first capsule would be diverted, after which the switch would automatically slide back to its neutral position, sending the remaining capsules in the straight direction. Therefore, the capsule that was meant to branch off had to be sent first.

Chapter 14

Air Brake (Road Vehicle)



Truck air actuated disc brake.

Air brakes are used in trucks, buses, trailers, and semi-trailers. George Westinghouse first developed air brakes for use in railway service. He patented a safer air brake on March 5, 1872. Originally designed and built for use on railroad train application, air brakes remain the exclusive systems in widespread use. Westinghouse made numerous alterations to improve his air pressured brake invention, which led to various forms of the automatic brake and the subsequent use on heavier road vehicles.

Compressed air brake system

Compressed air brake systems are typically used on heavy trucks and buses (Note the difference between pneumatic brakes and pneumatic/hydraulic). The system consists of service brakes, parking brakes, a control pedal, an engine-driven air compressor and a compressed air storage tank. For the parking brake, there is a disc or drum brake arrangement which is designed to be held in the 'applied' position by spring pressure. Air pressure must be produced to release these "spring brake" parking brakes. For the service brakes (the ones used while driving for slowing or stopping) to be applied, the brake pedal is pushed, routing the air under pressure (approx 100-125psi) to the brake chamber, causing the brake to reduce wheel rotation speed. Most types of truck air brakes are drum units, though there is an increasing trend towards the use of disc brakes in this application. The air compressor air draws filtered air from the atmosphere and forces it into high-pressure reservoirs at around 120 PSI. Most heavy vehicles have a gauge within the driver's view, indicating the availability of air pressure for safe vehicle operation, often including warning tones or lights. Setting of the parking/emergency brake releases the pressurized air pressure in the lines between the compressed air storage tank and the brakes, thus actuating the (spring brake) parking braking hardware. An air pressure failure at any point would apply full spring brake pressure immediately.

In the Florida CDL Handbook , this process is described. Here is the section describing the service brake:

5.1.7 - The Brake Pedal

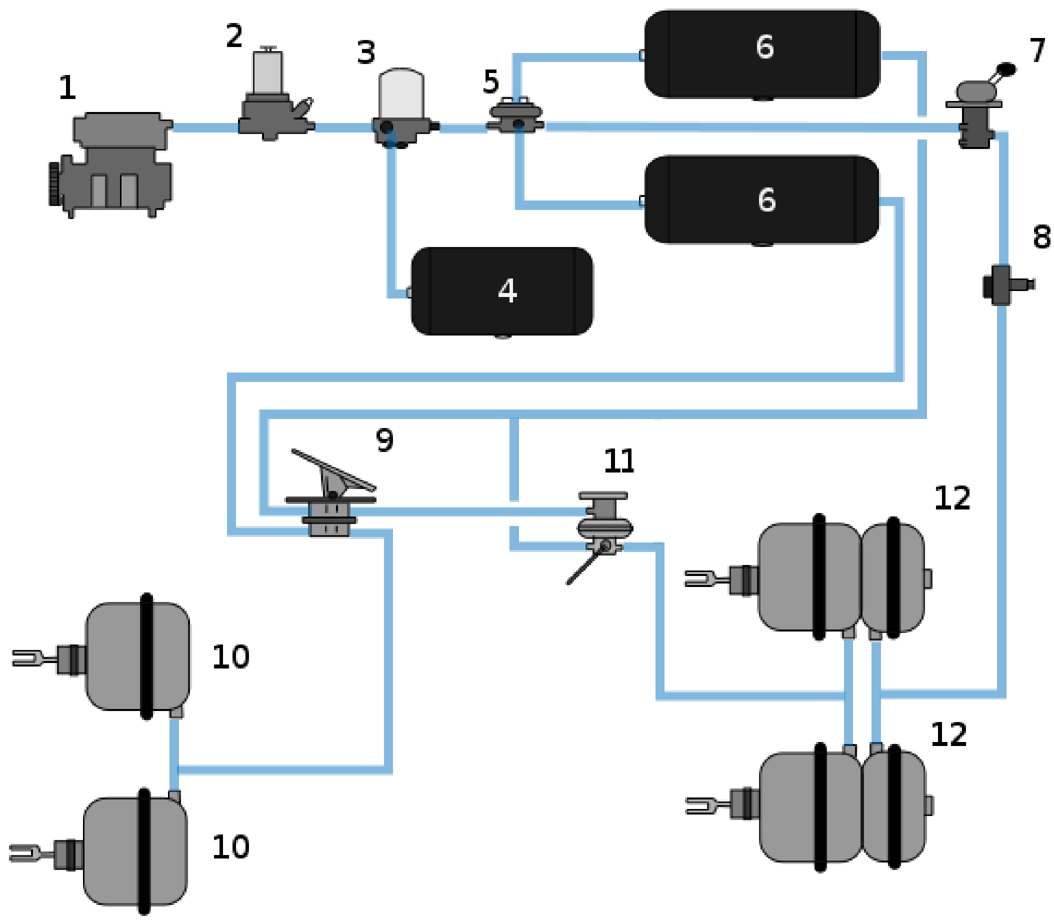
Brakes are applied by pushing down the brake pedal. (It is also called the foot valve or treadle valve.) Pushing the pedal down harder applies more air pressure. Letting up on the brake pedal reduces the air pressure and releases the brakes. Releasing the brakes lets some compressed air go out of the system, so the air pressure in the tanks is reduced. It must be made up by the air compressor. Pressing and releasing the pedal unnecessarily can let air out faster than the compressor can replace it. If the pressure gets too low, the brakes won't work.

