The role of experimental practice in the rise of technical thermodynamics at the University of Liège from 1868 to 1914

Vincent Lemort

Carnot Lille 2024 International Colloquium

Celebration of 200 years since Sadi Carnot's Réflexions sur la puissance motrice du Feu, 1824–2024

LIÈGE université

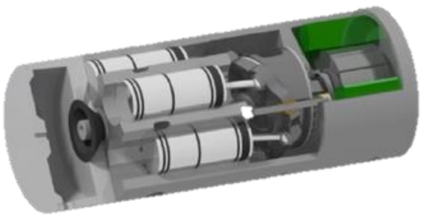
LABORATOIRE DE THERMODYNAMIQUE UNIVERSITÉ DE LIÈGE

UNIVERSITÉ PARIS 1 PANTHÉON SORBONNE

Introduction

About myself and the thermodynamics laboratory

- **Electromechanical engineer** (technical thermodynamics) with an interest in **history** of science and **technology**
- Research activities aim at developing **innovative thermal machines** and systems meeting our societal needs.
- Large interest in **updating/modernizing old techniques** (hybridized with newer techniques):
  - ✓ Heat pumps
  - ✓ Heat engines
  - ✓ Thermal storages…
  - ✓ …
  - ✓ Carnot batteries



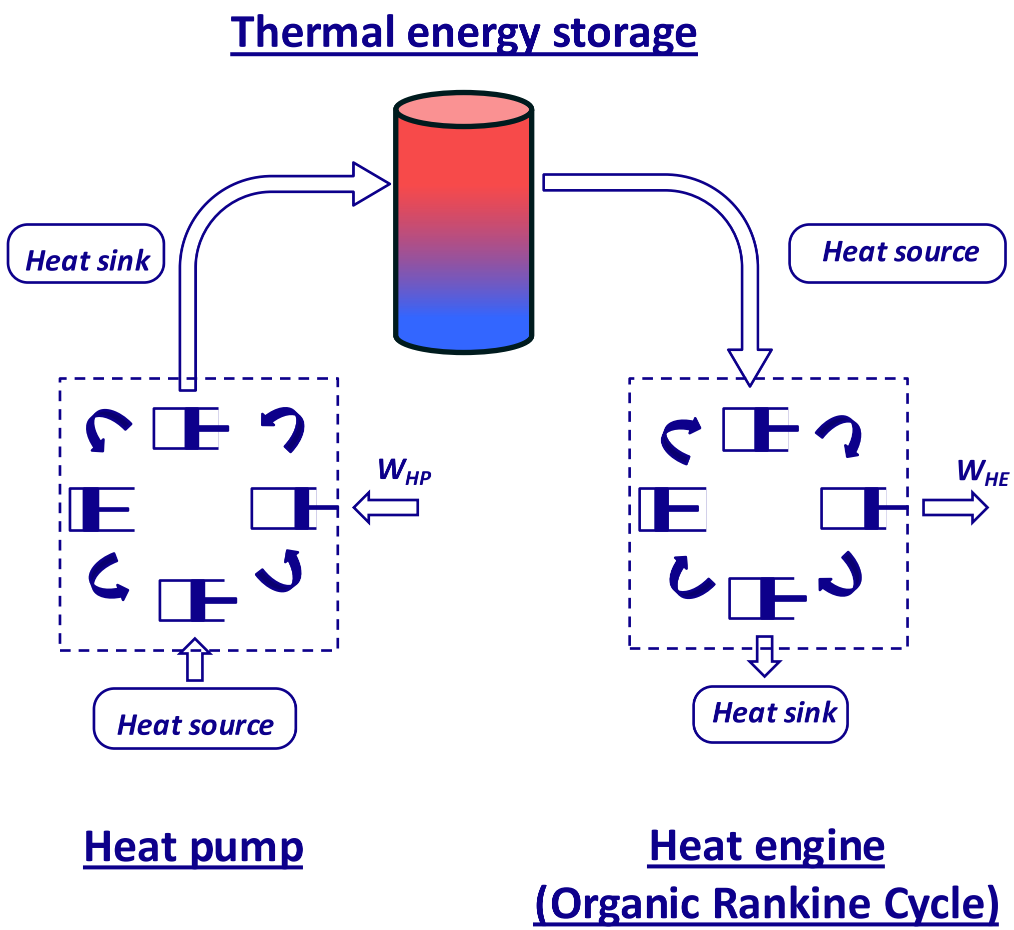
Modern axial piston expander inspired from 19th century machine and operated with a refrigerant (collaboration with Exoes)

Introduction

About myself and the thermodynamics laboratory

$$\eta_{P2P} = \frac{W_{HE}}{W_{HP}} = COP_{hp}\,\eta_{ORC}$$

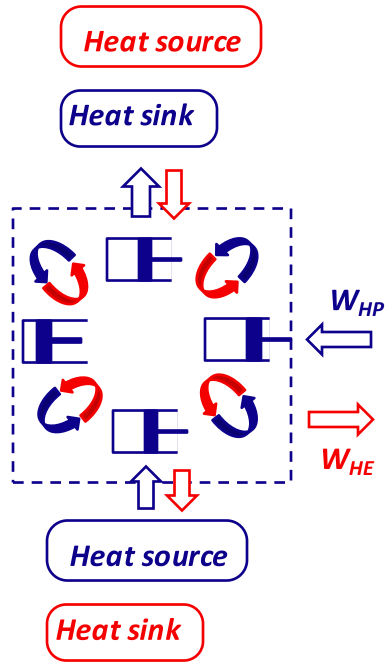
$$= \eta_{II}^{hp}\eta_{II}^{ORC}COP_{HP}^{carnot}\eta_{ORC}^{carnot}$$

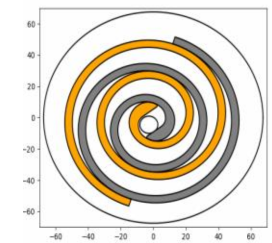


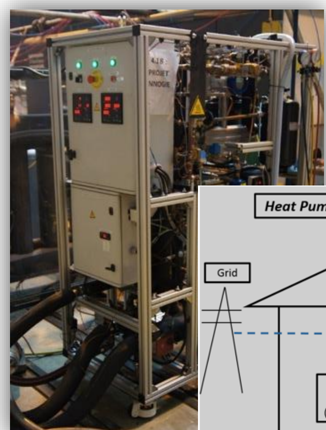
Introduction

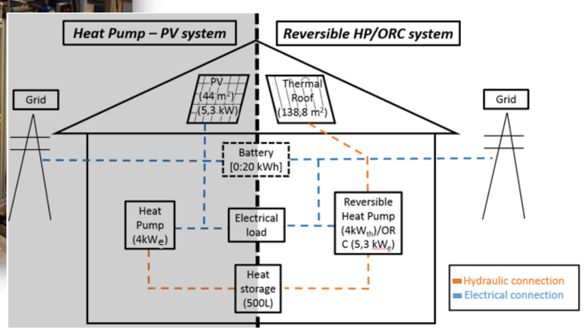
About myself and the thermodynamics laboratory

- To what extent a heat pump can be practically made (reversible) inversible into a heat engine.









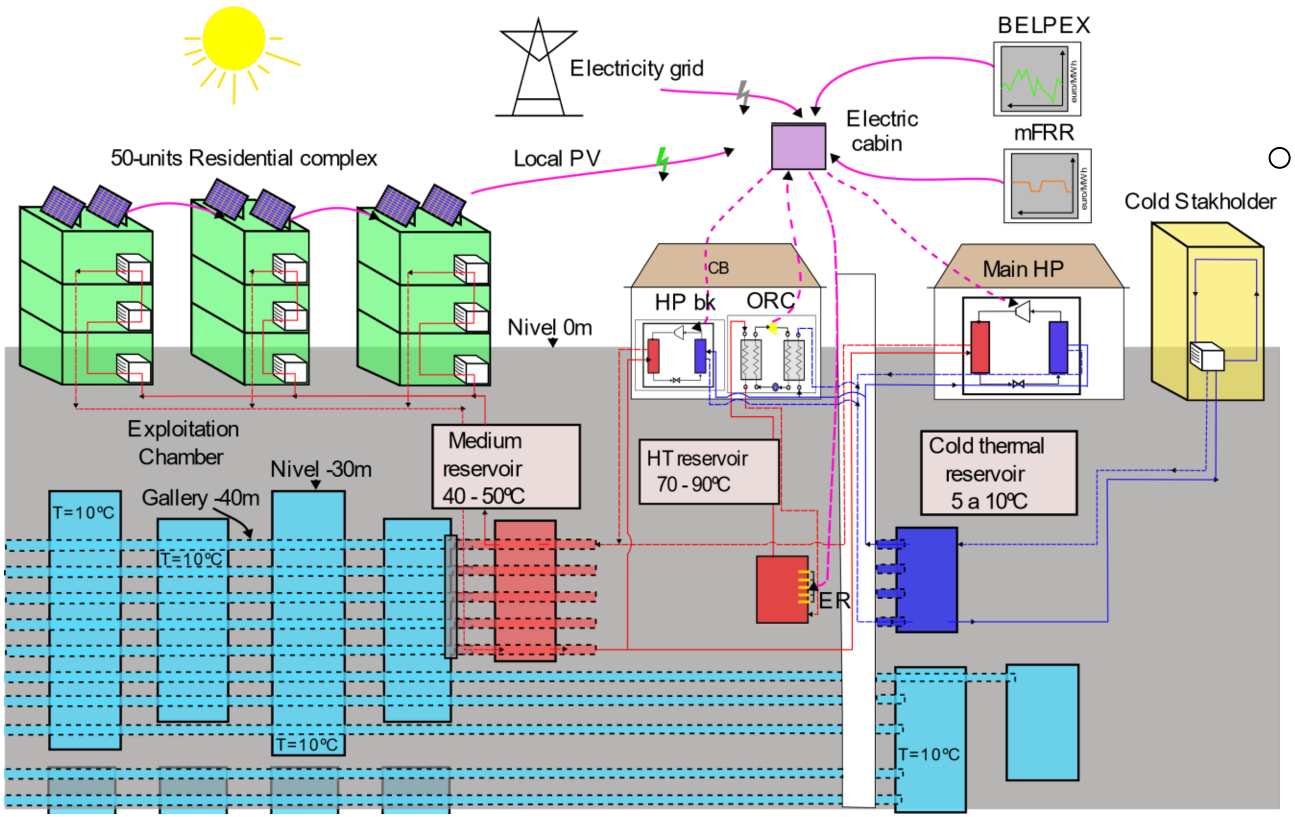
2016: First inversible heat pump/heat engine (organic Rankine cycle): electricity production

