ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

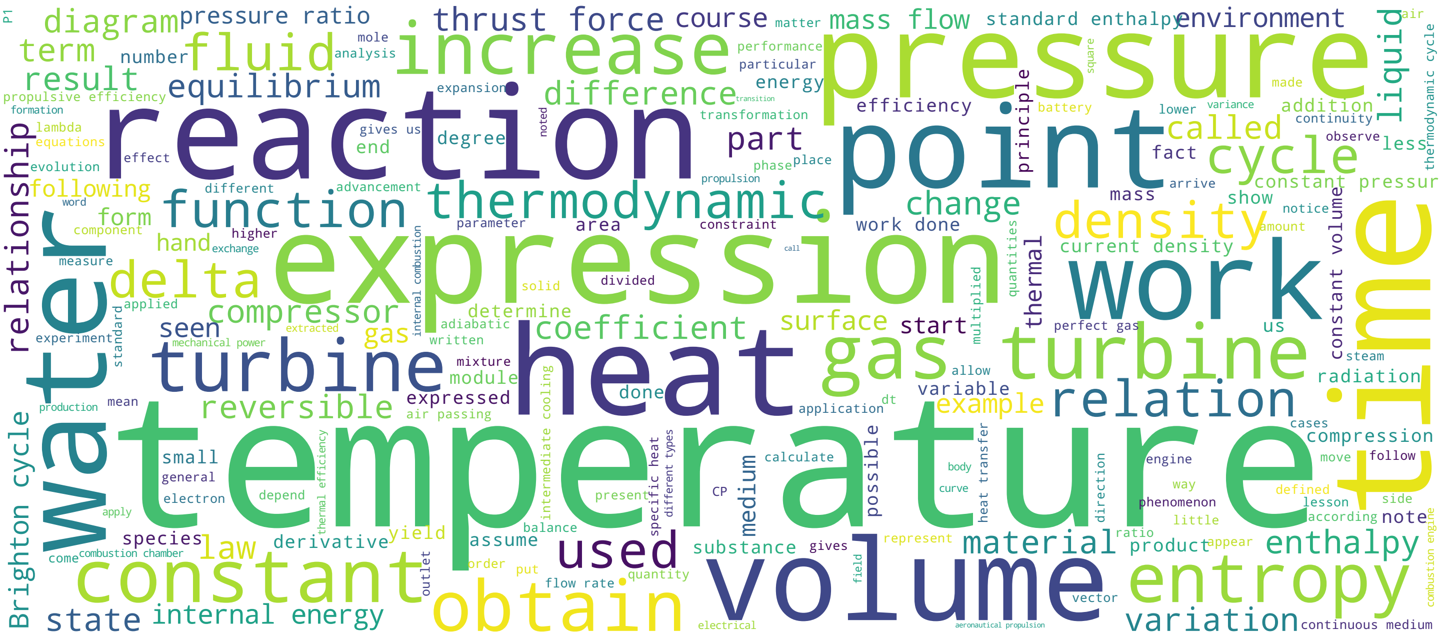
RESCIF
Réseau d'excellence des sciences de l'ingénieur de la Francophonie

Thermodynamique

Cycles de turbine à gaz

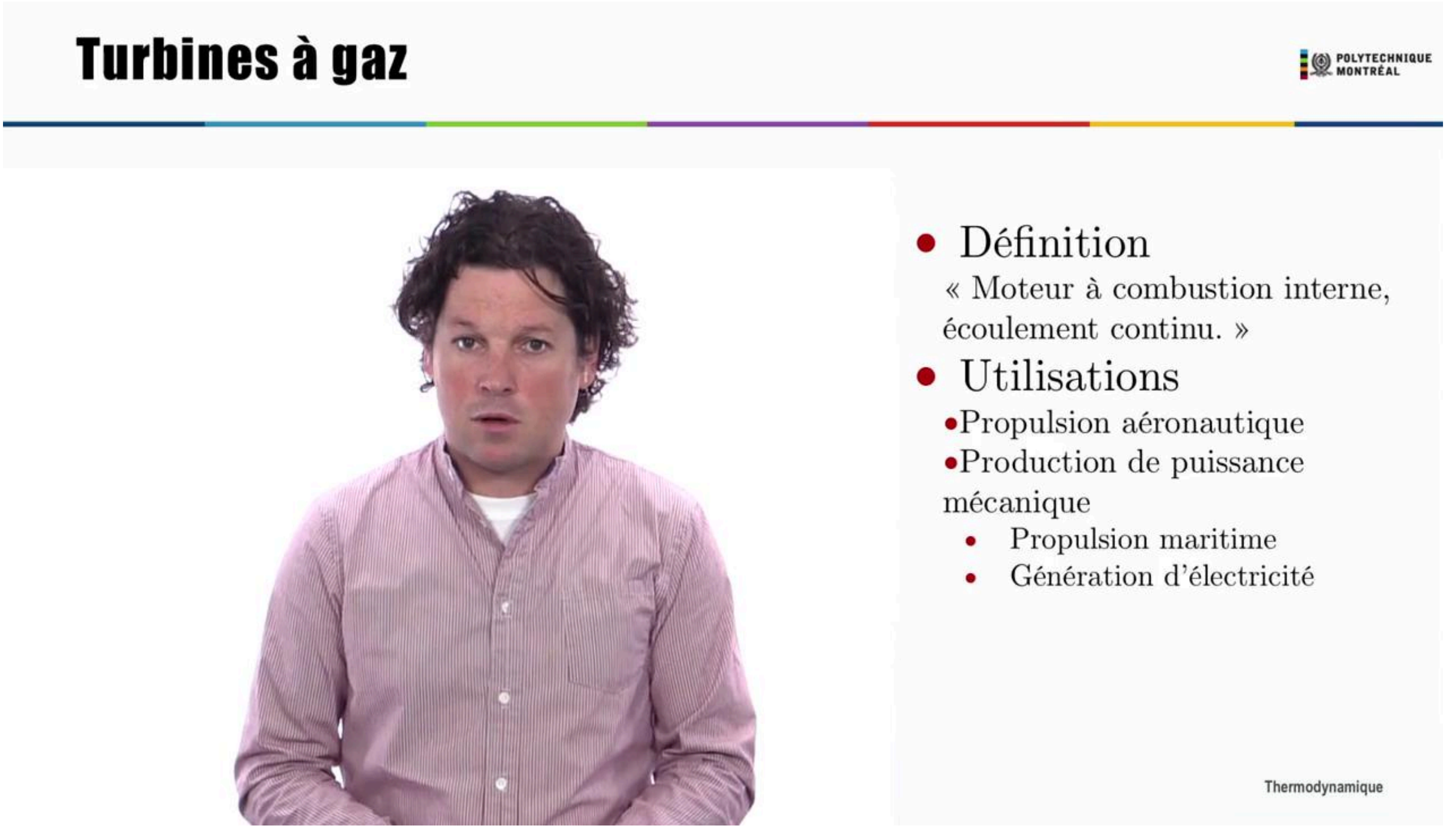
POLYTECHNIQUE MONTRÉAL Prof. Etienne Robert

Nicolas Léonard Sadi Carnot, 1796-1832



Video

EPFL



Hello. Welcome to this module which deals with thermodynamic cycles used in gas turbines. It is once again, as in the previous module, of gas power cycle which aims at the production of mechanical work from thermal power. In this module, I will discuss the different types of of gas turbines that exist, particularly with respect to their use for aeronautical propulsion. I will then present the main differences between the real cycles and the thermodynamic cycle that is used for modeling. I then presented the Brighton cycle, which is the main cycle used in gas turbines, as well as some strategies that can be put in place to increase the yield. Firstly, we can define the turbines engines as internal combustion engines, but which operate a flow continuous as opposed to the piston-cylinder system seen in the previous model. The gas turbines make it possible to obtain extremely high power densities, in the order of ten kW per kilo. This unique characteristic is a major reason why the turbines are used on a large scale in all applications that have constraints on the volume or weight of the propulsion systems, therefore, among other things, for aeronautical propulsion. In addition to aircraft propulsion, gas turbines are used for the propulsion of some ships and also for the production of electricity on the ground.