These large vehicles also have an emergency brake system, in which the compressed air holds back a mechanical force (usually a spring) which will otherwise engage the brakes. Hence, if air pressure is lost for any reason, the brakes will engage and bring the vehicle to a stop.

Design and function

A compressed air brake system is divided into a supply system and a control system. The supply system compresses, stores and supplies high-pressure air to the control system as well as to additional air operated auxiliary truck systems (gearbox shift control, clutch pedal air assistance servo, etc.).

Supply system



" Over simplified" air brake diagram on a commercial road vehicle (does not show all air reservoirs and all applicable air valves).

The air compressor is driven off of the engine either by crankshaft pulley via a belt or directly off of the engine timing gears. It is lubricated and cooled by the engine lubrication and cooling systems. Compressed air is first routed through a cooling coil and into an air dryer which removes moisture and oil impurities and also may include a pressure regulator, safety valve and a smaller purge reservoir. As an alternative to the air dryer, the supply system can be equipped with an anti freeze device and oil separator. The compressed air is then stored in a reservoir (also called a wet tank) from which it is then distributed via a four way protection valve into the front and rear brake circuit air reservoir, a parking brake reservoir and an auxiliary air supply distribution point. The system also includes various check, pressure limiting, drain and safety valves.

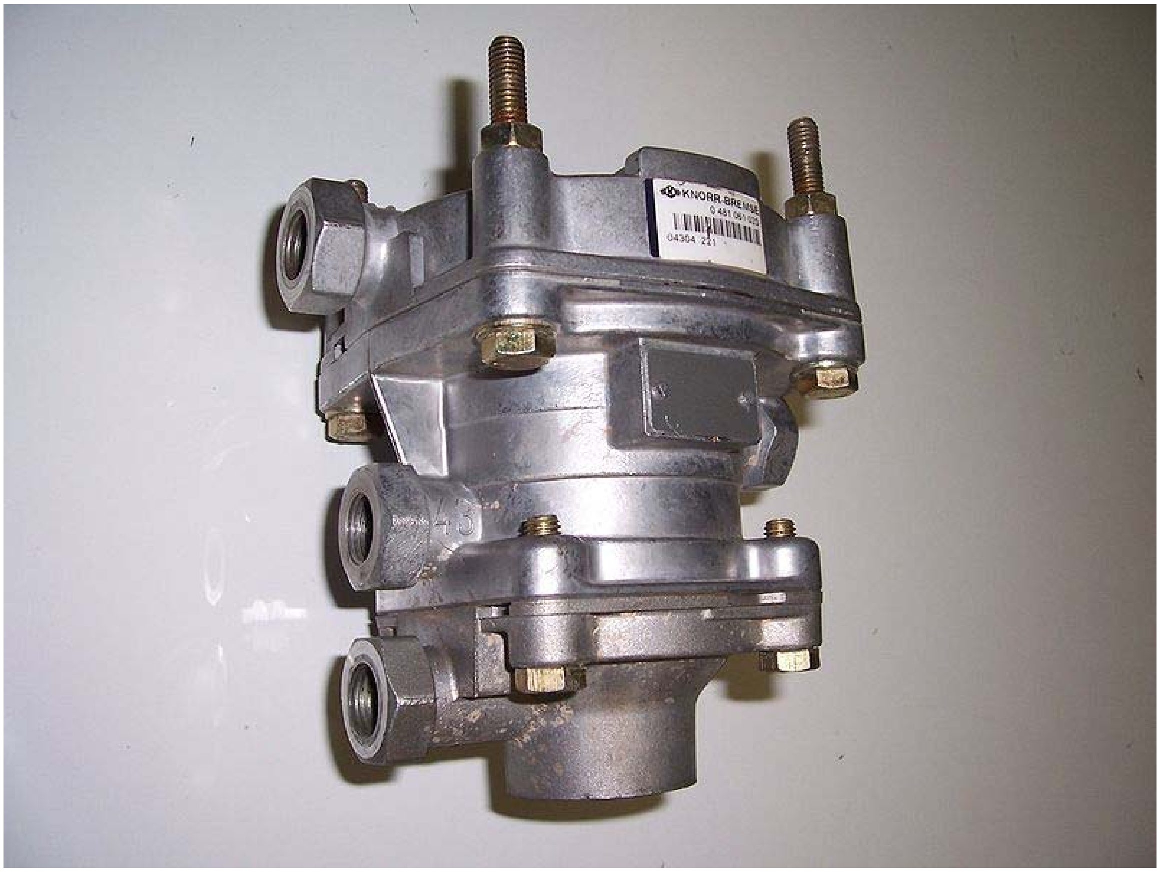
Control system

The control system is further divided into two service brake circuits: the parking brake circuit and the trailer brake circuit. This dual brake circuit is further split into front and rear wheel circuits which receive compressed air from their individual reservoirs for added safety in case of an air leak. The service brakes are applied by means of a brake pedal air valve which regulates both circuits. The parking brake is the air operated spring brake type where its applied by spring force in the spring brake cylinder and released by compressed air via hand control valve. The trailer brake consists of a direct two line system: the supply line (marked red) and the separate control or service line (marked blue). The supply line receives air from the prime mover park brake air tank via a park brake relay valve and the control line is regulated via the trailer brake relay valve. The operating signals for the relay are provided by the prime mover brake pedal air valve, trailer service brake hand control (subject to a country's relevant heavy vehicle legislation) and the prime mover park brake hand control.