2018: First inversible 1kWe heat pump/heat engine (organic Rankine cycle) Carnot battery: electricity storage

2020-2026: 5 kWe inversile Carnot battery (under construction)

Introduction

About myself and the thermodynamics laboratory

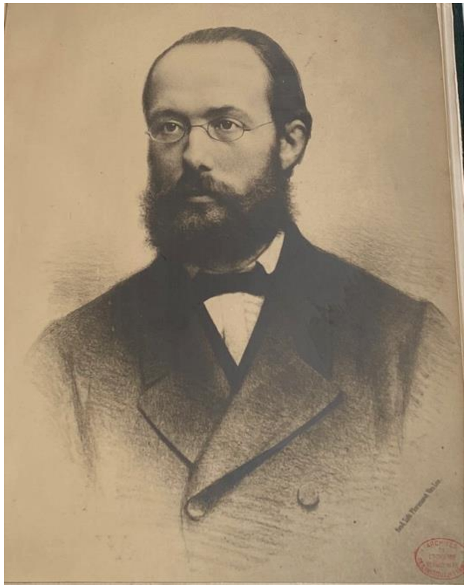


- 3 water chambers
  - **800 m3 at HT (90-70°C)**
  - 6840 m3 at MT (50-40°C)
  - 80000 m3 at LT (10-5°C)

Introduction
About myself and the thermodynamics laboratory

- Established in **1887** by Victor Dwelshauvers-Dery
- Originally named « **Mechanics Laboratory** », but mechanical workshop already existed in the 1840s.
- Currently a laboratory of technical thermodynamics
- Library preserves archives (handwritten lecture notes, lab notebooks), lab contains old measurement devices

Garnier-type engine indicator (largeur du papier : 10,3 mm). Laboratoire de Thermodynamique de l'Université de Liège. Photos par l'auteur (Août 2023 et Novembre 2021).

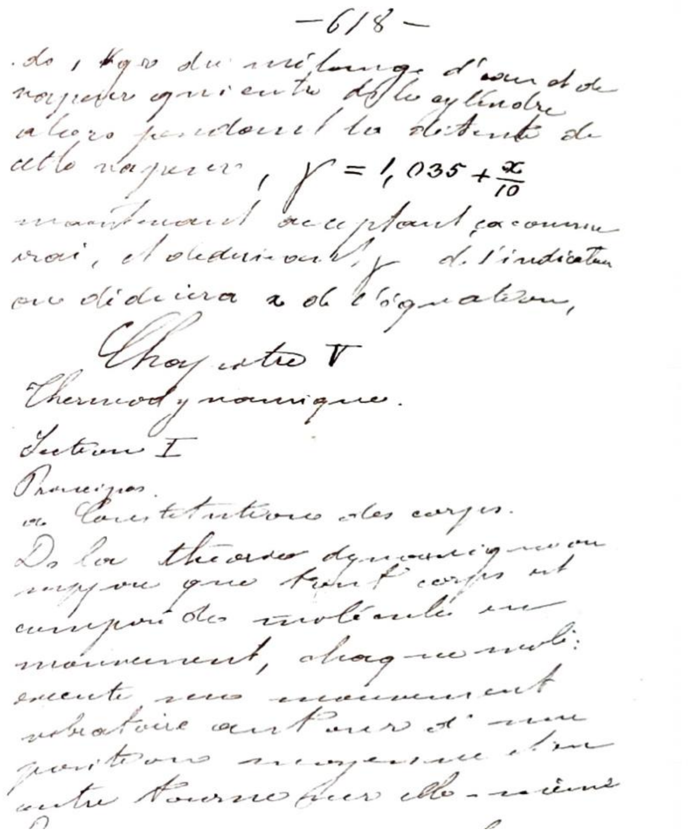


Dossier de M. Dwelshauvers-Dery, Archives de l'Académique des Sciences à Paris. Photos par l'auteur.

- Through the history of this laboratory in the second half of the long 19th century (ca. 1868-1914):
  - Understand how technical thermodynamics has emerged as a new engineering discipline
  - Understand the diffusion of thermodynamics concepts in mechanical engineering education
  - (understand how the laboratory was organized, working, funded; who were active people)

Victor Dwelshauvers-Dery (1868-1904)

Herman Hubert (1904-1919)


— 618 —

$\gamma = 1,035 + \frac{x}{10}$

Chapitre V

Thermodynamique.

Section I

Thermodynamics introduced by Dwelshauvers in education in 1868. Victor Dwelshauvers-Dery, *Mécanique Appliquée*, ULiège Library, MS4602, 1868-1869, p. 645

Agenda of the presentation

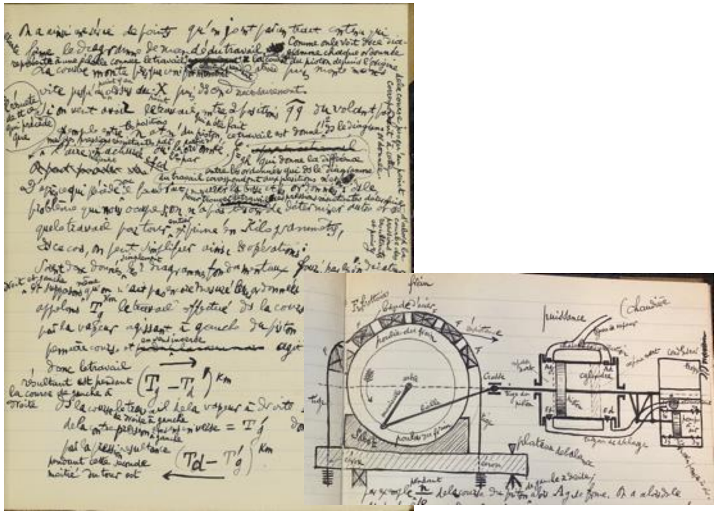
1. Introduction
2. **Investigated sources and archives**
3. Creation of the Mechanics Laboratory (1868 - 1887)
4. Experimental facilities of the Laboratory
5. Scientific/technical contributions of the Laboratory
6. The role of the laboratory in teaching technical thermodynamics
7. Conclusions

Investigated sources and archives

Applied mechanics, Industrial physics … and thermodynamics

- Archives and Library of the University of Liège
  - **Scientific Production**: Part of the scientific output of Victor Dwelshauvers-Dery, Herman Hubert, and other researchers from the laboratory, including both handwritten and printed sources.
  - **Lecture notes**: Courses on applied mechanics and industrial physics by Victor Dwelshauvers-Dery, Jean-Baptiste Brasseur, and Herman Hubert (**1868-1913**)
  - **Administrative Archives**: Administrative archives of the University of Liège related to the academic careers of Victor Dwelshauvers-Dery and Herman Hubert.
  - Laboratory Artifacts: Measuring devices, collections of models, and photographs from the **Laboratory of Mechanics**.
- Institut d'histoire ouvrière, économique et sociale (Seraing)
- (Maison de la Métallurgie et de l'Industrie de Liège)

Collection of lecture notes by Dwelshauvers-Dery and Hubert (from 1888 to 1907), Manuscripts, University of Liège

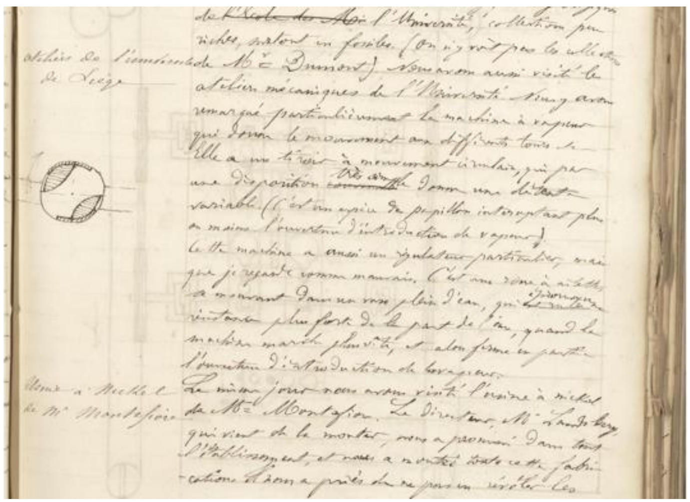


Dwelshauvers-Dery, Victor, et Omer De Bast, Mécanique Appliquée, ULiège Library, MS4488, c.a. 1890.

Investigated sources and archives

Applied mechanics, Industrial physics … and thermodynamics

- Archives of the Academy of Sciences in Paris
- Archives of the Conservatoire des Arts et Métiers in Paris
- Archives of Ecole des Mines de Paris



(Journal de) voyage en Belgique et en Angleterre par MM. Peslin, élève ing. et Gatellier, élève externe, 1857, Journal N°182, Fonds manuscrit da la Bibliothèque de l'Ecole des Mines

Agenda of the presentation

1. Introduction
2. Investigated sources and archives
3. **Creation of the Mechanics Laboratory (1868 - 1887)**
4. Experimental facilities of the Laboratory
5. Scientific/technical contributions of the Laboratory
6. The role of the laboratory in teaching technical thermodynamics
7. Conclusions

Creation of the Mechanics Laboratory

- **Around 1840**, a **mechanical workshop** equipped with a Watt machine (with a Prony brake) was accessible to students
- The **long process of creation** of a research and teaching mechanics laboratory (**ca. 1870-1887**) has been described by previous authors

  Kenneth BERTRAMS, Universités & entreprises : milieux académiques et industriels en Belgique 1890-1970, Bruxelles, Le Cri édition, 2006.