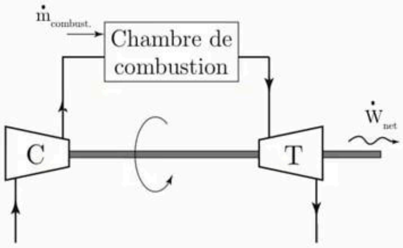
Notes

Summary

0m 04s

Turbines à gaz

POLYTECHNIQUE MONTRÉAL



- Définition

  « Moteur à combustion interne, écoulement continu. »
- Utilisations
  - Propulsion aéronautique
  - Production de puissance mécanique
    - Propulsion maritime
    - Génération d'électricité

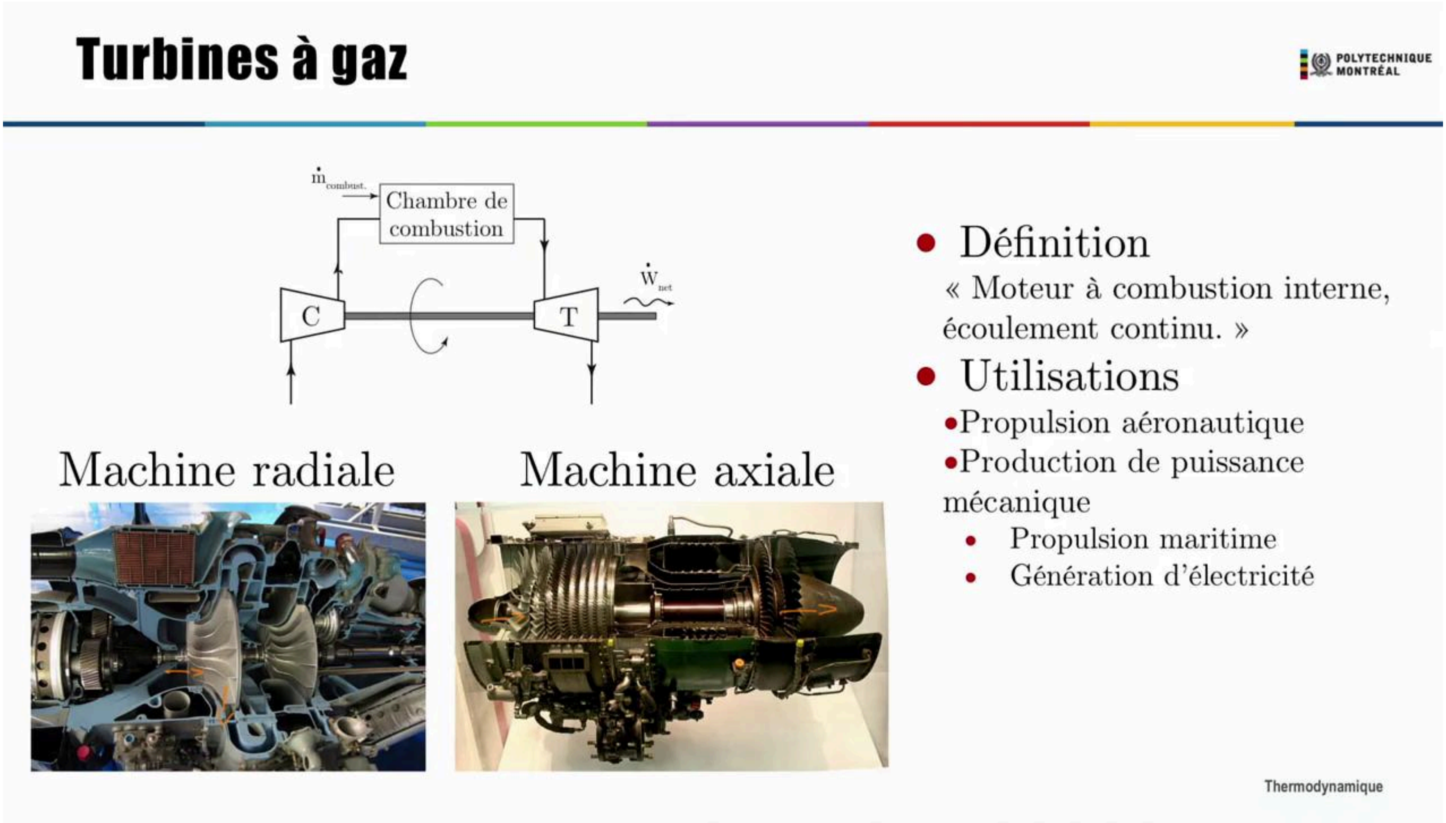
Thermodynamique

In a gas turbine, there is a compressor where the volume specific working fluid is reduced. A combustion chamber where the fluid acquires internal energy and a turbine or its expansion is performed to produce work. In general, the compressor and the turbine share a common smooth rotation axis. The net mechanical power produced by the system can be extracted.

Notes

Summary

1m 19s



The turbo machines used in gas turbines, i.e. compressors and turbines, can be either radial or axial. In a radial machine, the working fluid enters in parallel with to the axis of rotation and comes out perpendicular. While in an axial machine, the fluid inlet and outlet are parallel to the axis of rotation. In general, radial constructions are reserved for small-scale facilities. power, such as small aircraft engines or turbochargers used in in the automotive industry for aeronautical propulsion.