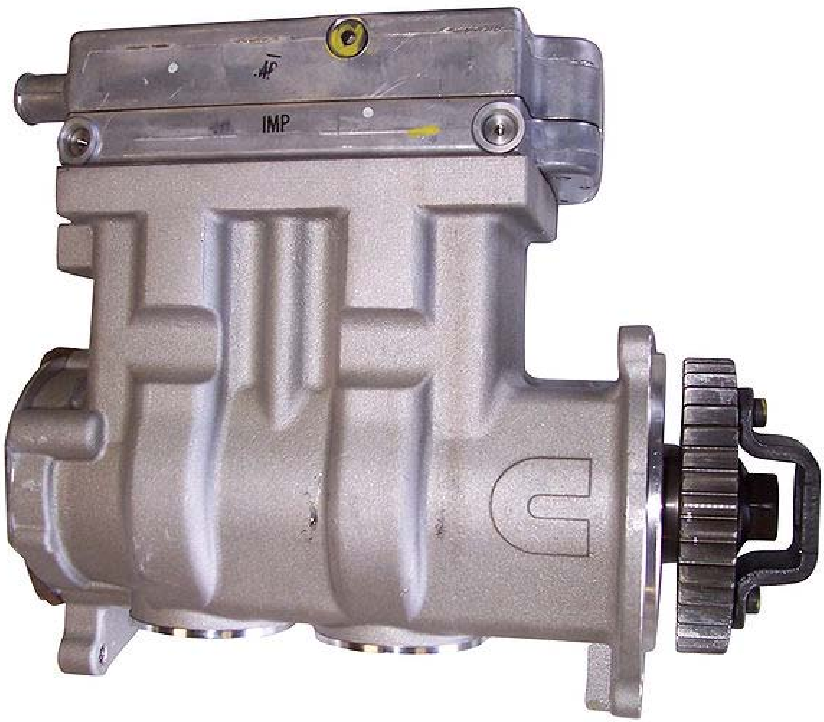
Park brake valve

Spring brake cylinder

Air brake foot valve



Trailer brake relay valve



Truck air compressor

Air dryer

Air brake relay valve

Four way protection valve

Exposed Physical Structure

This example of the air brake consists of a physical structure on the exterior of a vehicle that will increase the vehicle's drag coefficient, and therefore slow it down. Air brakes of this sort are ineffective at normal road vehicle speeds, and therefore are reserved for vehicles which need to quickly decelerate from high speeds, such as race and high performance sports cars.