  Robert FOX et Anna GUAGNINI. "Laboratories, Workshops, and Sites. Concepts and Practices of Research in Industrial Europe, 1800-1914." Historical Studies in the Physical and Biological Sciences, vol. 29, n° 1, University of California Press, 1998.

- At the end of the 19th century, many Mechanics Laboratories are established in Europe and USA. They contribute to the emergence of Applied Mechanics as a new branch of Engineering that is looking for academic recognition (mechanics was mainly mathematical and testing machines was a workshop activity).
- Dwelshauvers **faced a lot of opposition by local academic authorities**, but received support from Adolphe Hirn, local industrials, and other international colleagues (USA, UK, Fr…)
- Rigorous and clever experimental methods proposed by Dwelshauvers and collaborators certainly contributed to the **academic recognition of Applied mechanics** (He was elected at the Academy of Sciences in Paris at the time Gibbs and Boltzmann were elected).

Agenda of the presentation

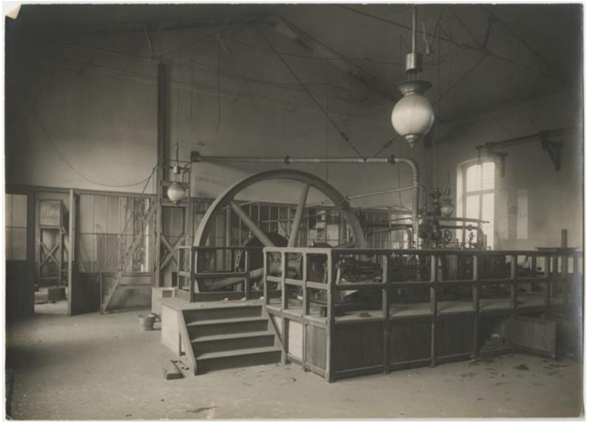
1. Introduction
2. Investigated sources and archives
3. Creation of the Mechanics Laboratory (1868 - 1887)
4. **Experimental facilities of the Laboratory**
5. Scientific/technical contributions of the Laboratory
6. The role of the laboratory in teaching technical thermodynamics
7. Conclusions

Experimental facilities of the Laboratory

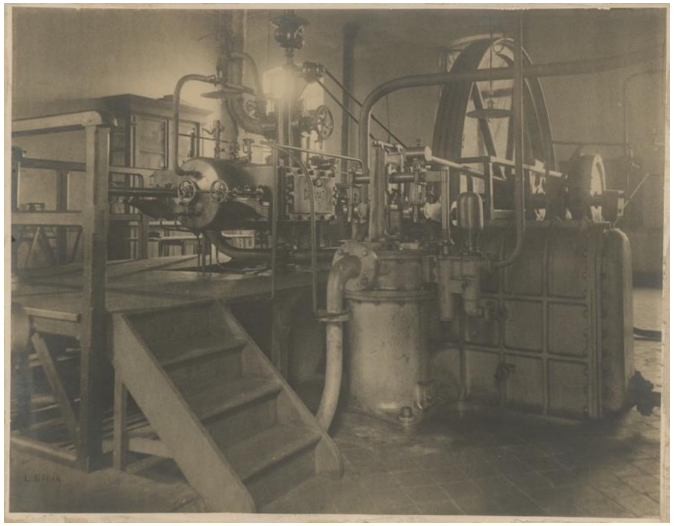
Description of the steam engine

Vue de la chaudière de la machine à vapeur. Morin, L. *Université de Liège - Faculté technique - Laboratoire de mécanique appliquée*, Photographie, 35 x 45 cm, Musée Wittert ULiège, Numéro d'inventaire 43233, s.d. © Musée Wittert ULiège

- Double-acting piston steam engine (19HP), well instrumented
- Machines for measuring materials strength
- From 1904: gas engines



Vue du moteur à vapeur Beer en 1918. *Université de Liège - Dommages de guerre - Laboratoire de mécanique - Salle des machines*, Fonds photographique des dommages de la guerre 1914-1918 faits aux bâtiments de l'Université de Liège (positifs), Musée Wittert ULiège, Numéro d'inventaire 43205, 1918. © Musée Wittert ULiège

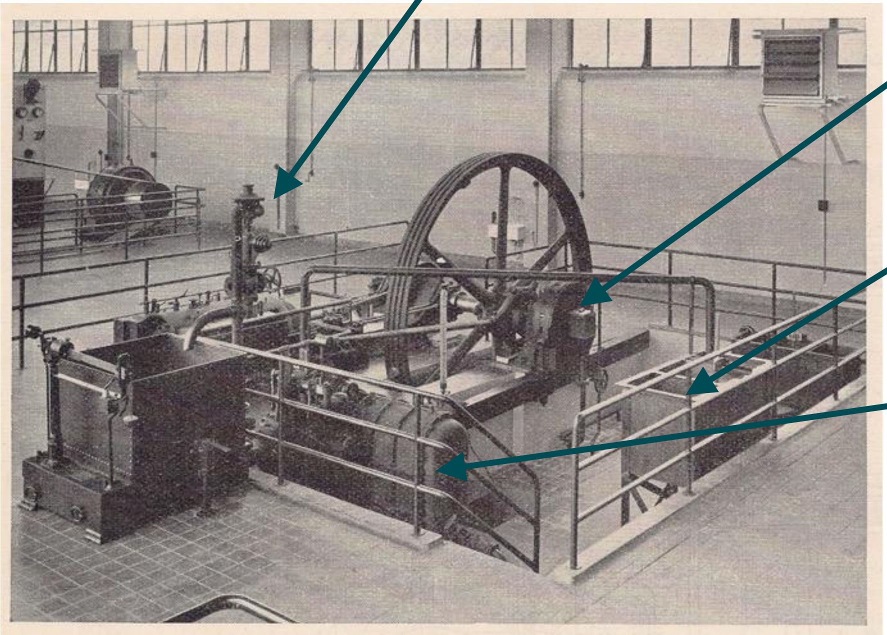


Autre vue du moteur à vapeur Beer. L. MORIN, *Université de Liège - Faculté technique - Laboratoire de mécanique appliquée*, Photographie, 35 x 45 cm, Musée Wittert ULiège, Numéro d'inventaire 43230, s.d. © Musée Wittert ULiège

Experimental facilities of the Laboratory

Description of the steam engine

The steam engine moved to the brand-new Thermodynamics Laboratory in 1937



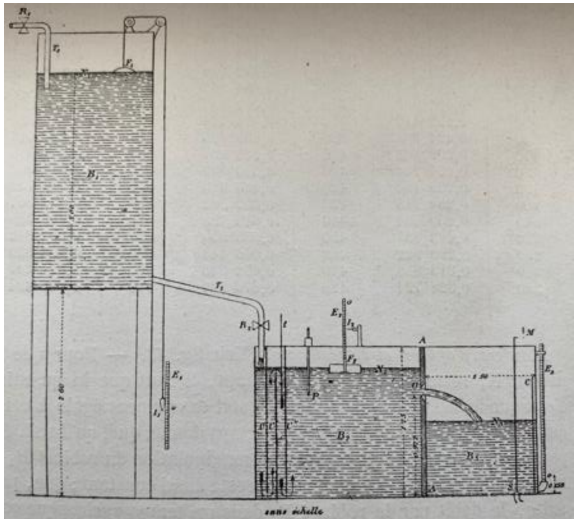
Vue de la "Machine Beer" installée dans le Nouveau Laboratoire de Thermodynamique du Val-Benoît vers 1937. Université de Liége, Faculté des Sciences Appliquées, « Centenaire de l'Ecole des Mines, inauguration des Institut Universitaires du Val-Benoît (Novembre 1937) », Edition de la Revue Universelle des Mines, Liége, 1937

Agenda of the presentation

1. Introduction
2. Investigated sources and archives
3. Creation of the Mechanics Laboratory (1868 - 1887)
4. Experimental facilities of the Laboratory
5. **Scientific/technical contributions of the Laboratory**
6. The role of the laboratory in teaching technical thermodynamics
7. Conclusions

Scientific/technical contributions

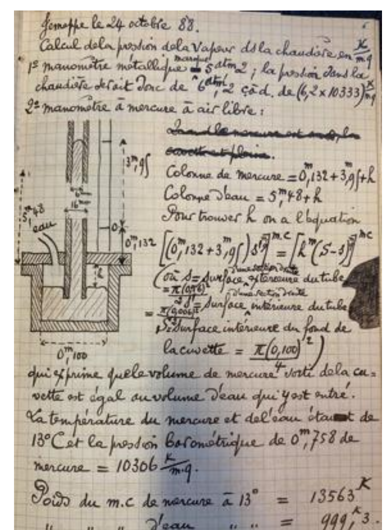
Experimental research



Vue en élévation de « l'appareil employé pour tarer l'orifice circulaire en mince paroi du frein ». Dans Victor DWELSHAUVERS-DERY, Données relatives à la machine à vapeur, Liége, Charles Desoer, 1897, p. 52.

Early activities of the Mechanics Laboratory (1887) allowed:

- To confirm the formulation of **Hirn's theory** (based on the conservation of energy known since 1842)
- To enrich the **testing methods of Hirn** (which he learnt in the 1870s in Colmar)
- To demonstrate that **heat transfer between steam and metal** can explain the difference between theoretical and measured performances



Manomètre à mercure à air libre du laboratoire de Jemeppe. Dans Dwelshauvers-Dery, Victor, et Omer De Bast, Carnet d'observation pour le cours de M. Dwelshauvers, Laboratoire de Jemeppe, année académique 1888-1889, ULiège Library, MS4525, c.a. 1888-1889, ff. 6.