Notes

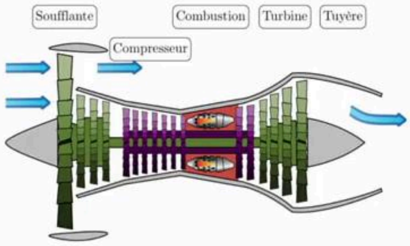
Summary

1m 41s

Propulsion aéronautique

POLYTECHNIQUE MONTRÉAL

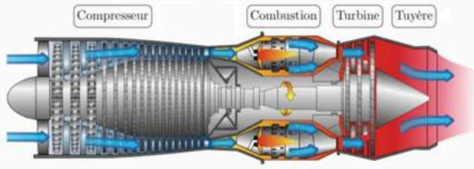
Turbosoufflante (turboréacteur à double flux)



$$\dot{W}_{Turbine} = \dot{W}_{Compresseur} + \dot{W}_{Soufflante}$$

$$BPR = \frac{\dot{m}_{Flux\ secondaire}}{\dot{m}_{Flux\ primaire}}$$

Turboréacteur



$$\dot{W}_{Turbine} = \dot{W}_{Compresseur}$$

$$\dot{W}_{Net,sortie} = 0$$

$$F = (\dot{m}V)_{Sortie} - (\dot{m}V)_{Entrée}$$

$$F = \dot{m}\,(V_{Sortie} - V_{Entrée})$$

$$\dot{W}_{Pousée} = F \cdot V_{Avion}$$

Thermodynamique

There are different types of gas turbines. Firstly, turbojet engines are gas turbines for which any the mechanical power that is extracted from the fluid by the turbine is used exclusively for running the compressor. So there is no mechanical power available to the rotating shaft to be extracted from the system, and in this case, it is the whole propulsive force that is transmitted to the aircraft comes from the difference in momentum between the input and output of the propulsion system. We can therefore calculate the thrust force as the mass flow rate of air passing through the system, multiplied by the difference in speed between the inlet and outlet. In this case, the contribution of the fluid can generally be neglected or the fuel itself for the thrust force and the mass flow rate. Because in general the mass flow of fuel used is very low in relation to the mass flow of air passing through the system. The applications for turbojet engines are generally limited to those that require a very high thrust force, often at the expense of propulsive efficiency. Basically, we are limited to military aviation. The vast majority of commercial aircraft use turbofan engines instead, also called turbofan engines.

Notes

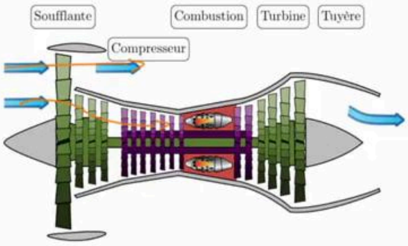
Summary

2m 17s

Propulsion aéronautique

POLYTECHNIQUE MONTRÉAL

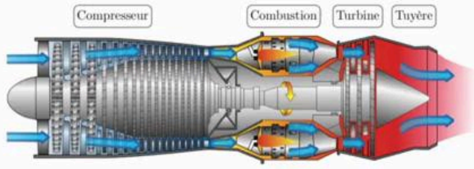
Turbosoufflante (turboréacteur à double flux)



$$\dot{W}_{Turbine} = \dot{W}_{Compresseur} + \dot{W}_{Soufflante}$$

$$BPR = \frac{\dot{m}_{Flux\ secondaire}}{\dot{m}_{Flux\ primaire}}$$

Turboréacteur



$$\dot{W}_{Turbine} = \dot{W}_{Compresseur}$$

$$\dot{W}_{Net,sortie} = 0$$

$$F = (\dot{m}V)_{Sortie} - (\dot{m}V)_{Entrée}$$

$$F = \dot{m}\left(V_{Sortie} - V_{Entrée}\right)$$

$$\dot{W}_{Pousée} = F \cdot V_{Avion}$$

Thermodynamique

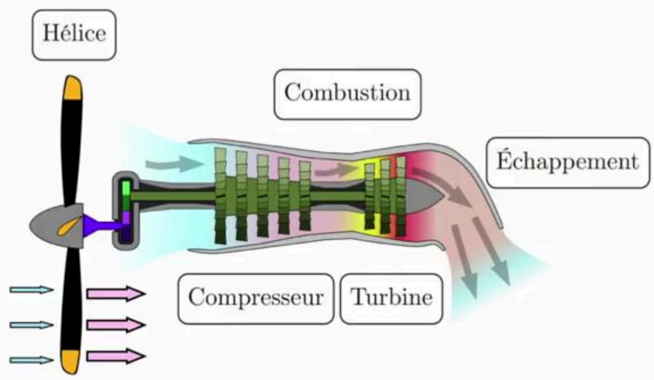
In these machines, the turbine produces more work than what that is required to drive the compressor and uses this excess to accelerate a secondary air flow around the turbine. The ratio between primary and secondary flows is called the dilution or bypass ratio in English and nowadays, large commercial aircraft all use turbofan engines with very high high dilution rate of about 8 to 12 to maximize propulsive efficiency. In other words, the air flow through the turbine is simply equal to about 10% of the total air that will flow around the turbine.

Notes

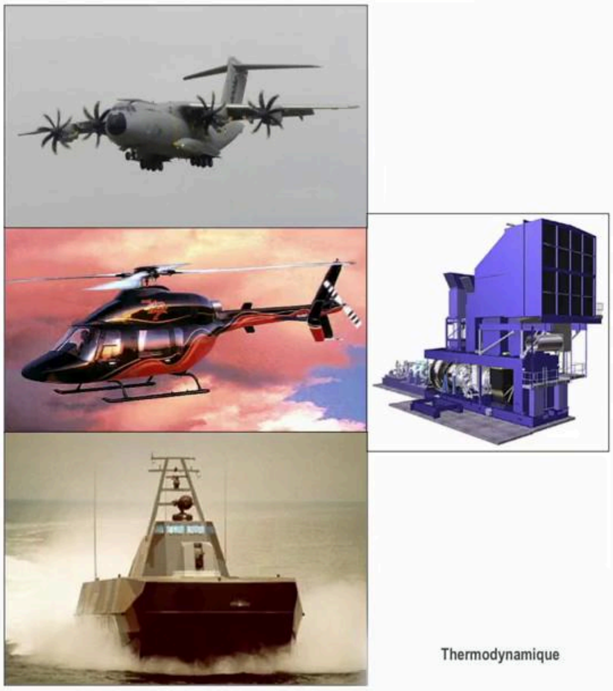
Summary

3m 30s

Turbomoteurs (turbopropulseurs)



$$\dot{W}_{turbine} = \dot{W}_{compresseur} + \dot{W}_{sortie}$$



Thermodynamique

If now the excess power is used to drive a propeller, we talk about turboprop or turboshaft. This is the principle of propulsion that prevails for low-speed aircraft speed, helicopters and maritime land applications. In any case, the turbine extract all possible energy to produce work to the rotating shaft, so that there is no energy left for the significant kinetics in the exhaust gas.

Notes

Summary

4m 05s

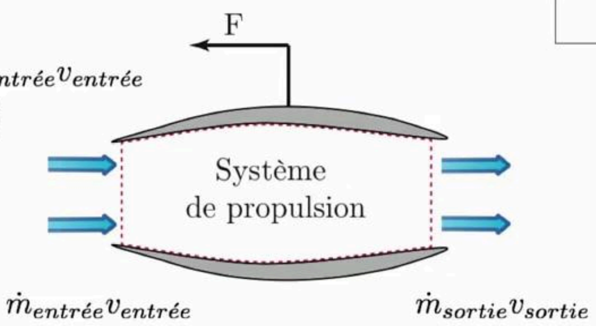
Choix de conception en propulsion aéronautique

