Accelerated Aging of SiC Coating: Numerical and Experimental Study

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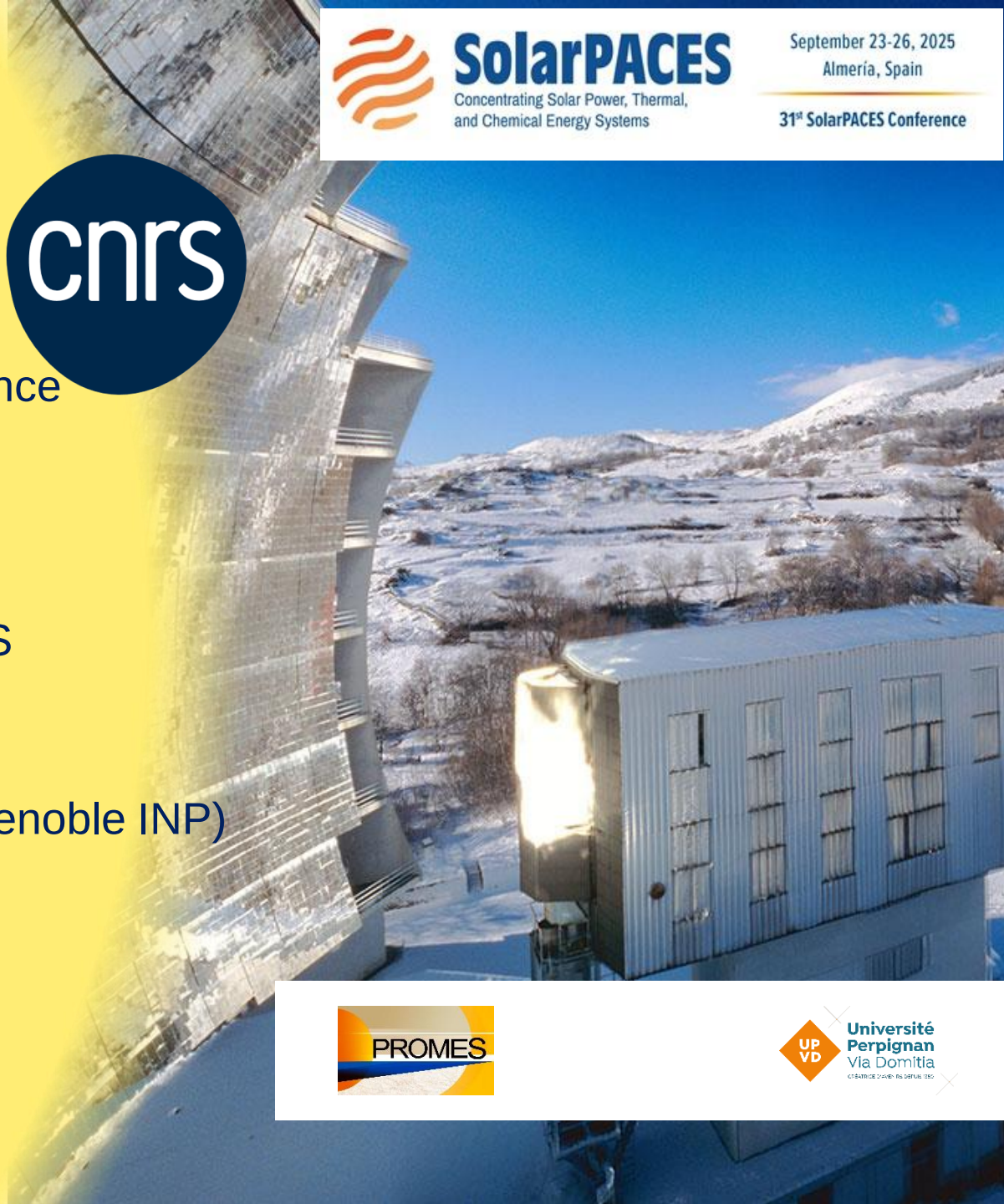
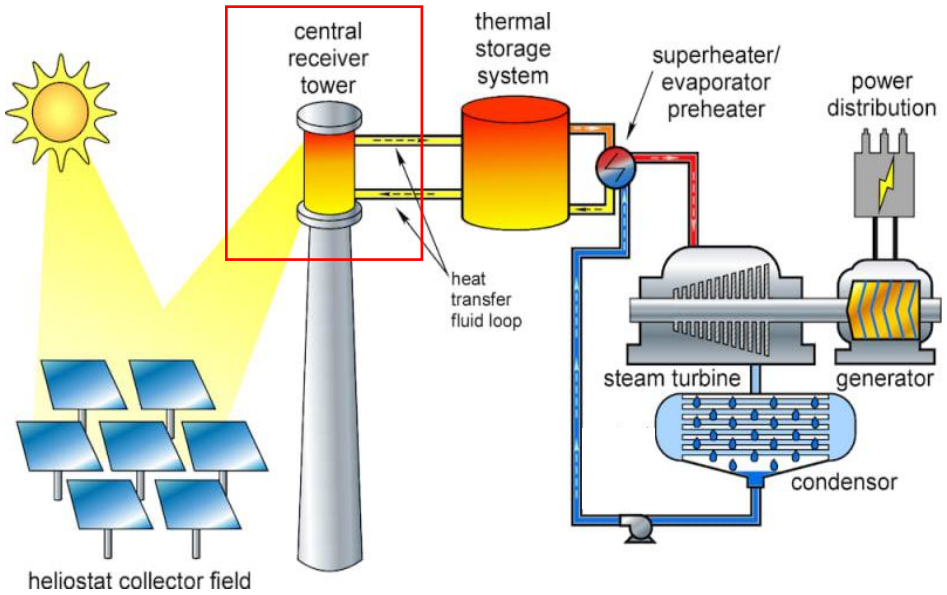