The Bugatti Veyron's hydraulic rear spoiler/air brake in the wing position.

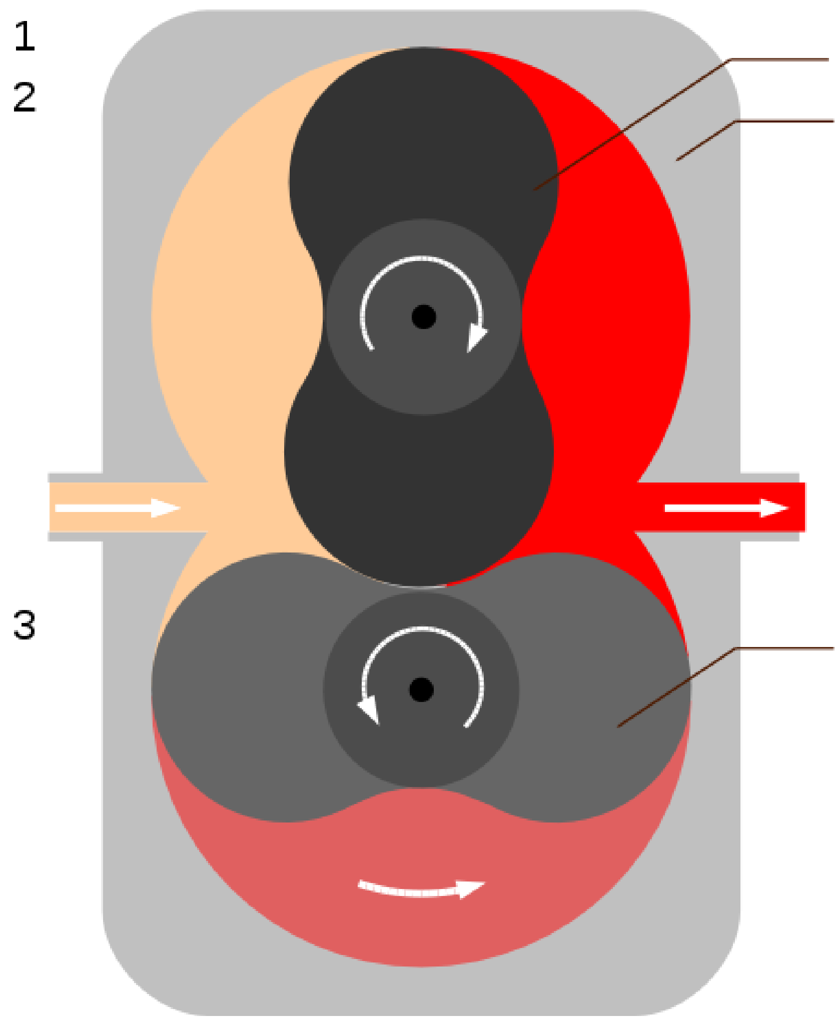
The Bugatti Veyron, the second fastest production car in the world, features a rear spoiler which, at speeds above 200 km/h (120 mph), also acts as an air brake, snapping to a 55° angle in 0.4 seconds once the brake pedal is pressed, providing an additional 0.68 g (6.66 m/s^2) of deceleration (equivalent to the stopping power of an ordinary hatchback). Top Fuel Dragsters and other drag racing cars that routinely reach speeds greater than 150 miles per hour use a physical air brake via a parachute(s) after the completion of a race.

