Evolving Design

Steam Engines

Tetsuo Tomiyama (t.tomiyama@tudelft.nl)
Overview

• A Small Question
  • History of Thermodynamics
• Steam Engines
  • Thomas Newcomen
  • James Watt
• After Watt
  • Improvements
  • Steam Cars
  • Steam Locomotives
  • Steamboats
• Exam 2008
Which is the Oldest?

- MIT
  1861

- Second Law of Thermodynamics
  1850 Rudolf Julius Emanuel Clausius (1822-1888)

- TU Delft
  1842
Definition of Mechanical Engineering

• “To Build and Run a Steam Engine!”
  • (Unofficial Version@ME MIT)
History of Thermodynamics

- 1660: Robert Boyle's Law
- 1712: Thomas Newcomen
- 1741: École Nationale des Ponts et Chaussés
- 1765: James Watt (Only the Idea)
- 1770: Steam Car
- 1776: James Watt (The Engine), Steamboat
- 1794: Ecole Polytechnique
- 1804: Steam Locomotive
- 1824: Sadi Carnot, Carnot Cycle
- 1842: TU Delft
History of Thermodynamics

• 1843: James Joule, Mechanical Equivalent of Heat
• 1847: Hermann von Helmholtz, Definitive Statement of the First Law of Thermodynamics
• 1849: William John Macquorn Rankine, Saturated Vapor Table (Pressure and Temperature)
• 1850: Rudolf Clausius, The Second Law of Thermodynamics
• 1851: Thomson an Alternative Statement of the Second Law
• 1854: Clausius, Found dQ/T, but Did Not Name It
• 1854: Rankine, Entropy
• 1865: Clausius, Modern Macroscopic Concept of Entropy
• 1876: Josiah Willard Gibbs, the Free Energy as the Driving Force behind Chemical Reactions
• 1877: Boltzmann, the Relationship between Entropy and Probability
Development of Science

- **Push-Pull Linear Model**
  - Science Pushes
  - Technology (or Society) Pulls
    - Bacteriolysis -> Antibiotics
    - Nuclear Fission -> Atomic Bomb

- **Non-Linear Model**
  - Design Existed First
    - Pumps
    - Steam Engines
    - Machine Tools
Hero(n) of Alexandria (10-70 AD)

- Pneumatica, Automata, Mechanica, Metrica, etc.
- Aeolipile
- Heron’s Formula

\[ A = \sqrt{s(s-a)(s-b)(s-c)} \]
\[ s = \frac{a + b + c}{2} \]
Temple Door Opening Mechanism
Edward Somerset (1601?-1667)
2nd Marquess of Worcester

Ca. 1664
Vacuum around 1640

- **Evangelista Torricelli**
  - 1643 Barometer
  - Torr

- **Otto von Guericke**
  - 1654 Magdeburg Hemispheres

- **Robert Boyle**
  - Ca. 1660 Vacuum Pump Made by Robert Hooke
Huygens Family

- Constantijn, Sr.
  - 1596-1687
  - Frederik Hendrik
  - William II
- Constantijn, Jr.
  - 1627-1698
  - William III
  - Glorious Revolution
- Christiaan
  - 1629-1695
  - Full Time Scientist in Paris
Christiaan Huygens (1629-1695)

- Gun Powder-Based Internal Combustion Engine
- Rudolf Diesel Had a Similar Idea (Dust Coal)!
Denis Papin (1647-ca. 1712, F)

- Huguenot
  - Worked for Christiaan Huygens
- Later Went to England
  - Connection to Robert Boyle
- Invented Safety Valve
Papin’s Digester (1690)
Thomas Savery (ca. 1650-1715)

- First Steam Engine
- 1698 Patented
- 1699 Demonstration at Royal Society
  - Atmospheric Engine to Suck Water
  - Positive Pressure to Pump Up Water
  - Miner’s Friend
  - No Piston

©2011 Tetsuo Tomiyama
Thomas Newcomen’s Atmospheric Engine (1664-1729)

http://www.sciencemuseum.org.uk/on-line/energyhall/theme_See%20the%20engines%20at%20work.asp
Atmospheric Engine (1712): Thomas Newcomen