POLYTECHNIQUE MONTRÉAL

Poussée

$$F = \dot{m}_{sortie} v_{sortie} - \dot{m}_{entrée} v_{entrée}$$

$$F \approx \dot{m}(v_{sortie} - v_{entrée})$$



$$\dot{W}_{air} = \frac{1}{2}\dot{m}(v_{sortie}^2 - v_{entrée}^2)$$

$$\dot{m} = \frac{2\dot{W}_{air}}{v_{sortie}^2 - v_{entrée}^2}$$

$$F \approx \frac{2\dot{W}_{air}}{v_{sortie} + v_{entrée}}$$

Efficacité propulsive

$$\eta_p = \frac{\dot{W}_{avion}}{\dot{W}_{air}} = \frac{\dot{m} \cdot v_{avion}}{\dot{W}_{air}}$$

$$\eta_p = \frac{2\dot{W}_{air}}{v_{sortie} + v_{entrée}} \cdot \frac{v_{entrée}}{\dot{W}_{air}}$$

$$\eta_p = \frac{2v_{entrée}}{v_{sortie} + v_{entrée}}$$

Thermodynamique

To make a choice of propulsion mode in aeronautics, one must first be aware of the trade-offs that exist between, on the one hand, the thrust force and on the other hand the propulsive efficiency. In all cases, the propulsive force will be the result of the acceleration of the air passing around and through the propulsion system, and this in the direction opposite to the movement of the aircraft. Neglecting the changes in flow due to the addition of the fuel, we obtain the force which is equal to the flow mass multiplied by the difference in velocity between the inlet and outlet. The work done to accelerate the air flow producing this thrust will be as follows to him expressed by the variation of kinetic energy. Combining the expression for this work with that of the push, we can obtain an expression for the thrust that relates the work done on the area and the exit speed. We will see later that these two parameters are very important. On the other hand, propulsive efficiency is defined as the ratio between the work done to move the air around the aircraft compared to the work done to accelerate the aircraft itself in terms of power. This is expressed as the product of the thrust force multiplied by the speed of the aircraft.

Notes

Summary

4m 30s

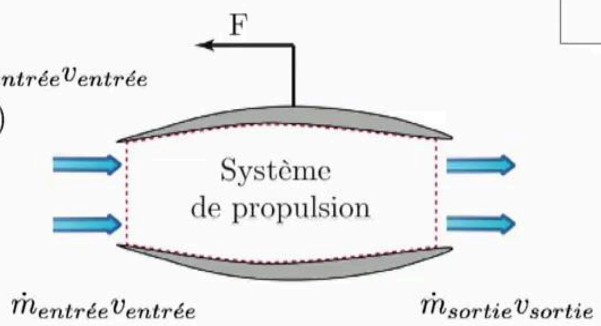
Choix de conception en propulsion aéronautique

POLYTECHNIQUE MONTRÉAL

Poussée

$$F = \dot{m}_{sortie} v_{sortie} - \dot{m}_{entrée} v_{entrée}$$

$$F \approx \dot{m}(v_{sortie} - v_{entrée})$$



Efficacité propulsive

$$\eta_p = \frac{\dot{W}_{avion}}{\dot{W}_{air}} = \frac{\dot{m} \cdot v_{avion}}{\dot{W}_{air}}$$

$$\eta_p = \frac{2\dot{W}_{air}}{v_{sortie} + v_{entrée}} \cdot \frac{v_{entrée}}{\dot{W}_{air}}$$

$$\eta_p = \frac{2v_{entrée}}{v_{sortie} + v_{entrée}}$$

$$\dot{W}_{air} = \frac{1}{2}\dot{m}(v_{sortie}^2 - v_{entrée}^2)$$

$$\dot{m} = \frac{2\dot{W}_{air}}{v_{sortie}^2 - v_{entrée}^2}$$

$$F \approx \frac{2\dot{W}_{air}}{v_{sortie} + v_{entrée}}$$

1. $v_{sortie} > v_{entrée}$
2. $F \nearrow$ si $v_{sortie} \nearrow$ et/ou si $\dot{m} \nearrow$
3. Pour un même $\dot{W}_{air}$, $F \nearrow$ si $v_{sortie} \searrow$
4. $\eta_p \nearrow$ si $v_{sortie} \searrow$