Scientific/technical contributions

Analysis of a controversy: "water against metal"

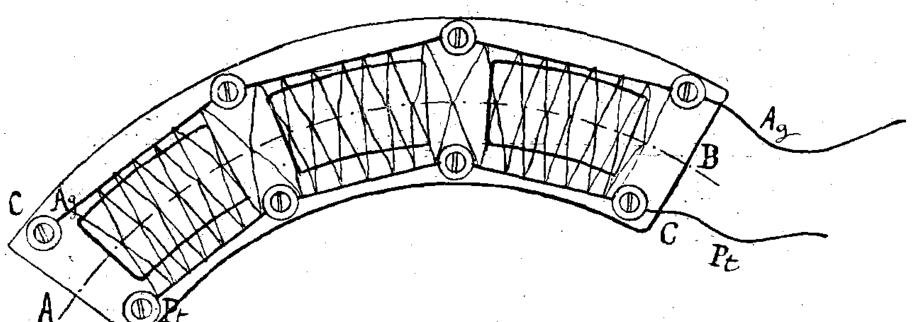
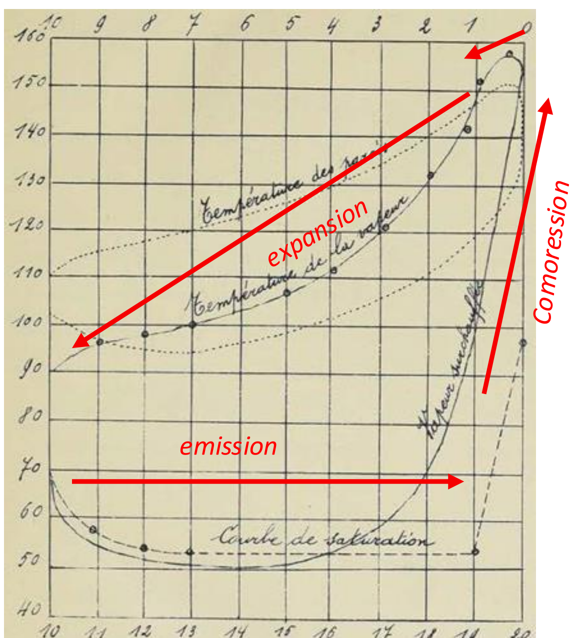


Fig. 1.

Thermoelectric couple thermometer used for measuring steam temperature. In Armand DUCHESNE, « La théorie de la machine à vapeur… des parois », **1904**, p. 69.



Diagrammes des températures pour un tour de la machine. Reproduction dans le cours de Hubert, H., et C. André, Mécanique Appliquée 1. ULiège Library, MS4336, p. 393.

What was the state of vapor at the end of emission?

Pioneer development and use of **thermocouples** (made possible by the development of electricity and chemistry) allowed intrusive and high-frequency temp measurement (lower inertia than thermometers)

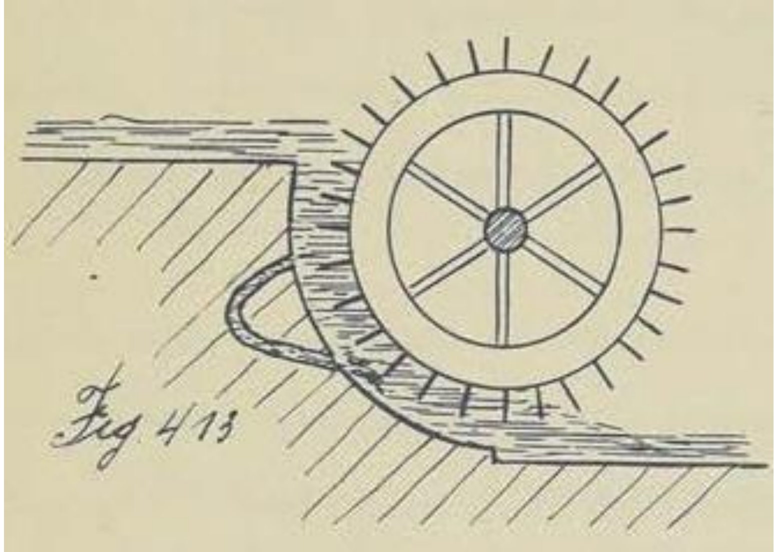
The steam is indeed superheated at the end of emission:

« dans la lutte de l'eau contre le métal, ce fut le métal qui eut raison »

(H. LEAUTE, Élection d'un Correspondant dans la section de Mécanique. 4 décembre 1893, Rapport sur les Travaux de M. Dwelshauvers-Dery, Dossier de M. Dwelshauvers-Dery, Archives de l'Académique des Sciences à Paris.)

Scientific/technical contributions

Analysis of a controversy: “water against metal”



Losses due to heat exchange between the steam and the walls: analogy with the hydraulic motor. In H. HUBERT et C. ANDRÉ, Mécanique Appliquée 2. ULiège Library, MS4336, p. 391.

The expansion of the **heat lost** during admission is not ideal because the heat is returned at a lower temperature level than the one at which it was absorbed.

Dwelshauvers-Dery compares this loss to what would happen in a **water wheel** where *« a portion of the water would leave the motor through a crack, only to re-enter the wheel at a lower level. »*

Scientific/technical contributions

Reproduction of a test analysis

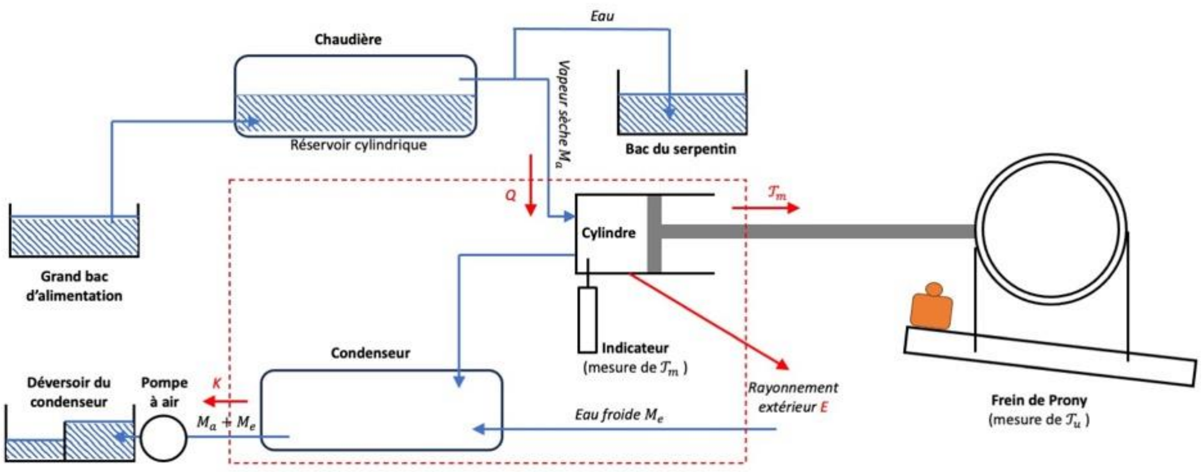
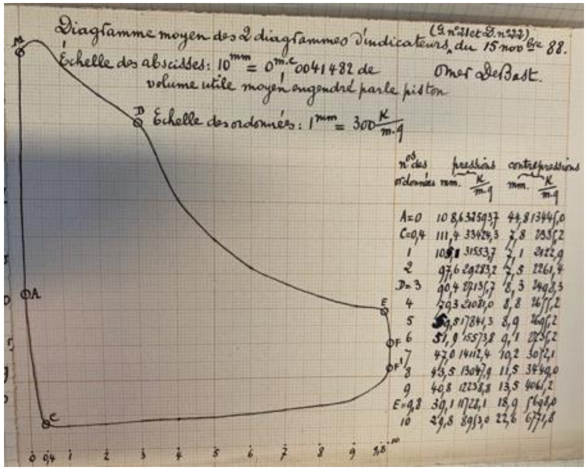


Schéma de l'installation expérimentale du Laboratoire de Jemeppe

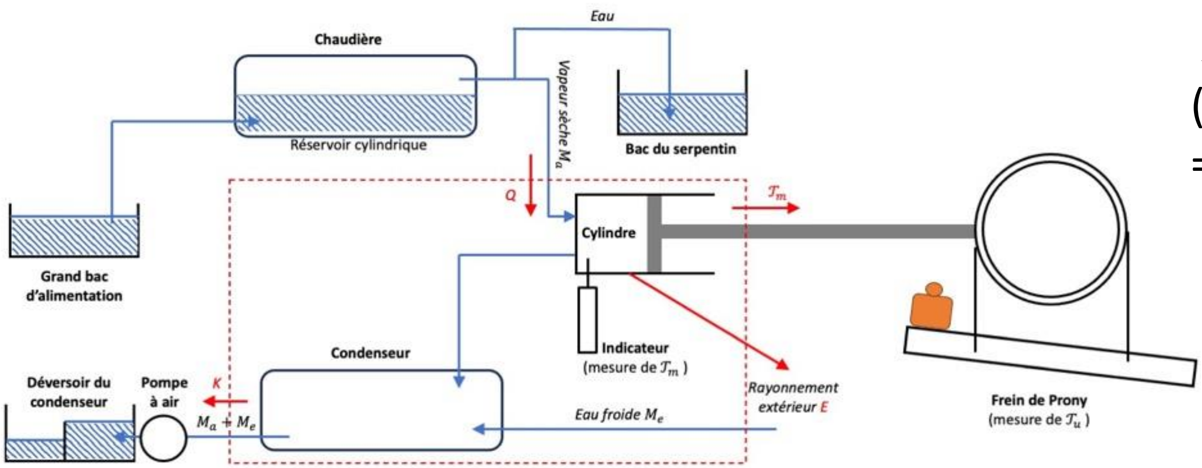


« Diagramme moyen des 2 diagrammes d'indicateurs du 15 novembre 88 ». Dans Victor Dwelshauvers-Dery et Omer De Bast, Carnet d'observation pour le cours de M. Dwelshauvers, Laboratoire de Jemeppe, année académique 1888-1889, ULiège Library, MS4525, c.a. 1888-1889

An experiment from the Jemeppe Laboratory (1888) and an experiment from the Liège Laboratory (1893) were analyzed using modern thermodynamic analysis tools (see Otto Sibum's approach), which allowed for 1) <u>understanding</u> the analyses conducted in the 19th century; 2) <u>verifying</u> the accuracy of the measurements; 3) <u>comparing</u> the state of 19th century knowledge to current knowledge.