- At Most, 1 Bar
- Used for Pumping Up Water in Coal Mines
  - Length 10.5 Feet
  - Diameter 74 Inches
- Inefficient
  - Heating Up, Cooling Down
  - Steam Leaks!
  - Brass Boiler
    - Good Conductor and Radiator
John Smeaton

- Circularity Error 1/2 Inch for a 28 Inch-Diameter Cylinder

- Also a Civil Engineer
- Coined the Term “Civil Engineering”
James Watt (1736–1819)

- **Apprentice as Instrument Maker**
  - 1756-1764
    - University of Glasgow
    - Prof. Joseph Black
  - **1759**
    - Business Partnership with John Craig
  - **1763**
    - Prof. John Anderson
    - A Model of Newcomen Engine
  - **1765 Eureka!**
    - External Condenser
Toward Watt’s Steam Engine

- **First Sponsor**
  - John Roebuck, The Founder of Carron Iron Works
  - Patent was Difficult
  - Watt Obliged to Work as a Surveyor for 8 Years

- **Second Sponsor**
  - In 1775 Matthew Boulton, The Owner of Soho Foundry Works Near Birmingham
  - Boulton and Watt, Co. (B&W)
Steam Engine (1776): James Watt

- **Efficient**
  - Higher Pressure
  - External Condenser
  - Cylinder Jacket
  - Insulation

- **Needed Accuracy**
  - John Wilkinson’s Boring Machine
  - 72 Inches Diameter
  - “6 Pence Coin” Accuracy

http://www.sciencemuseum.org.uk/on-line/energyhall/theme_See%20the%20engines%20at%20work.asp
James Watt’s Steam Engine

1797年
Element 1: Accurate Machining

- John (Iron-Mad) Wilkinson
  - Double Supported Rotating Boring Bar
  - Watt was Proud of His Accuracy of 3/8\(^{th}\) a Inch (=1cm) from True Cylinders
- Wilkinson’s Machine Could Make 10 Times More True
  - 4-5 Times More Power (25 to 40 HP Up from 5 to 8)
  - Wilkinson Obtained the Exclusive Rights to Supply Precision Cylinders to B&W
Element 2: Sun and Planetary Gear

- **Need for Rotational Motion**
  - Rather Than Reciprocating Motion
  - James Pickard Had Patented the Crank Mechanism and a Flywheel in 1780

- **James Watt’s Workaround**
  - The Same as Pickard, but Less Efficient
  - Only in 1794, B&W Could Use the Crank
Element 3: Governor

- Governor
  - The First Feedback Control
  - “Flyballs”
Element 4: Indicator

• Kept as “Trade Secret”
Element 5: Watt’s Parallel Motion
Element 6: Patent

• In 1769,
  • “...in life there is nothing more foolish than inventing, here I work five or more years contriving an engine, and Mr. Moore hears of it, is more evil, gets three patents at once, publishes himself in the newspapers, hires 2,000 men, sets them to work for the whole world in St. George's Fields, gets a fortune at once, and prosecutes me for using my own inventions.”

• Even Disputes with William Mordoch (His Assistant)

• Business Expansion
  • While His Patent was Valid, UK Added about 750 HP/Year
  • After Expiration, 4,000 HP/Year
  • Fuel Efficiency Improved by a Factor of Five between 1810 and 1835
Element 7: Boulton’s Original Business Model (Product Service System)

- **Charge the Customer an Annual Fee based on the Fuel Saved**
  - B&W Asked How Many Horses the Mine Owned
  - Installed a Steam Engine
  - Charge One Third of the Annual Cost of Each Horse It Replaced, Over the Life of the Patent (Until 1800)

- **A Horse Cost about £15/Year**
  - Components for a 4 HP Engine £200-300, a 50 HP Around £1200
  - A 4 HP Engine = £60/Year, the Fee = £20/Year
  - ROI Starts 10 Years
  - A 50 HP Engine Charging £250 Yields Profits Only After 6 Years Over 25 Years!
Before and After Patent Expiration

• **Before Their Patent Expiration**
  • Trying to Extract Hefty Royalties through Licensing (Main Income)
  • Independent Contractors (e.g., Soho Foundry) Produced Most of the Parts, and B&W Merely Oversaw the Assembly of the Components by the Customer