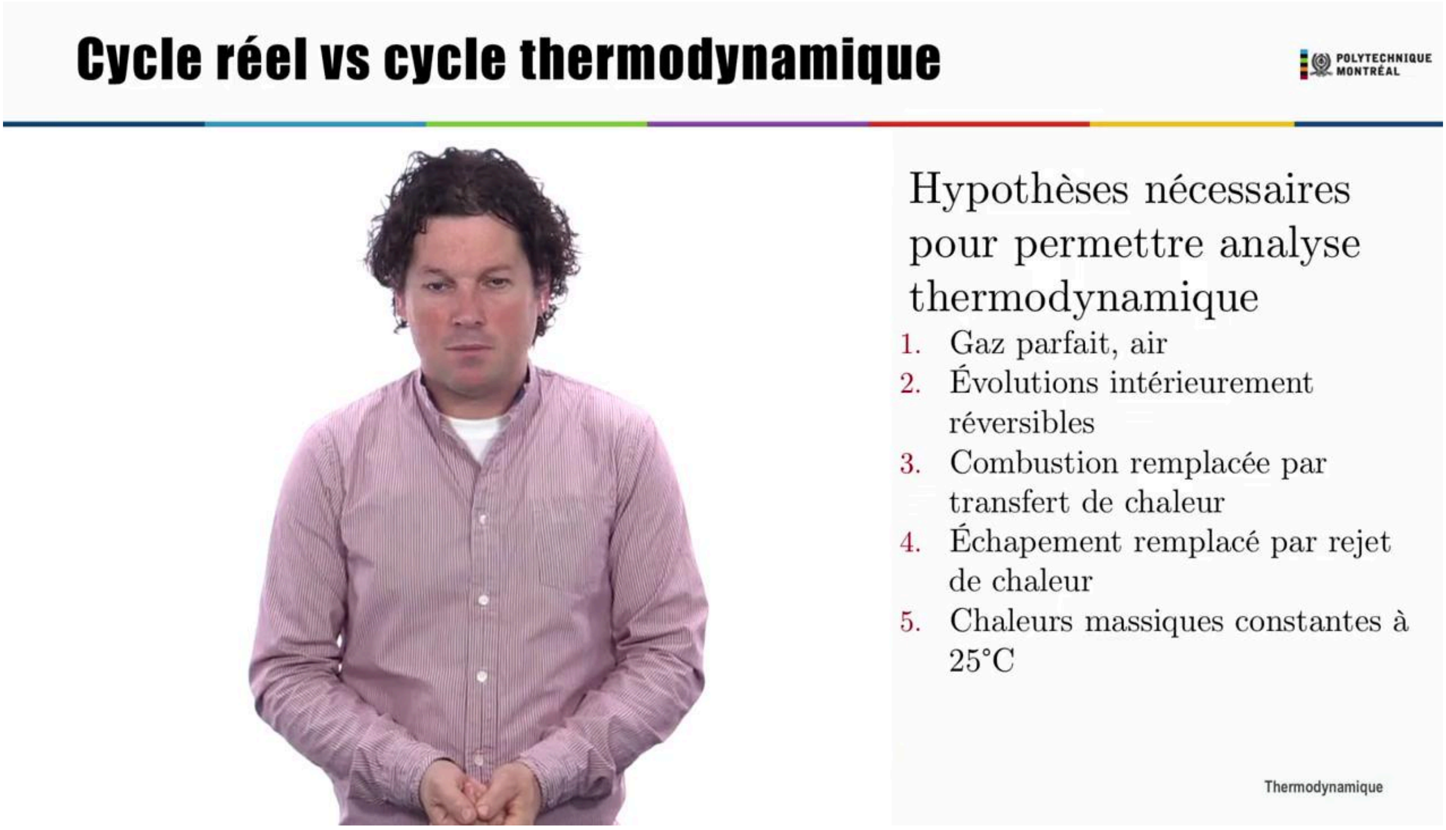
Thermodynamique

By replacing the expression. We previously found. For mass flow rates, the influence of work done on the air disappears and only the speeds remain. From these simple relationships, it is possible to draw some general conclusions that can guide design choices. First, since the output speed is always higher than the speed the thrust force increases if the speed of the output increases or if the mass night increases. Secondly, if the work done on the is supposed to constant, the thrust force increases if the output speed decreases. And finally the propulsive efficiency increases if the exit speed decreases. This observation motivates the use of gas turbines at dilution height which result in an increase of the mass flow. Decrease in output speed.

Notes

Summary

5m 41s

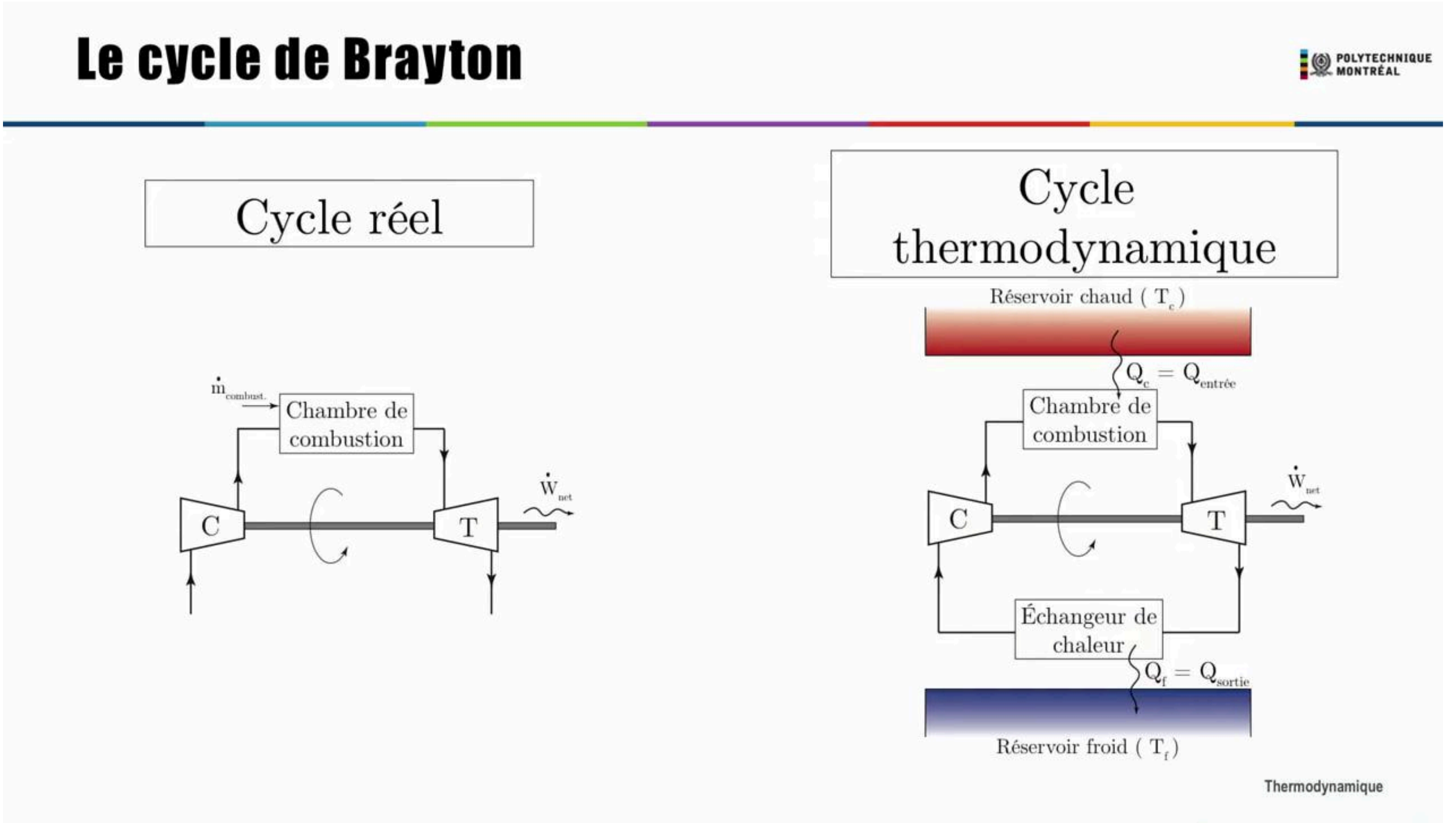


All of which results in both increased efficiency and the thrust force to allow an analysis of the thermodynamics of gas turbine cycles, we will again use the following at standard simplifying assumptions and standard cold air. We will therefore again assume that the work flow is air and that it is a perfect gas. We will also assume that the developments that involve. A change in pressure. Relaxation and compression are irreversible. Therefore, it entropies. And finally, we will be able to replace again the exchange of matter between the system and its environment by equivalent heat exchanges.