Scientific/technical contributions

Reproduction of a test analysis



$\mathcal{T}_u = 1194{,}684\ kgm$ per rotation (Prony brake)
=> Power of 19,38 HP

- Efficiency: $\eta = 425\ \times \mathcal{T}_u\ /(2\ Q) = 4.142\%$ (test of 15th of November 1888)
- « total heat » is used rather than « **enthalpy** of steam »
- The machine is **not considered as a closed cycle** (unsteady regime of boiler, condensates may not be recovered)
- **Isentropic efficiency** of expander not computed. Assuming a low pressure of $0{,}06826$ $\mathrm{K/cq}$ (not measured), it would be 17,03%.

$$\eta_{s,exp} = \frac{\mathcal{T}_u/2}{M_a\left(h_{in} - h_{out,s}\right)}$$

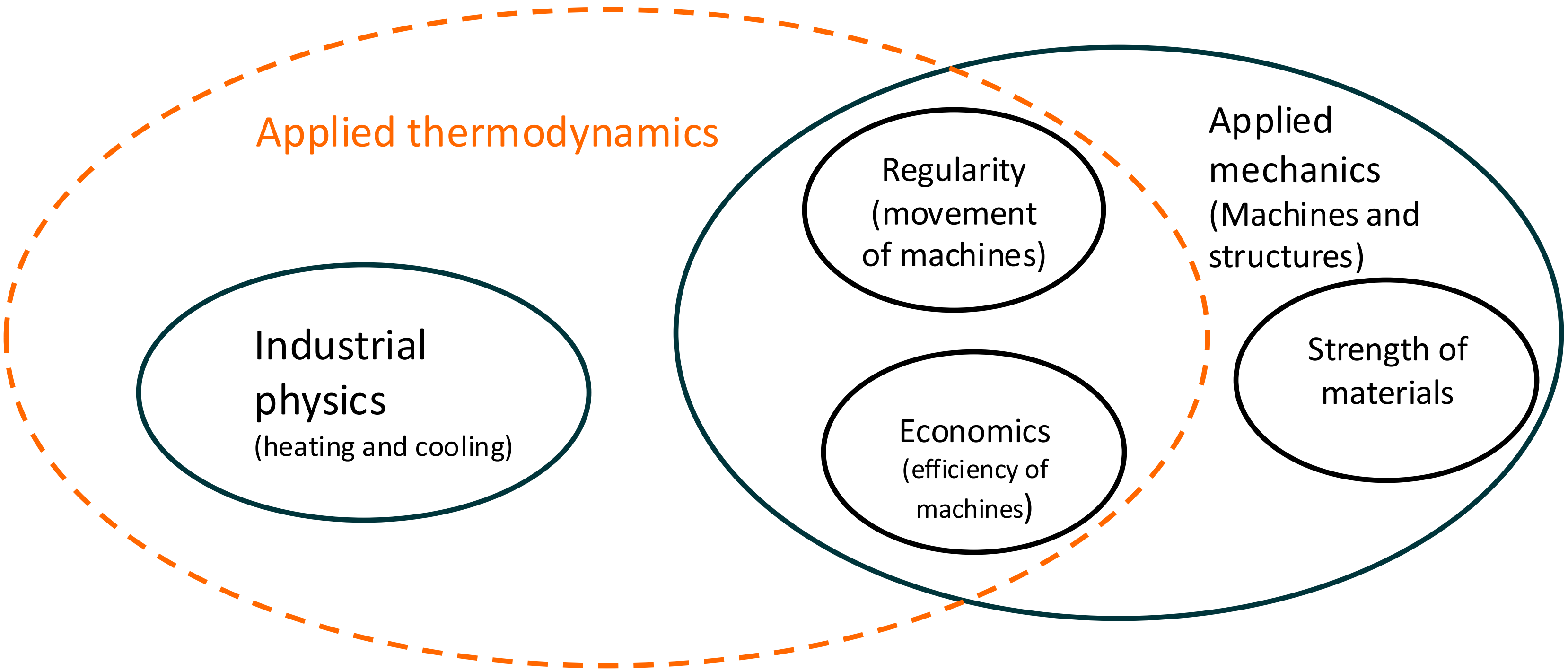
Agenda of the presentation

1. Introduction
2. Investigated sources and archives
3. Creation of the Mechanics Laboratory (1868 - 1887)
4. Experimental facilities of the Laboratory
5. Scientific/technical contributions of the Laboratory
6. **The role of the laboratory in teaching technical thermodynamics**
7. Conclusions

The role of the laboratory in teaching thermodynamics

Emergence of applied thermodynamics

- The current teaching of **applied thermodynamics** inherits/emerged from industrial physics and applied mechanics

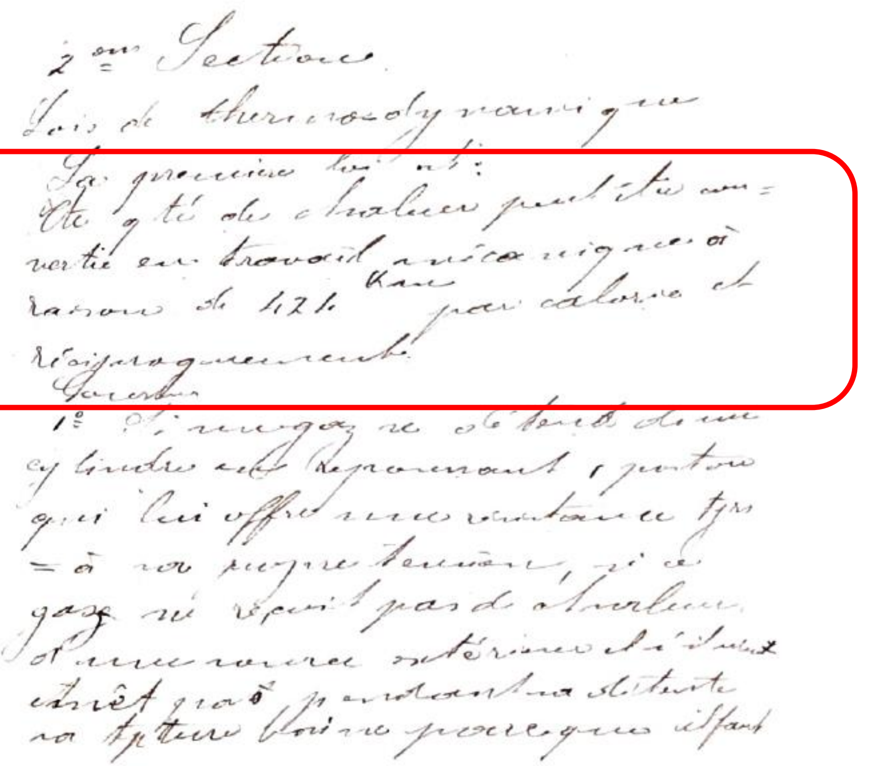


The role of the laboratory in teaching thermodynamics

Dissemination of thermodynamic concepts: : 1st law

What about dissemination of thermodynamic concepts?

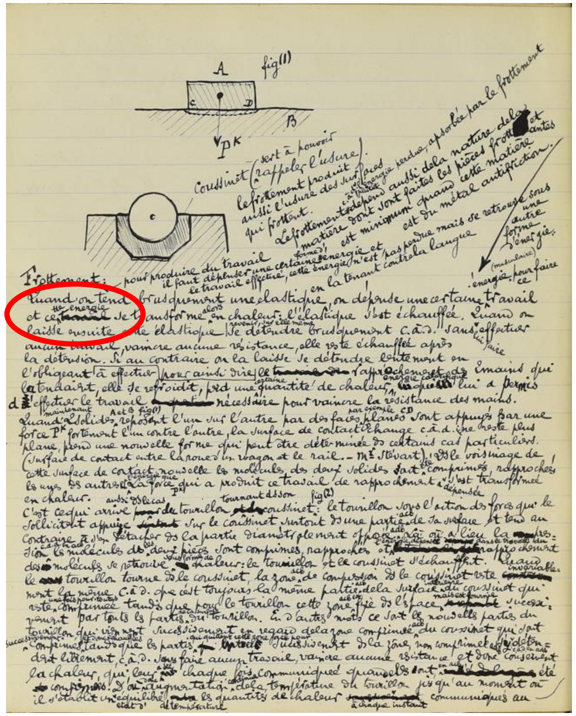
First law was mentioned for the first time in **1868-1869** in Applied Mechanics lecture notes

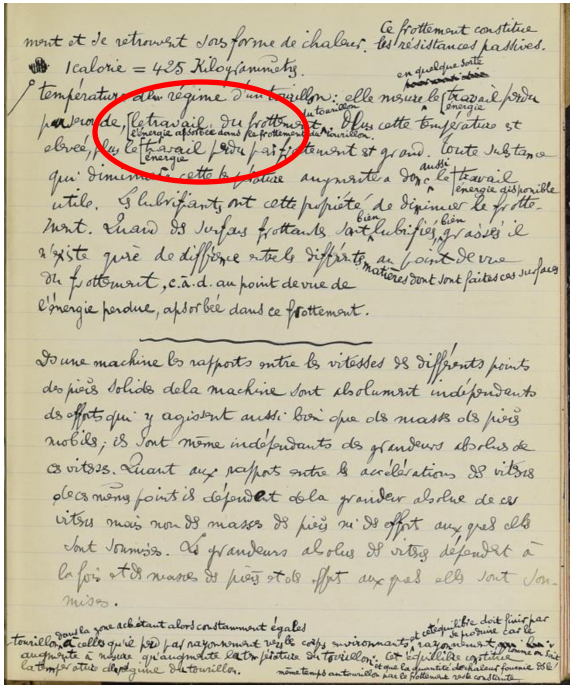

2ème Section.
Lois de thermodynamique
La première loi dit:
Toute quantité de chaleur peut être con-
vertie en travail mécanique à
raison de 424 Km par calorie et
réciproquement.