• **After Patent Expiration**
  • B&W Started to Seriously Manufacture Steam Engines
  • Competitors Principally Aimed at Cheapness Rather than Excellence
  • B&W for Many Years Afterwards Could Keep Up Price and Increase Orders, Emphasizing Manufacturing and Service Activities

• **New Business Model after 1794**
  • Complete Manufacturing of Steam Engines without Depending on Subcontractors
  • Formed New Company: Boulton, Watt & Sons
Nicolas Léonard Sadi Carnot (1796-1832)

- **Carnot Cycle (1824)**
  - 1->2: Adiabatic Compression
  - 2->3: Isothermal Expansion
    - Absorbing $Q_H$ at $T_H$
  - 3->4: Adiabatic Expansion
  - 4->1: Isothermal Compression
    - Radiating $Q_L$ at $T_L$

\[
\eta = 1 - \frac{T_L}{T_H}
\]

- **Carnot Theorem**
  - No Engine Operating Between Two Heat Reservoirs Can Be More Efficient Than a Carnot Engine Operating Between Those Same Reservoirs.
Indicator Diagrams
Efficiency

![Graph showing the efficiency of steam engines over time with key dates and inventors marked: Newcomen, Watt, Cornish, Parson. The x-axis represents years from 1600 to 2000, and the y-axis represents efficiency in percentage.]
After Watt

- **Double Action**
- **High Pressure Engine**
  - Watt’s Engine was Effectively an Atmospheric Engine
  - Cornish Engine
    - Cornwall was a Mining Area
  - Crucuius
    - The World’s Biggest (Cornish Type) Steam Engine
- **Steamboat, Steam Locomotives**
- **Reheating**
- **Superheating**
Nicolas-Joseph Cugnot (1725-1804)

- 1770 The First Steam Engine Driven Vehicle
  - 2.5 tons tare, 4 tons Payload
  - 8 km/h
- Before Watt!
Stanley Steam Car (1923)
Steam Locomotives

- **1804**
  - Richard Trevithick and Andrew Vivian
  - Penydarren
- **1825**
  - George Stephenson
  - Locomotion
- **1829**
  - George Stephenson
  - Rocket
Richard Trevithick (1771-1833)

- **1801 High Pressure Engine**
  - A Neighbor of William Mordoch (Engineer at Boulton & Watt)
    - No Condenser
    - Watt Never Tried High Pressure
- **1801 Puffing Devil**
  - The First Steam Car
- **1804 Penydarren**
  - The First Steam Locomotive
- **Richard Francis and Francis Henry (His Grandsons) were Invited to Japan to Start Railways**

http://www.sciencemuseum.org.uk/on-line/energyhall/page91.asp
George Stephenson (1781-1848)

- **1825**
  - Locomotion
  - Stockton-Darlington Railway
- **1829**
  - Rocket
  - Liverpool-Manchester Railway
Working principle of a steam locomotive model using fuel gas

- Water filling
- Safety valve
- Steam regulator
- Gas filling
- Gas flow
- Reversing valve
- Simplified valve gear
Mersey Railway 0-6-4T No.5 "Cecil Raikes"

- Condenser
  - For Tunnel Use
Crucuius

http://www.cruquiusmuseum.nl/framesenglish.htm

Navy Propulsion System

©2011 Tetsuo Tomiyama
Superheating Steam Turbine

What happens to the temperature of outgoing vapor when the temperature of incoming water increases? (increases, decreases, remains the same?)

• Thermodynamical Equations?
Answer

• The incoming water $\rightarrow$ hotter
• The amount of heat needed to boil the water $\rightarrow$ reduced
• The water will boil $\rightarrow$ sooner
• The rate of steam production $\rightarrow$ increased
• The time the steam spends in the superheater $\rightarrow$ decreased
• The amount of heat transferred to the steam $\rightarrow$ decreased
• Thus the steam temperature at the outlet $\rightarrow$ will decrease
Claude-François-Dorothée, Marquis de Jouffroy d'Abbans (1751–1832)

- In 1776, Palmipède, the First Paddle-Driven Steamboat
Robert Fulton (1765-1815, USA)

• 1803
  • North River Steamboat (Clermont)
  • First Commercial Steamboat between New York and Albany
Sir Charles Algernon Parsons (1854-1931)

- **Steam Turbine (1887)**
  - Turbinia: 34 Knots
Conclusions

- **First Design, Not First Science**
- **Steam Engine**
  - High Power
  - High Efficiency
  - Lighter
- **Internal Combustion Engines Replaced External Combustion Engines as Power Source for Vehicles**
  - Coming Back?
    - Stirling Engine
    - Environmental Considerations
    - Hybrid, Motor Driven
Exam 2008

• Governor
  • The First Feedback Control
  • “Flyballs”
Consider Only 2 Masses

B1. Derive the equations that govern this mechanism focusing only on gravity and centrifugal force. Write your answer in the box below.