Notes

Summary

6m 36s

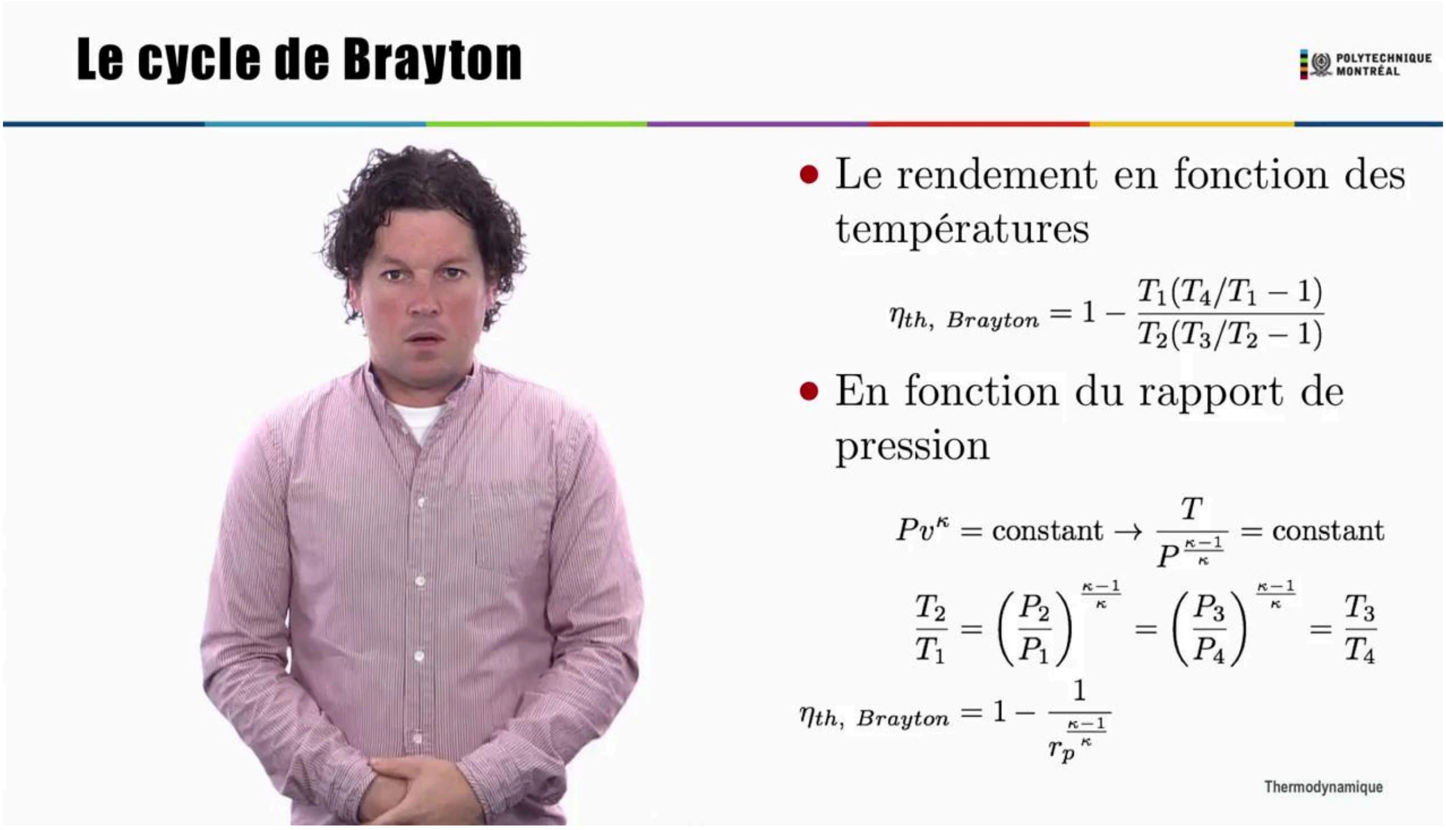


These simplifying assumptions have to replace the real mechanical cycle, which is called the Brighton cycle in which the circuit is open and the fluid flows successively in a compressor and a combustion chamber and a turbine. By an equivalent thermodynamic cycle which is realized in closed circuit in the equivalent circuits. Combustion and release of burnt gases to the atmosphere are replaced by by heat transfers with hot and cold reservoirs respectively.

Notes

Summary

7m 10s

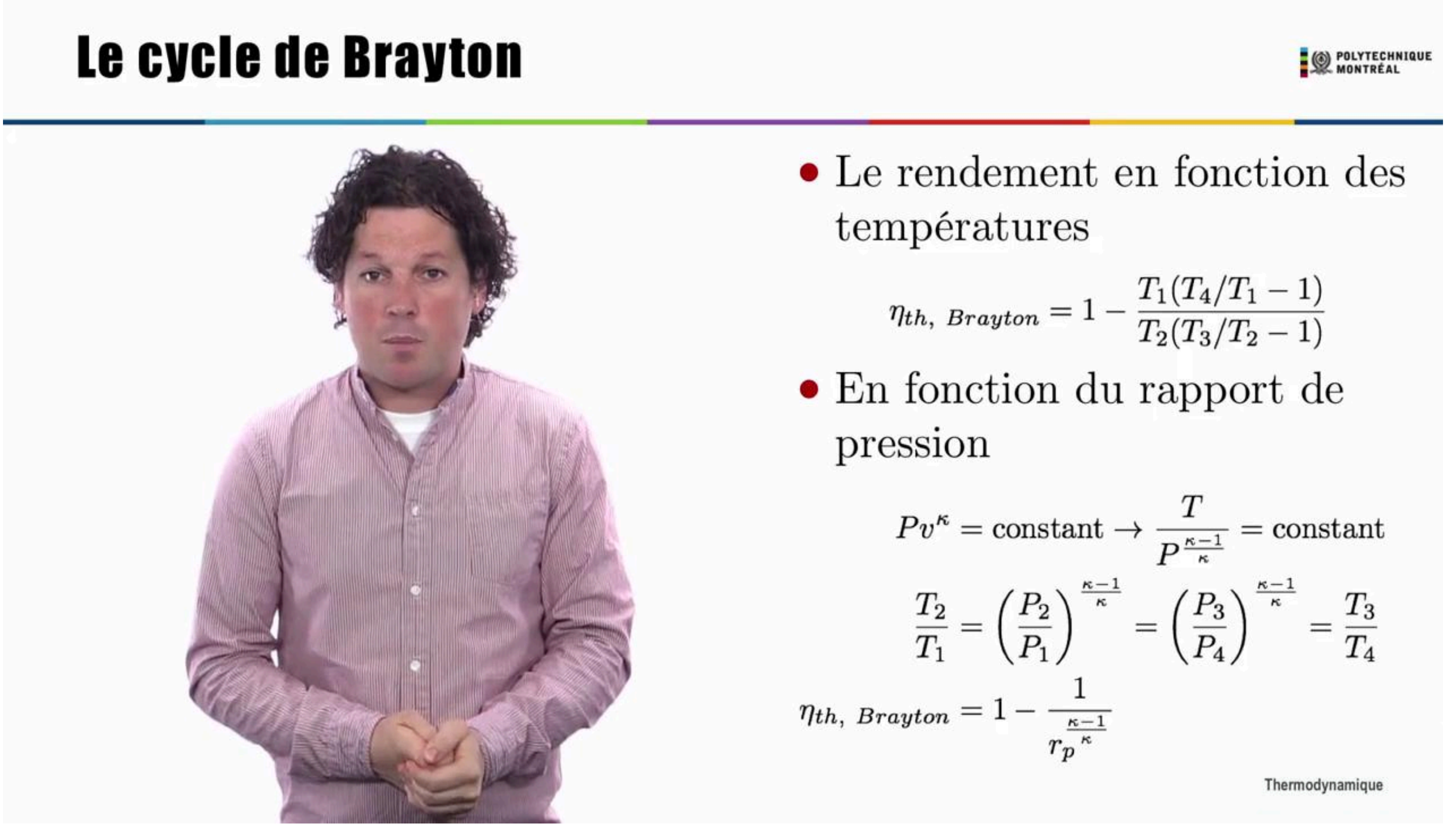


The century of Brighton idealized, is again composed of four evolutions and the compression and expansion stages being adiabatic and reversible are again entropic. As for the piston engine cycles. This time. However, since the circuit is open, Heat exchanges are done at constant pressure, as shown in the PV and TS diagrams between points one and two. Entropic compression results in an increase in pressure and temperature, then between points two and three. Only the temperature increases and the pressure remains constant during the heat share. The reverse operations are done in the same way. First, a relaxation and entropy and then a heat rejection at constant pressure. Again, the area bounded by the circle represents the net work of the circle in the PV diagram. In addition, we can still obtain a simple expression for the thermal efficiency of the cycle, which depends only on the temperature ratios between the different points. If we assume that the thermal capacities are constant and following the same reasoning as for the analysis of the cycles of piston engines, we obtain an expression for the efficiency which depends only on these temperature ratios.