First Law statement. in Victor DWELSHAUVERS-DERY, *Mécanique Appliquée*, ULiège Library, MS4602, 1868-1869, p. 319

« La première loi dit:
Toute quantité de chaleur peut être convertie en travail mécanique à raison de 424 km par calorie et réciproquement »

« **Energy** » word (1849) : «travail » replaced by « énergie » introduced in lectures handwritten notes around **1890**

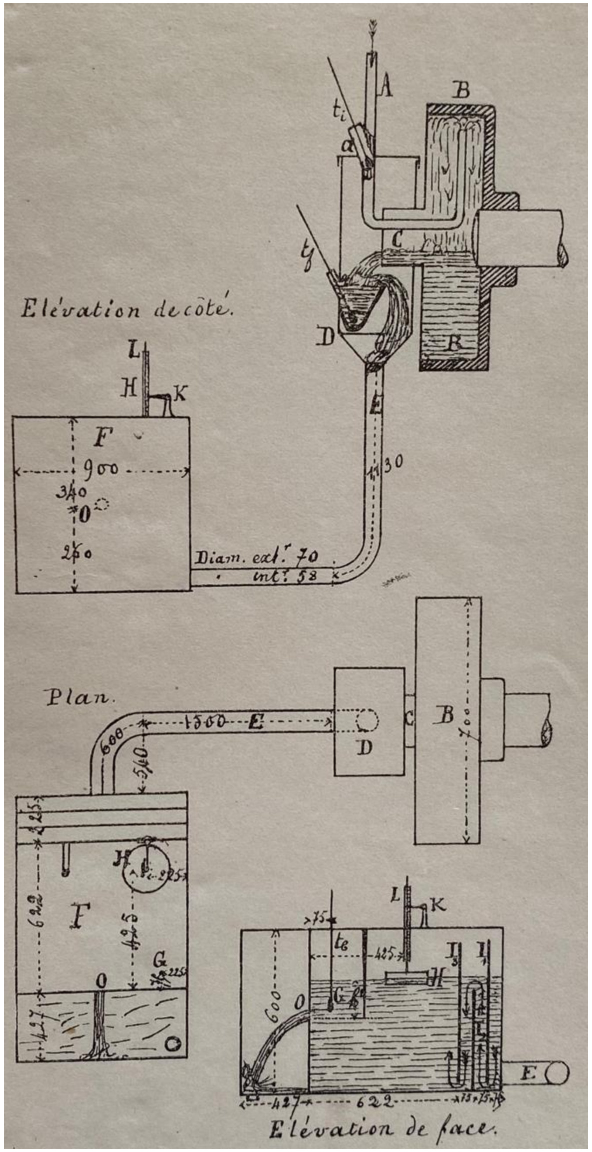




Introduction of the concept of energy in Applied Mechanics course by DWELSHAUVERS-DERY and Omer DE BAST, ULiège Library, MS4488, ca. 1890.

The role of the laboratory in teaching thermodynamics

Dissemination of thermodynamic concepts: : 1st law

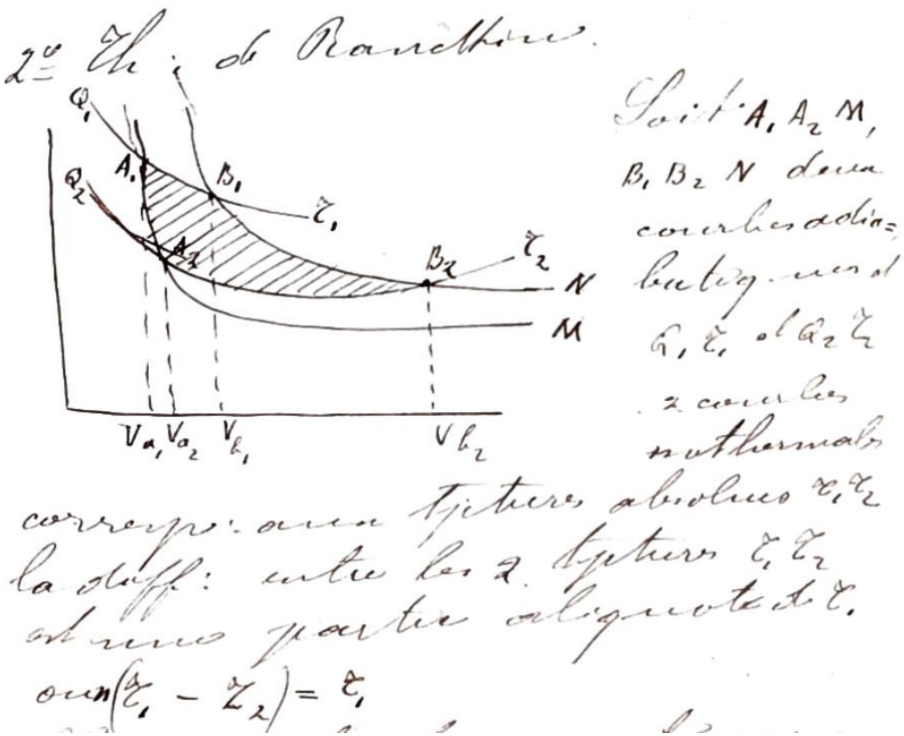


Around 1897, students are assigned to measure the mechanical equivalent of heat by expressing the energy balance on the water cooling circuit of the Prony brake dynamometer.

Représentation schématique des éléments constituant le système de refroidissement de la poulie B du frein. Dans Victor DWELSHAUVERS-DERY, *Données relatives à la machine à vapeur*, Liége, Charles Desoer, 1897, Annexes

The role of the laboratory in teaching thermodynamics

Dissemination of thermodynamic concepts: 2nd Law: Rankine Theorem



Représentation graphique du théorème de Rankine. Dans Victor DWELSHAUVERS-DERY, *Mécanique Appliquée*, ULiège Library, MS4602, 1868-1869, p. 645

In 1868, 2nd Law is presented by means of Rankine theorem (and Cazin theorem).

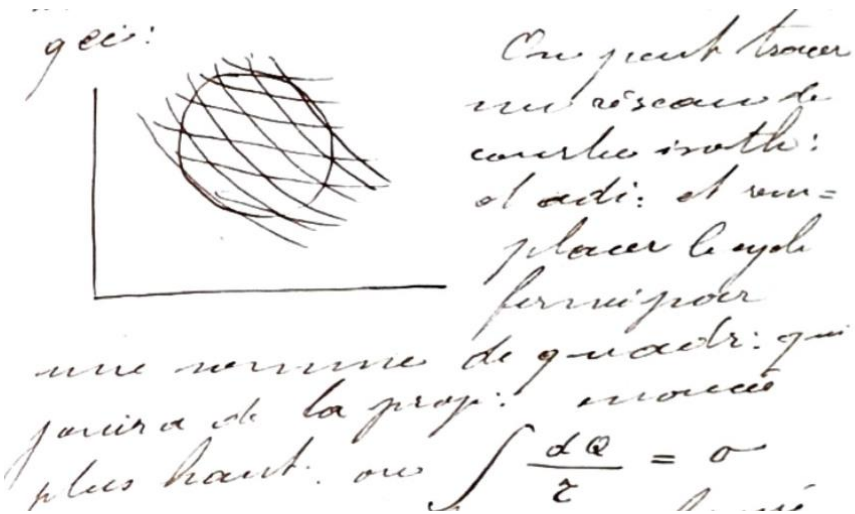
Observing that

- heat Q_1 absorbed to go from A_1 to B_1 is equal to area MA_1B_1N and heat Q_2 rejected to go from B_2 to A_2 is area MA_2B_2N,
- $\tau_1 - \tau_2 = \tau_1/n$ and $Q_1 - Q_2 = Q_1/n$

=> $\frac{Q_1}{\tau_1} - \frac{Q_2}{\tau_2} = 0$

The role of the laboratory in teaching thermodynamics

Dissemination of thermodynamic concepts: 2nd Law: Rankine Theorem



Extrapolation à un cycle quelconque. Dans Victor DWELSHAUVERS-DERY, Mécanique Appliquée, ULiège Library, MS4602, 1868-1869, p. 648.

- This could be generalized to any (reversible) cycle in which we could inscribe a grid of adiabatic and isothermal cruves. Summing curved quadrilateral

$$\Rightarrow \int dQ/\tau = 0$$

- Irreversible cycles are then treated, leading (1906) to the Gouy theorem (close to the modern exergy formulation)