Centrifugal Force: \( m r \omega^2 \)

Gravity: \( mg \)

\[ T \sin \theta = m r \omega^2 \]

\[ T \cos \theta = mg \]
B2. Solve the equations and obtain $\theta$ and $x$ as a function of $\omega$. Draw rough graphs in the box below that illustrate $\theta$ and $x$ as a function of $\omega$.

\[
\begin{align*}
r &= L_1 \sin \theta \\
T \sin \theta &= mL_1 \sin \theta \omega^2 \\
T \cos \theta &= mg \\
mL_1 \omega^2 \cos \theta &= mg \\
\theta &= \cos^{-1} \left( \frac{g}{L_1 \omega^2} \right) \\
x &= 2L_2 \cos \theta = 2 \frac{L_2}{L_1} \frac{g}{\omega^2}
\end{align*}
\]
Solve Equations and Draw Graphs!

B2. Solve the equations and obtain $\theta$ and $x$ as a function of $\omega$. Draw rough graphs in the box below that illustrate $\theta$ and $x$ as a function of $\omega$.

$$r = L_1 \sin \theta$$
$$T \sin \theta = mL_1 \sin \theta \omega^2$$
$$T \cos \theta = mg$$
$$mL_1 \omega^2 \cos \theta = mg$$
$$\theta = \cos^{-1} \left( \frac{g}{L_1 \omega^2} \right)$$
$$x = 2L_2 \cos \theta = 2 \frac{L_2 \cdot g}{L_1 \omega^2}$$

$$0 \leq \cos \theta \leq 1$$
$$0 \leq \frac{g}{L_1 \omega^2} \leq 1$$
$$\omega \geq \sqrt[2]{\frac{g}{L_1}}$$
So, What Happens When $\omega_0$ Is Small???

- Until $\omega$ Becomes Bigger Than $\omega_0$
  - The Mechanism Doesn’t Open!
  - Some Fun Fair Machines Have an Offset

\[
\theta = \cos^{-1}\left(\frac{g}{L_1 \omega^2}\right)
\]

\[
\frac{g}{L_1 \omega_0^2} = 1
\]

\[
\omega_0 = \sqrt{\frac{g}{L_1}}
\]
B3. The governor engages only when the angular velocity $\omega$ is faster than a certain speed. For a governor with $L_1 = 0.2 \text{ m}$, calculate this engaging speed $\omega_0$ and write the answer in the box below. Assume that there is no limiting mechanism.

$$\omega_0 = \sqrt{\frac{g}{L_1}} = \sqrt{\frac{9.8}{0.2}} = \sqrt{49} = 7$$
Limiting Mechanism

B4. What are the purposes of the limiting mechanism?

• To Prevent “Sudden” Opening
  • Lower Side $\theta_1$
• To Prevent Complete Closing at Higher Speed
  • Complete Closing = Explosion
  • Higher Side $\theta_2$
Design Consideration

B5. In order to change the operational characteristics of the governor (e.g., gain, engaging speed, etc.), what kind of design changes can be made? Assume there is a limiting mechanism.

- Change $L_1, L_2$
- Change $\theta_1, \theta_2$
- Add Another Mass
  - Change of $m$ Doesn’t Contribute
  - Change of Effective $L_1$

\[
\theta = \cos^{-1}\left(\frac{g}{L_1\omega^2}\right)
\]

\[
x = 2L_2 \cos \theta = 2 \cdot \frac{L_2}{L_1} \cdot \frac{g}{\omega^2}
\]
Complete Analysis

• In Fact, Watt’s Governor is Not Trivial
  • Initiated “Control Theory” and “Control Engineering”
    • Mathematical Treatment for “Feedback Control”
    • Cybernetics
  • Still Modern Analyses Are Published