Notes

Summary

7m 38s



There is, however, a major difference between the internal combustion engines of the Céline piston type that we have seen to previous models and gas turbine engines. In the case of piston-cylinder engines, the compression ratio is provided, therefore the ratio of volumes to characterize the configuration. In the case of gas turbines, the pressure ratio is provided instead P2 on P1, which characterizes both the turbine and the compressor. We therefore seek to modify the expression of the thermal efficiency. Which is given according to temperatures to make the pressure vapor appear. And again, we will use an isotopic relationship. This time, we will use of the two kinds T1 which is equal to P2 on P1 and the average Kappa on Kappa. And we will also remember that the ratio P2 to P1 is equal to the ratio P3 to P4. So we can make all the pressure relations disappear that we find in the upper equation and obtain a simplified expression for the optimal efficiency of the Brighton cycle, which is assumed to be reversible. And that's a minus to one on the pressure ratio at the average Kappa power.

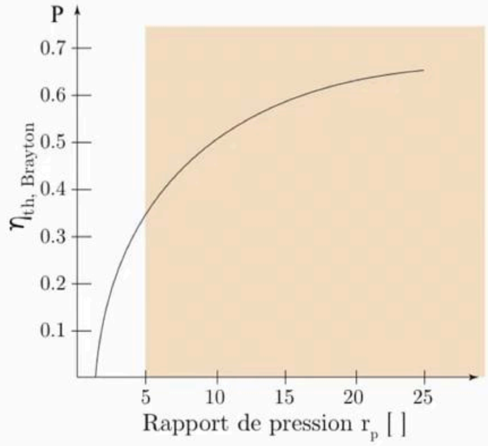
Notes

Summary

8m 46s

Le cycle de Brayton

POLYTECHNIQUE MONTRÉAL



- Le rendement en fonction des températures

$$\eta_{th,\ Brayton} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

- En fonction du rapport de pression

$$Pv^\kappa = \text{constant} \rightarrow \frac{T}{P^{\frac{\kappa-1}{\kappa}}} = \text{constant}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\kappa-1}{\kappa}} = \left(\frac{P_3}{P_4}\right)^{\frac{\kappa-1}{\kappa}} = \frac{T_3}{T_4}$$

$$\eta_{th,\ Brayton} = 1 - \frac{1}{r_p^{\frac{\kappa-1}{\kappa}}}$$

Thermodynamique

The efficiency therefore increases with the pressure ratio and can exceed 60%. for the pressure ratios achieved in the industry, which can reach up to 30, as mentioned in the introduction module. On the other hand, the efficiency of the machines It is difficult for the actual numbers to exceed 40 percent.

Notes

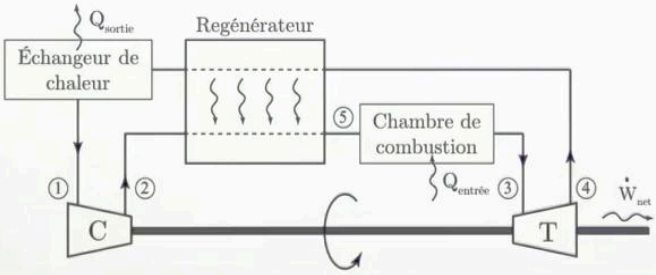
Summary

9m 48s

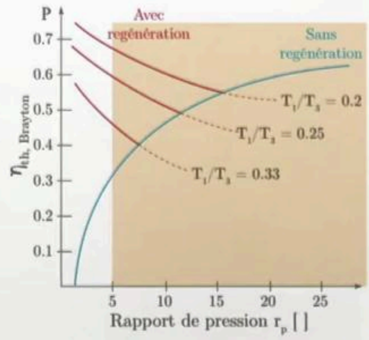
Stratégies d'accroissement du rendement

POLYTECHNIQUE MONTRÉAL

Regénération



$$\eta_{th,\ regen.} = 1 - \left(\frac{T_1}{T_3}\right) r_p^{\frac{\kappa-1}{\kappa}}$$