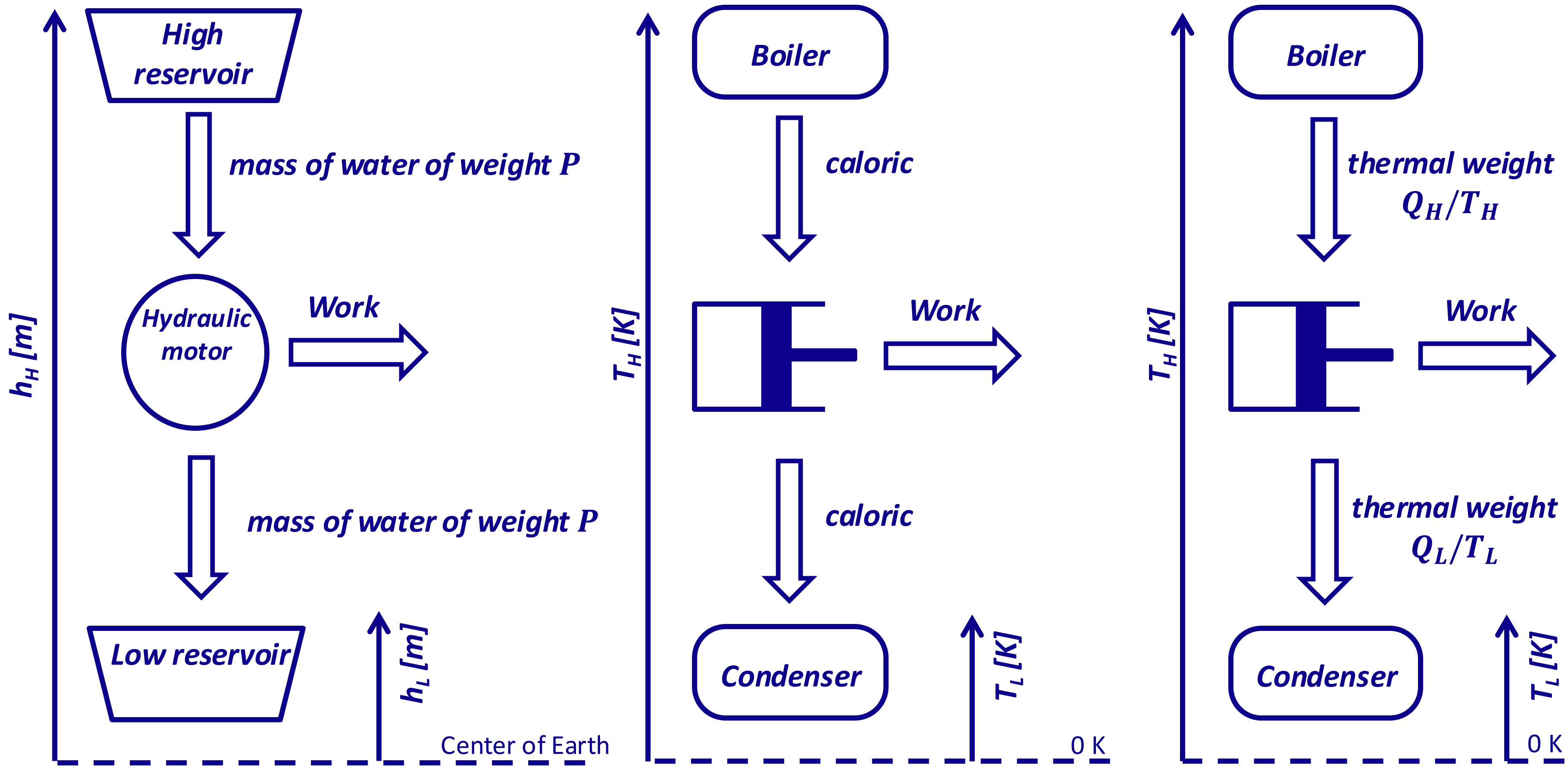
$$= G_1 - G_2 = \text{Exergy variation!}$$

$$\mathcal{T}_e = (U - T_0\ S + p_a\ V)_1 - (U - T_0\ S + p_a\ V)_2 - T_0 \int_1^2 dP + W_1 - W_2$$

G is the useful energy of the machine in contact with environment at T_0 and p_a => Maximum works is $G_1 - G_2$

The role of the laboratory in teaching thermodynamics

Dissemination of thermodynamic concepts: 2nd Law: thermal weight



Hydraulic motor and water fall

Carnot (1824)

Dwelshauvers Dery (1868)

Ideal (reversible) machine:

$Q_H/T_H = Q_L/T_L$

The role of the laboratory in teaching thermodynamics

Dissemination of thermodynamic concepts: 2nd Law: thermal weight

Dwelshauvers-Dery (as early as 1868) gave the name of **« thermal weight »** to the ratio Q/τ , due to its **analogy with weight in dynamics**, and denoted it by G. If the weight G « falls » from τ_1 to τ_2 , then it will produce work equal to $Q_1 - Q_2 = G(\tau_1 - \tau_2)$ with $G = Q_1/\tau_1 = Q_2/\tau_2$.

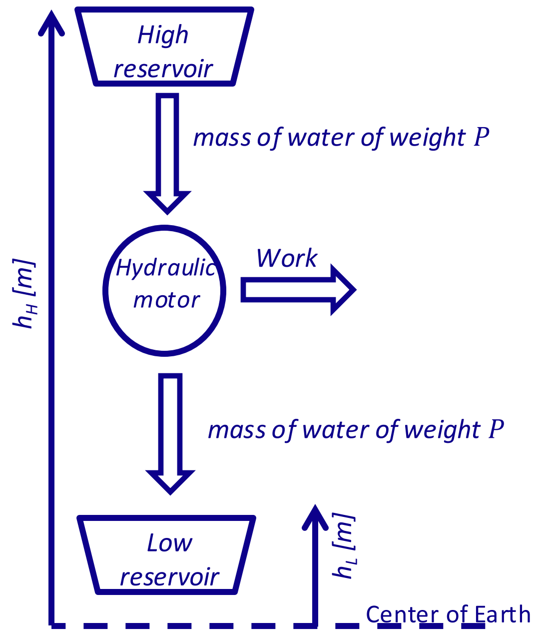
A similar definition is given around 1888-1889: One could say that *"a body containing C calories at τ absolute degrees has a thermal weight of de $C/\tau = constant$, and the maximum work it can perform when dropping from τ to τ' degrees is $(C/\tau)(\tau - \tau')$ calories"*

The concept can also be used in heat pump mode (« thermal pump »). Dwelshauvers-Dery wrote in 1868

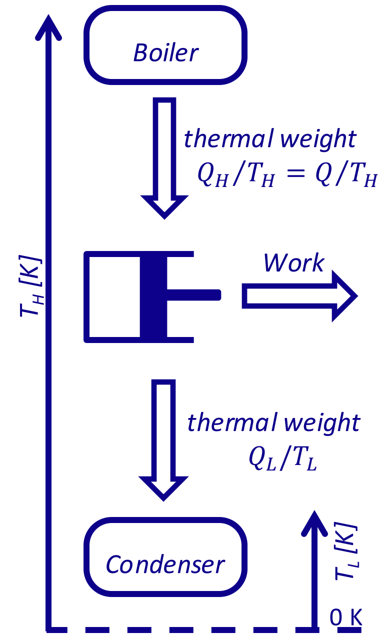
« The thermal weight G can never transfer by itself from body K to a hotter body K'; such a transfer requires an expenditure of work, the minimum of which is $Q_1/\tau_1(\tau_1 - \tau_2)$ »

The role of the laboratory in teaching thermodynamics

Dissemination of thermodynamic concepts: 2nd Law: thermal weight



Hydraulic motor



Dwelshauvers Dery (1868)

Maximum work provided by the hydraulic motor:

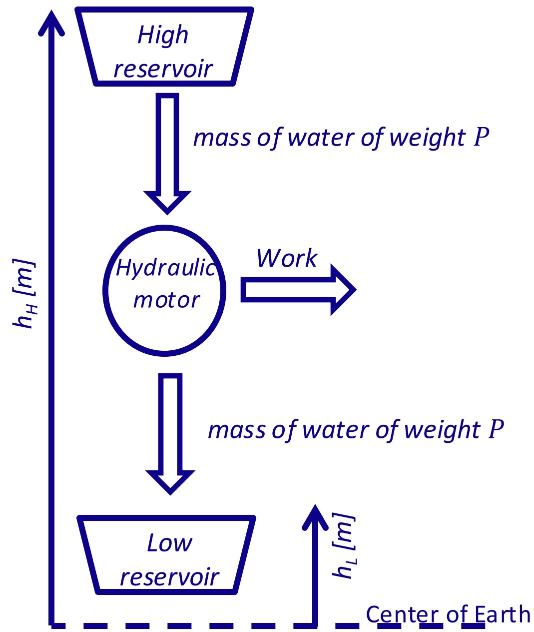
$$P\ (h_H - h_L)\ [kgm]$$

Maximum work provided by the heat engine:

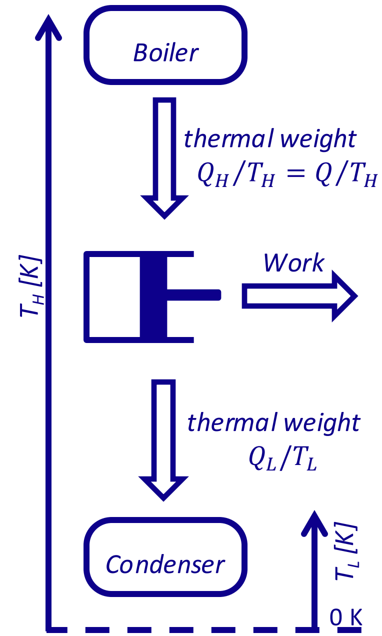
$$425\frac{Q}{T_H}(T_H - T_L)\ [kgm]$$

The role of the laboratory in teaching thermodynamics

Dissemination of thermodynamic concepts: 2nd Law: thermal weight



Hydraulic motor



Dwelshauvers Dery (1868)

Efficiency of the actual hydraulic motor:

$$\eta = \frac{Useful\ work}{P\ (h_H - h_L)}\ [\%]$$

Efficiency of the actual heat engine

$$\eta = \frac{Useful\ work}{425\ Q}\ [\%]$$

« Irrational definition »

The role of the laboratory in teaching thermodynamics

Dissemination of thermodynamic concepts: 2nd Law: thermal weight

Efficiency of the actual hydraulic motor:

$$\eta = \frac{Useful\ work}{P\ (h_H - h_L)}\ [\%]$$

Efficiencies of hydraulic wheels: 50-90%

(it would be much lower considering an Earth radius of 6370000 meters and $\eta = \frac{Useful\ work}{P\ h_H}$)

Efficiency of the actual heat engine

$$\eta = \frac{Useful\ work}{425\ Q}\ [\%]$$

« Irrational definition »

Efficiencies of steam engines: around 5-10%

➡ Dwelshauvers introduced (in 1888) the « corrected efficiency »:

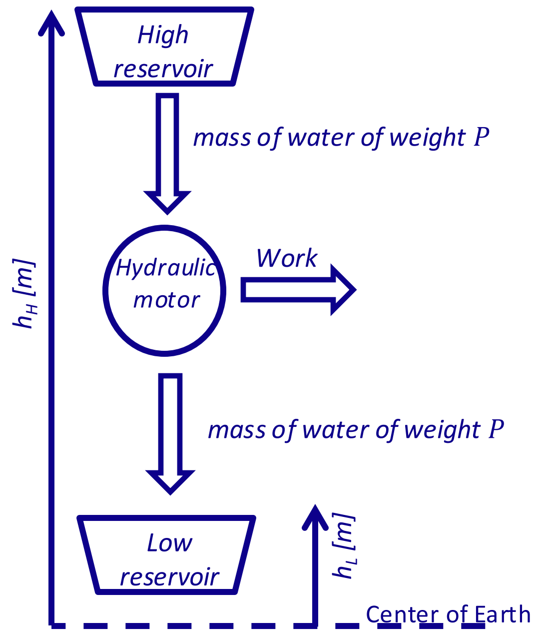
$$\eta_{cor} = \frac{Useful\ work}{\frac{Q}{T_h}(T_h - T_L)}\ [\%]$$