In 1994, NASCAR introduced roof flaps to the cars, which are designed to keep cars from becoming airborne and possibly flipping. Following Rusty Wallace's crash at Talladega, Penske Racing designed the original roof flaps. NASCAR team owner Jack Roush helped improve on the design of the roof flaps, in conjunction with Embry-Riddle Aeronautical University, Daytona, Florida, USA. During a spin, the car rotates it eventually reaches an angle where the oncoming air reacts with the profile of the vehicle in the same manner as a wing. If the speed is high enough, air flowing over this aerofoil shape will create sufficient lift to force the car to become airborne. To prevent this, NASCAR developed a set of flaps that are recessed into pockets on the roof of the car. As a car is turned around and reaches an angle where significant lift occurs, the low pressure above the flaps causes them to deploy. The first flap, oriented 140 degrees from the centerline of the car, typically deploys first. After flap deployment, higher pressure air is forced through an air tube which connects to a second flap, deploying it. This second flap ensures that, should the car continue to spin, no further lift will be created as the vehicle's angle changes. The deployment of these flaps eliminates most of the lift on the vehicle.

The roof flaps generally keep the cars on the ground as they spin, although it is not guaranteed.

Chapter 15

Vacuum Pump



The Roots blower is one example of a vacuum pump

A **vacuum pump** is a device that removes gas molecules from a sealed volume in order to leave behind a partial vacuum. The vacuum pump was invented in 1650 by Otto von Guericke.

Types

Pumps can be broadly categorized according to three techniques:

- **Positive displacement** pumps use a mechanism to repeatedly expand a cavity, allow gases to flow in from the chamber, seal off the cavity, and exhaust it to the atmosphere.
- **Momentum transfer** pumps, also called **molecular pumps**, use high speed jets of dense fluid or high speed rotating blades to knock gas molecules out of the chamber.
- **Entrapment** pumps capture gases in a solid or adsorbed state. This includes **cryopumps**, **getters**, and **ion pumps**.

Positive displacement pumps are the most effective for low vacuums. Momentum transfer pumps in conjunction with one or two positive displacement pumps are the most common configuration used to achieve high vacuums. In this configuration the positive displacement pump serves two purposes. First it obtains a rough vacuum in the vessel being evacuated before the momentum transfer pump can be used to obtain the high vacuum, as momentum transfer pumps cannot start pumping at atmospheric pressures. Second the positive displacement pump backs up the momentum transfer pump by evacuating to low vacuum the accumulation of displaced molecules in the high vacuum pump. Entrapment pumps can be added to reach ultrahigh vacuums, but they require periodic regeneration of the surfaces that trap air molecules or ions. Due to this requirement their available operational time can be unacceptably short in low and high vacuums, thus limiting their use to ultrahigh vacuums. Pumps also differ in details like manufacturing tolerances, sealing material, pressure, flow, admission or no admission of oil vapor, service intervals, reliability, tolerance to dust, tolerance to chemicals, tolerance to liquids and vibration.

Performance measures

- **Pumping speed** refers to the volume flow rate of a pump at its inlet, often measured in volume per unit of time. Momentum transfer and entrapment pumps are more effective on some gases than others, so the pumping rate can be different for each of the gases being pumped, and the average volume flow rate of the pump will vary depending on the chemical composition of the gases remaining in the chamber.
- **Throughput** refers to the pumping speed multiplied by the gas pressure at the inlet, and is measured in units of pressure·volume/unit time. At a constant temperature, throughput is proportional to the number of molecules being pumped per unit time, and therefore to the mass flow rate of the pump. When discussing a leak in the system or backstreaming through the pump, **throughput** refers to the

volume leak rate multiplied by the pressure at the vacuum side of the leak, so the leak throughput can be compared to the pump throughput.