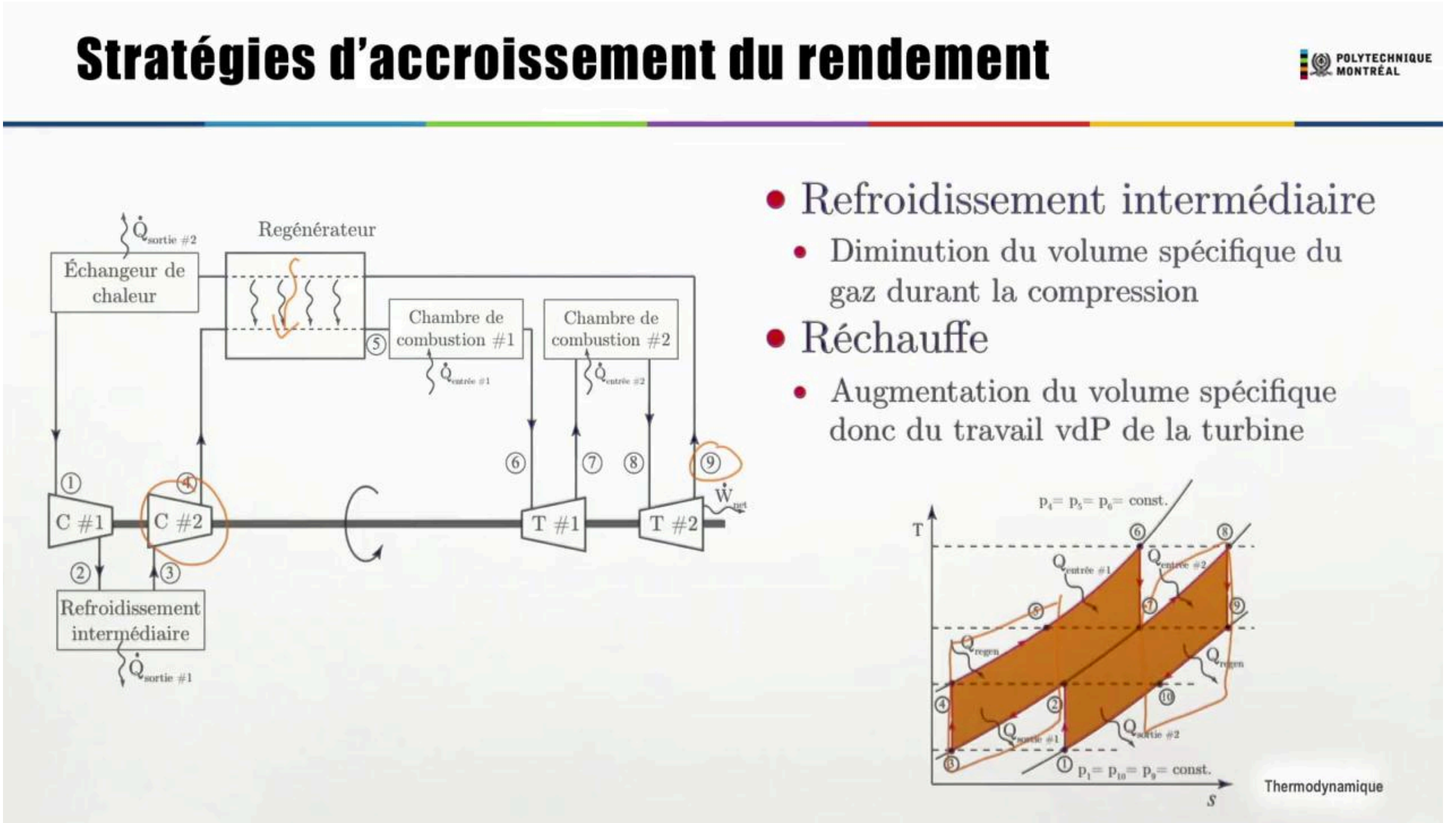
Thermodynamique

Several strategies are available to try to increase the efficiency of Brighton's cycles. We can start by mentioning regeneration, which consists in using part of the stored energy in the fields, in the flue gas at the outlet of the turbine to try to heat the fluid upstream of the chamber of combustion and thus save fuel. This approach requires the use of a specialized heat exchanger called the regenerator, which transfers part of the energy of the fluids leaving the turbine to the high pressure fluid after the compressor. Of course, this approach is only achievable if the temperature T4 at the turbine outlet is higher than the T2 temperature at the compressor outlet. This limitation imposes the fact that the generation approach is especially feasible and benefits mainly systems with a high ratio of compression or a relatively low pressure rate. If the pressure rate is high, the temperature T2 will be high and therefore T4 will have to be kept at a very high temperature to be able to use the regeneration. We thus obtain a new equation for the maximum thermal efficiency that the Brighton cycle can achieve using regeneration. But when you look at the results in a diagram that relates the efficiency to the pressure ratio, we see that the increase in yield is only materialized for relatively low pressure ratios.

Notes

Summary

10m 03s

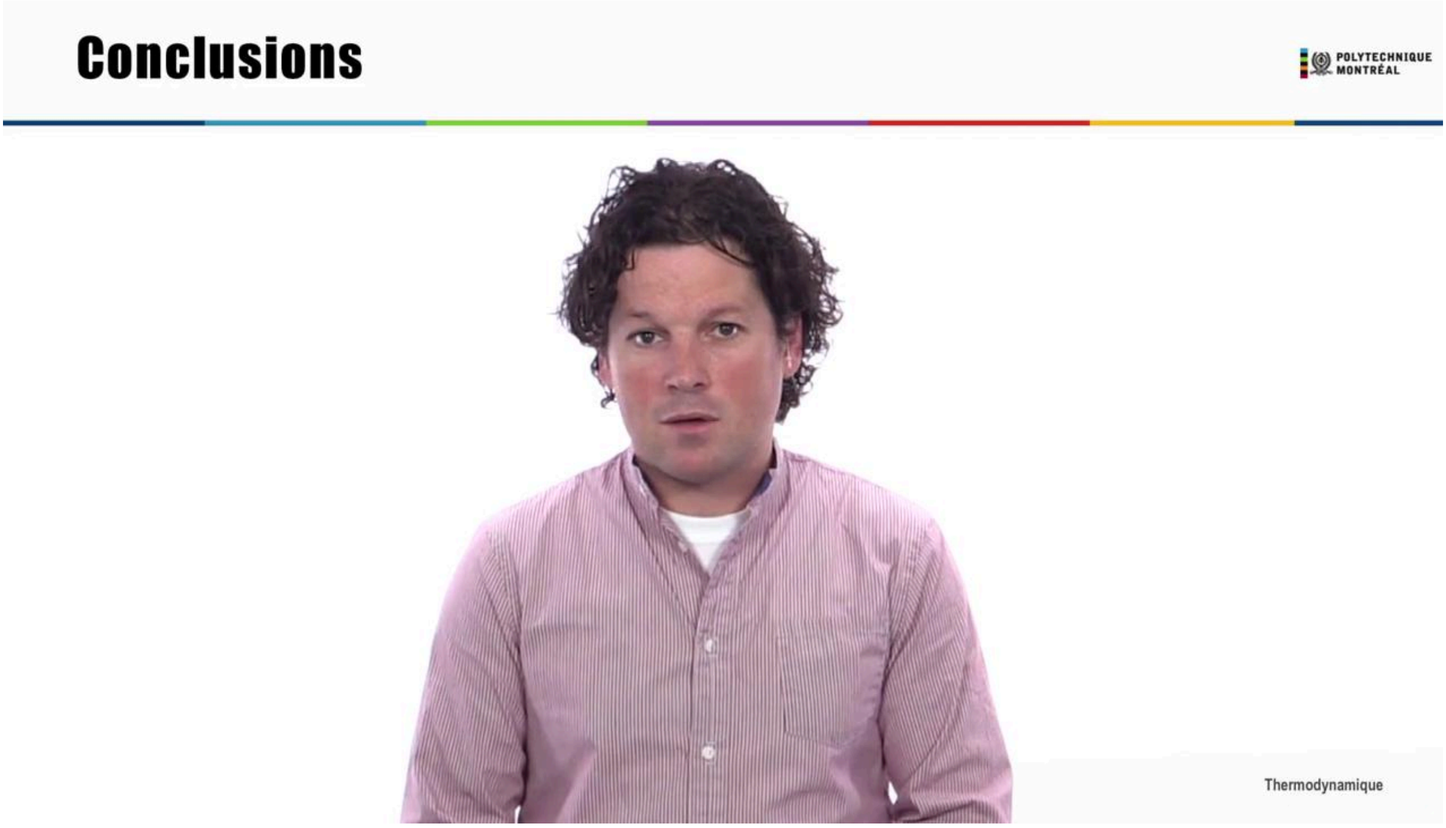


We can also increase the yield of a cycle by performing an intermediate cooling during compression and a warming up during the relaxation. In this figure is represented a circle in which we have made both intermediate cooling, reheating and regeneration. Firstly, the intermediate cooling of the fluid during the compression process allows to lower its specific volume and thus to decrease the work that it is necessary to to perform in the second compression stage. Then, the regenerator allows to obtain a part of the necessary heat to raise the temperature of the fluid to its maximum level, and this from a flow for which all the potential to generate of the work has already been exhausted since it comes from the turbine output. Finally, the use of a second combustion chamber allows to increase the the amount of work produced by the cycle. Graphically, we notice that we have increased the area in the TS diagram which is occupied by the cycle, so the total net work that was produced was increased. The intermediate cooling allowed to add this area, while reheating added that one. Here.

Notes

Summary

11m 25s



In conclusion, in this module, we have seen why gas turbines, because of their exceptional power density, have as many applications, in particular for aircraft propulsion. By reviewing the different types of of turbines available for aircraft propulsion, it was possible to observe the influence of the main design parameters which are the mass flow rate of air passing through the system and the exit velocity of the air. By applying the standard cold air assumptions, it was also possible to to obtain a simplified relationship for the performance of the Brighton cycle, depending on the pressure ratio of the cycle. We also reviewed two different approaches that are available to increase the efficiency of the Brighton cycles, which are therefore the regeneration and intermediate cooling and heating.

Notes

Summary

12m 35s