This is the definition of nowadays 2nd Law Efficiency (or exergy efficiency)

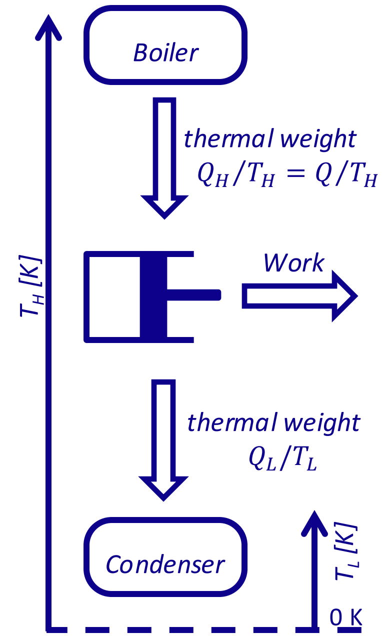
The role of the laboratory in teaching thermodynamics

Dissemination of thermodynamic concepts: 2nd Law: thermal weight

A modern consensus… :



Hydraulic motor



Dwelshauvers Dery (1868)

Exergy efficiency of the actual hydraulic motor:

$$\eta_{ex} = \frac{Useful\ work}{P\ (h_H - h_L)}\ [\%]$$

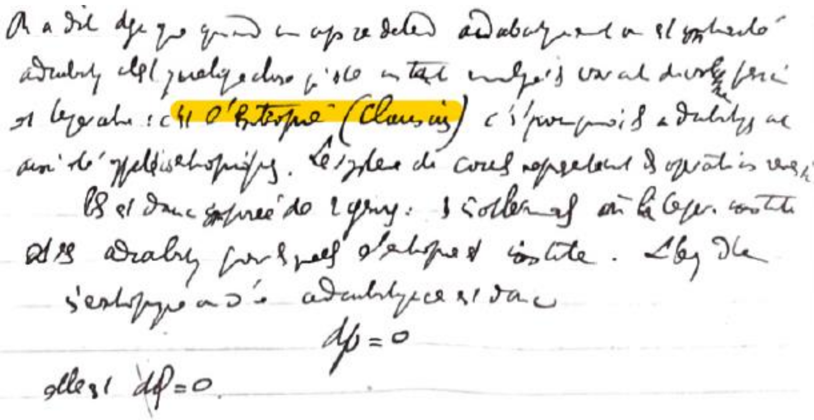
Exergy efficiency of the actual heat engine

$$\eta_{ex} = \frac{Useful\ work}{\frac{Q}{T_h}(T_h - T_L)}\ [\%]$$

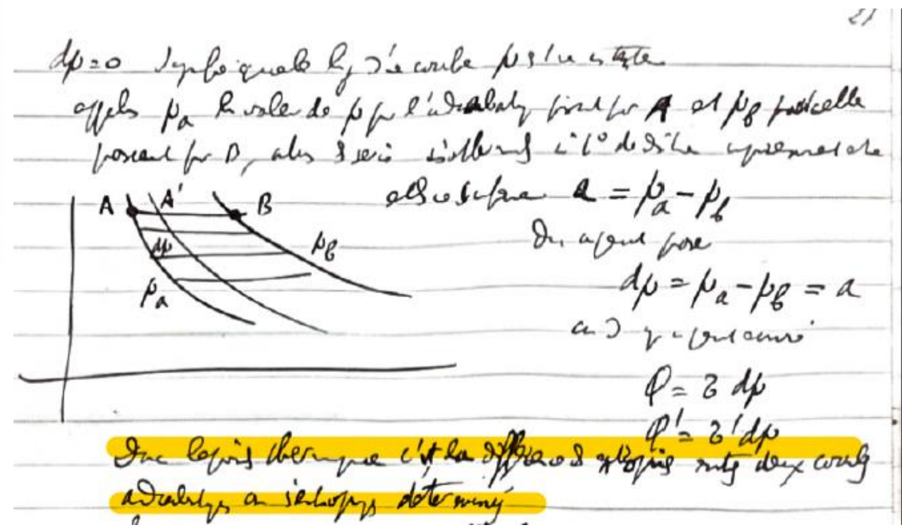
The role of the laboratory in teaching thermodynamics

Dissemination of thermodynamic concepts: 2^{nd} Law: entropy

In his lecture notes from 1888-1889, Dwelshauvers-Dery mentions **Clausius** (to our knowledge, for the first time in lecture notes) and **entropy** μ . He links it to the thermal weight Q/τ : *“Thus, **thermal weight is the difference in entropy** between two determined adiabatic or isentropic curves.”* Hence $Q/\tau = \mu_a - \mu_b$, with μ_a being the value of μ for the adiabatic passing through *a* (and conversely for *b*)



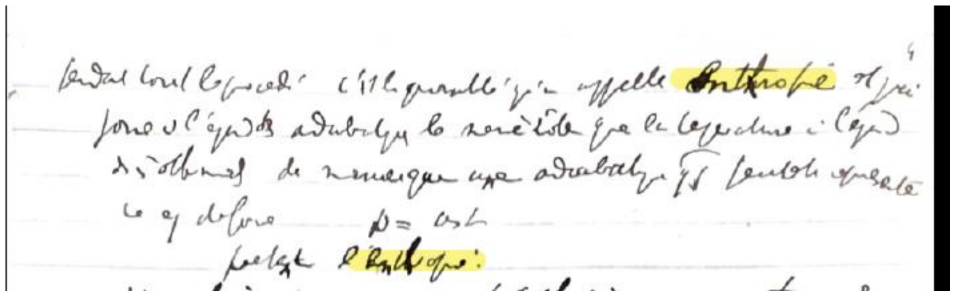
Victor DWELSHAUVERS-DERY et Omer DE BAST, *Physique Industrielle*, ULiège Library, MS4512, ca. 1888, p. 20-21.



The role of the laboratory in teaching thermodynamics

Dissemination of thermodynamic concepts

… originally written « Anthropie »



Victor DWELSHAUVERS-DERY et Omer DE BAST, *Physique Industrielle*, ULiège Library, MS4512, ca. 1888, p. 4.

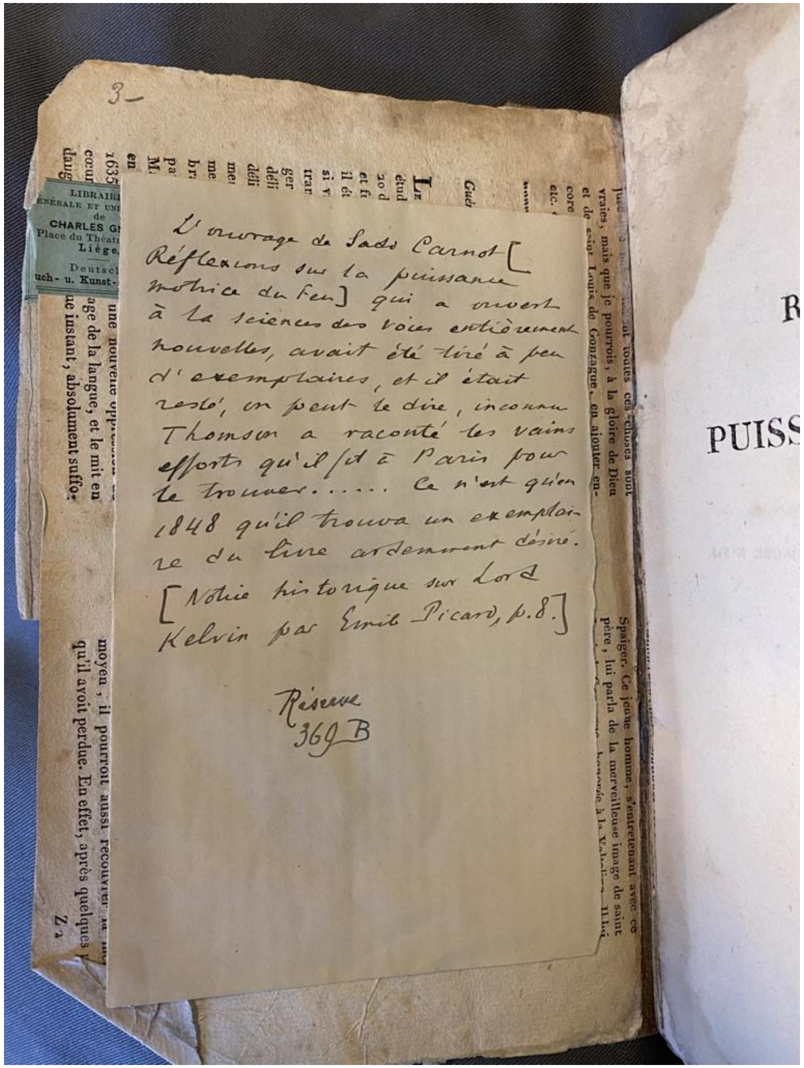
Conclusions

- **Research** at the end of the 19th century was mainly **experimental** and aimed at analyzing performance of machines: thermal and mechanical performance.
- **No development of simulation tools** (future topic of research)
- Applied mechanics benefited from development of electrical and chemical engineering (thermocouples)
- Rigorous and clever experimental methods and new measurements techniques contributed to the academic recognition of Applied mechanics.
- Applied thermodynamics emerged from Applied mechanics and Industrial physics and is currently taught as a separate course.
- Still **vivid analogy between heat engines and hydraulic motors** when teaching thermodynamics (both machines were taught by the same professor)
- Concepts close to **exergy** and **2nd law efficiency** are emerging, but 2nd law performance indicators are not commonly used (f.i. isentropic efficiency not used)

Thank you for your attention!

Vincent Lemort

Vincent.Lemort@uliege.be



Book bougth in dec 1935 for 245 frs

www.carnot2024.uliege.be