Positive displacement and momentum transfer pumps have a constant volume flow rate, (pumping speed,) but as the chamber's pressure drops, this volume contains less and less mass. So although the pumping speed remains constant, the throughput and mass flow rate drop exponentially. Meanwhile, the leakage, evaporation, sublimation and backstreaming rates continue to produce a constant throughput into the system.

Positive displacement

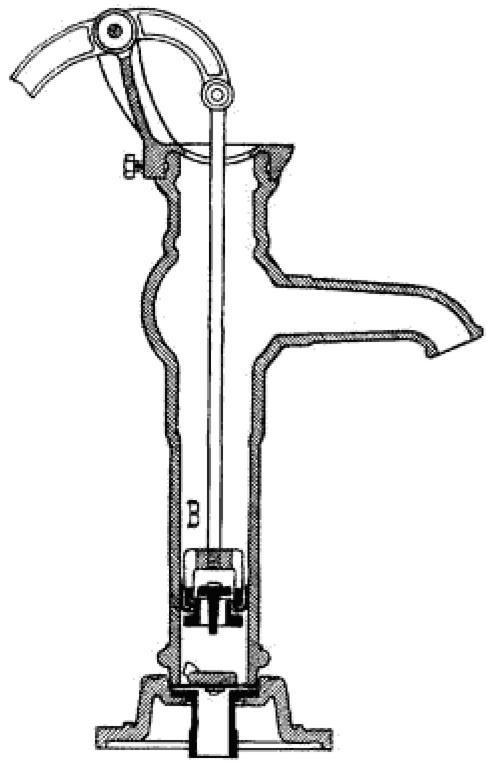


Fig. 9.

The manual water pump draws water up from a well by creating a vacuum that water rushes in to fill. In a sense, it acts to evacuate the well, although the high leakage rate of dirt prevents a high quality vacuum from being maintained for any length of time.

Mechanism of a scroll pump

Fluids cannot be pulled, so it is technically impossible to create a vacuum by suction. Suction is the movement of fluids into a vacuum under the effect of a higher external pressure, but the vacuum has to be created first. The easiest way to create an artificial vacuum is to expand the volume of a container. For example, the diaphragm muscle expands the chest cavity, which causes the volume of the lungs to increase. This expansion reduces the pressure and creates a partial vacuum, which is soon filled by air pushed in by atmospheric pressure

To continue evacuating a chamber indefinitely without requiring infinite growth, a compartment of the vacuum can be repeatedly closed off, exhausted, and expanded again. This is the principle behind *positive displacement pumps,* like the manual water pump for example. Inside the pump, a mechanism expands a small sealed cavity to create a deep vacuum. Because of the pressure differential, some fluid from the chamber (or the well, in our example) is pushed into the pump's small cavity. The pump's cavity is then sealed from the chamber, opened to the atmosphere, and squeezed back to a minute size.

More sophisticated systems are used for most industrial applications, but the basic principle of cyclic volume removal is the same:

- Rotary vane pump, the most common
- Diaphragm pump, zero oil contamination
- Liquid ring pump
- Piston pump, cheapest
- Scroll pump, highest speed dry pump
- Screw pump (10 Pa)
- Wankel pump
- External vane pump
- Roots blower, also called a **booster pump**, has highest pumping speeds but low compression ratio
- Multistage Roots pump that combine several stages providing high pumping speed with better compression ratio
- Toepler pump
- Lobe pump

The base pressure of a rubber- and plastic-sealed piston pump system is typically 1 to 50 kPa, while a scroll pump might reach 10 Pa (when new) and a rotary vane oil pump with a clean and empty metallic chamber can easily achieve 0.1 Pa.

A positive displacement vacuum pump moves the same volume of gas with each cycle, so its pumping speed is constant unless it is overcome by backstreaming.

Momentum transfer

A cutaway view of a turbomolecular high vacuum pump

In a **momentum transfer** pump, gas molecules are accelerated from the vacuum side to the exhaust side (which is usually maintained at a reduced pressure by a positive displacement pump). Momentum transfer pumping is only possible below pressures of about 0.1 kPa. Matter flows differently at different pressures based on the laws of fluid dynamics. At atmospheric pressure and mild vacuums, molecules interact with each other and push on their neighboring molecules in what is known as viscous flow. When the distance between the molecules increases, the molecules interact with the walls of the chamber more often than the other molecules, and **molecular pumping** becomes more effective than positive displacement pumping. This regime is generally called **high vacuum.**

Molecular pumps sweep out a larger area than mechanical pumps, and do so more frequently, making them capable of much higher pumping speeds. They do this at the expense of the seal between the vacuum and their exhaust. Since there is no seal, a small pressure at the exhaust can easily cause backstreaming through the pump; this is called

stall. In high vacuum, however, pressure gradients have little effect on fluid flows, and molecular pumps can attain their full potential.

The two main types of molecular pumps are the diffusion pump and the turbomolecular pump. Both types of pumps blow out gas molecules that diffuse into the pump by imparting momentum to the gas molecules. Diffusion pumps blow out gas molecules with jets of oil or mercury, while turbomolecular pumps use high speed fans to push the gas. Both of these pumps will stall and fail to pump if exhausted directly to atmospheric pressure, so they must be exhausted to a lower grade vacuum created by a mechanical pump.

As with positive displacement pumps, the base pressure will be reached when leakage, outgassing, and backstreaming equal the pump speed, but now minimizing leakage and outgassing to a level comparable to backstreaming becomes much more difficult.

- Diffusion pump
- Turbomolecular pump

Entrapment

Entrapment pumps may be cryopumps, which use cold temperatures to condense gases to a solid or adsorbed state, **chemical** pumps, which react with gases to produce a solid residue, or ionization pumps, which use strong electrical fields to ionize gases and propel the ions into a solid substrate. A cryomodule uses cryopumping.

- Ion pump
- Cryopump
- Sorption pump
- Non-evaporative getter

Other pump types

- Venturi vacuum pump (aspirator) (10 to 30 kPa)
- Steam ejector (vacuum depends on the number of stages, but can be very low)

Techniques

Vacuum pumps are combined with chambers and operational procedures into a wide variety of vacuum systems. Sometimes more than one pump will be used (in series or in parallel) in a single application. A partial vacuum, or rough vacuum, can be created using a positive displacement pump that transports a gas load from an inlet port to an outlet (exhaust) port. Because of their mechanical limitations, such pumps can only achieve a low vacuum. To achieve a higher vacuum, other techniques must then be used, typically in series (usually following an initial fast pump down with a positive displacement pump). Some examples might be use of an oil sealed rotary vane pump (the most common positive displacement pump) backing a diffusion pump, or a dry scroll pump backing a turbomolecular pump. There are other combinations depending on the level of vacuum being sought.

Achieving high vacuum is difficult because all of the materials exposed to the vacuum must be carefully evaluated for their outgassing and vapor pressure properties. For example, oils, and greases, and rubber, or plastic gaskets used as seals for the vacuum chamber must not boil off when exposed to the vacuum, or the gases they produce would prevent the creation of the desired degree of vacuum. Often, all of the surfaces exposed to the vacuum must be baked at high temperature to drive off adsorbed gases.

Outgassing can also be reduced simply by desiccation prior to vacuum pumping. High vacuum systems generally require metal chambers with metal gasket seals such as Klein flanges or ISO flanges, rather than the rubber gaskets more common in low vacuum chamber seals. The system must be clean and free of organic matter to minimize outgassing. All materials, solid or liquid, have a small vapour pressure, and their outgassing becomes important when the vacuum pressure falls below this vapour pressure. As a result, many materials that work well in low vacuums, such as epoxy, will become a source of outgassing at higher vacuums. With these standard precautions, vacuums of 1 mPa are easily achieved with an assortment of molecular pumps. With careful design and operation, 1 µPa is possible.

Several types of pumps may be used in sequence or in parallel. In a typical pumpdown sequence, a positive displacement pump would be used to remove most of the gas from a chamber, starting from atmosphere (760 Torr, 101 kPa) to 25 Torr (3 kPa). Then a sorption pump would be used to bring the pressure down to 10^{-4} Torr (10 mPa). A cryopump or turbomolecular pump would be used to bring the pressure further down to 10^{-8} Torr (1 µPa). An additional ion pump can be started below 10^{-6} Torr to remove gases which are not adequately handled by a cryopump or turbo pump, such as helium or hydrogen.

Ultra high vacuum generally requires custom-built equipment, strict operational procedures, and a fair amount of trial-and-error. Ultra-high vacuum systems are usually made of stainless steel with metal-gasketed conflat flanges. The system is usually baked, preferably under vacuum, to temporarily raise the vapour pressure of all outgassing materials in the system and boil them off. If necessary, this outgassing of the system can also be performed at room temperature, but this takes much more time. Once the bulk of the outgassing materials are boiled off and evacuated, the system may be cooled to lower vapour pressures to minimize residual outgassing during actual operation. Some systems are cooled well below room temperature by liquid nitrogen to shut down residual outgassing and simultaneously cryopump the system.

In ultra-high vacuum systems, some very odd leakage paths and outgassing sources must be considered. The water absorption of aluminium and palladium becomes an unacceptable source of outgassing, and even the absorptivity of hard metals such as stainless steel or titanium must be considered. Some oils and greases will boil off in extreme vacuums. The porosity of the metallic chamber walls may have to be considered, and the grain direction of the metallic flanges should be parallel to the flange face.

The impact of molecular size must be considered. Smaller molecules can leak in more easily and are more easily absorbed by certain materials, and molecular pumps are less effective at pumping gases with lower molecular weights. A system may be able to evacuate nitrogen (the main component of air) to the desired vacuum, but the chamber could still be full of residual atmospheric hydrogen and helium. Vessels lined with a highly gas-permeable material such as palladium (which is a high-capacity hydrogen sponge) create special outgassing problems.

Uses of vacuum pumps

Vacuum pumps are used in many industrial and scientific processes including:

- Composite Plastic moulding processes (VRTM)
- Driving some of the flight instruments in most aircraft.
- The production of most types of electric lamps, vacuum tubes, and CRTs where the device is either left evacuated or re-filled with a specific gas or gas mixture
- Semiconductor processing, notably ion implantation, dry etch and PVD, ALD, PECVD and CVD deposition and soon in photolithography
- Electron microscopy
- Medical processes that require suction
- Medical applications such as such Radiotherapy, Radiosurgery, Radiopharmacy
- Analytical instrumentation to analyse gas, liquid, solid, surface and bio materials
- Mass spectrometers to create an ultra high vacuum between the ion source and the detector
- Vacuum Coating for decoration, for durability, for energy saving
- Glass coating for low e glass
- Hard coating for engine (as in Formula One)
- Ophthalmic coating
- Milking Machines
- Air conditioning service - removing all contaminants from the system before charging with refrigerant
- Trash compactor
- Vacuum engineering
- Sewage systems
- Freeze Drying
- As the main source of vacuum in dairy shed plant

Vacuum may be used to power, or provide assistance to mechanical devices. In diesel engined motor vehicles, a pump fitted on the engine (usually on the camshaft) is used to produce vacuum. In petrol engines, instead, vacuum is obtained as a side-effect of the operation of the engine and the flow restriction created by the throttle plate. This vacuum may then be used to power:

- The vacuum servo booster for the hydraulic brakes
- Motors that move dampers in the ventilation system
- The throttle driver in the cruise control servomechanism

In an aircraft, the vacuum source is often used to power gyroscopes in the various flight instruments. To prevent the complete loss of instrumentation in the event of an electrical failure, the instrument panel is deliberately designed with certain instruments powered by electricity and other instruments powered by the vacuum source.