Plan

- ❑ Introduction
- ❑ Materials
- ❑ Methods
- ❑ Results and Discussion
- ❑ Conclusion and Perspectives

❑ Context: Concentrated Solar Technologies (CST)

- ➢ Conversion of solar energy → thermal energy → electricity or heat
- ➢ Low Efficiency (~16%) due to moderate operating temperature (~600 °C)
- ➢ Bottleneck: mechanical and oxidation limits of the receiver



❑ Objectives:

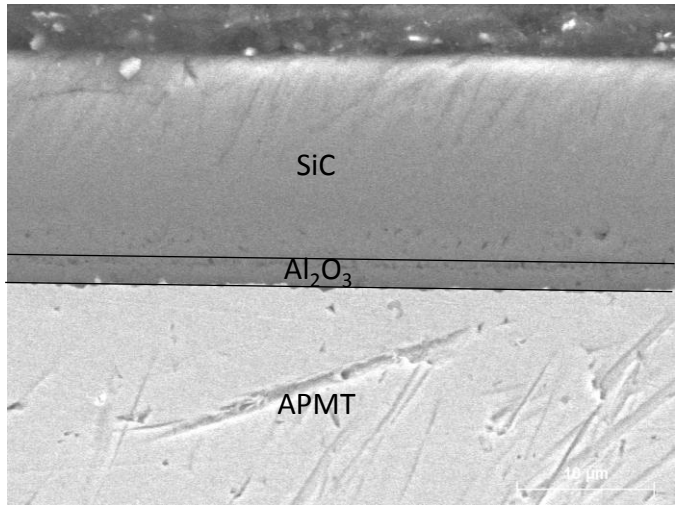
- ➢ **Operating at higher temperatures > 1000 °C**
  - ✓ Front side → exposed to concentrated solar flux (1000 kW/m²)
  - ✓ Rear side → thermal exchange with heat transfer fluid
- ➢ **Design of a high-performance receiver:**
  - ✓ Oxidation resistant
  - ✓ Good creep resistance and thermal cycling durability
  - ✓ Retention of optical properties

❑ Proposed Approach:

➢ Receiver made of a metal alloy coated with ceramic layers:

✓ Alloy provides mechanical strength

✓ Ceramic enhances solar-to-thermal conversion efficiency



❑ Methodology:

➢ **Numerical simulation:** estimation of stresses

✓ APMT oxidation ✓ SiC deposition ✓ Thermal cycling

➢ **Experimental test under solar flux:**

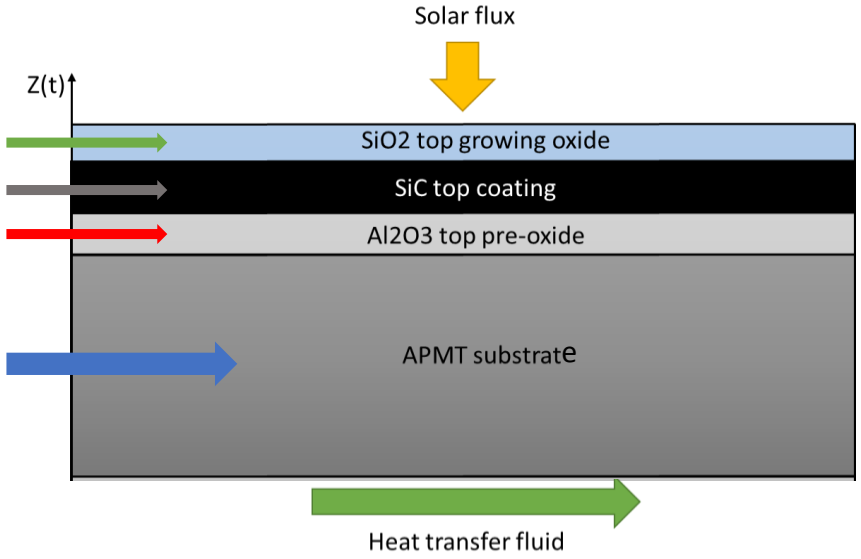
✓ Cycling under solar flux ✓ Temperature evaluation

➢ **Comparison of numerical and experimental approaches:**

✓ Improvement of the numerical model

✓ Optimization of the multilayer structure

- **Substrate layer:** Kanthal APMT (Fe-bal-Cr_{21-22}-Al_5-Mo_3)
  - Creep-resistant up to **1250** °C
  - Oxidation-resistant (FeCrAl alloy)
- **Intermediate Layer:** Alumina (Al_2O_3)
  - Substrate oxidation prior to deposition
  - Facilitates accommodation of SiC
  - High Thermal stability up to **1700** °C

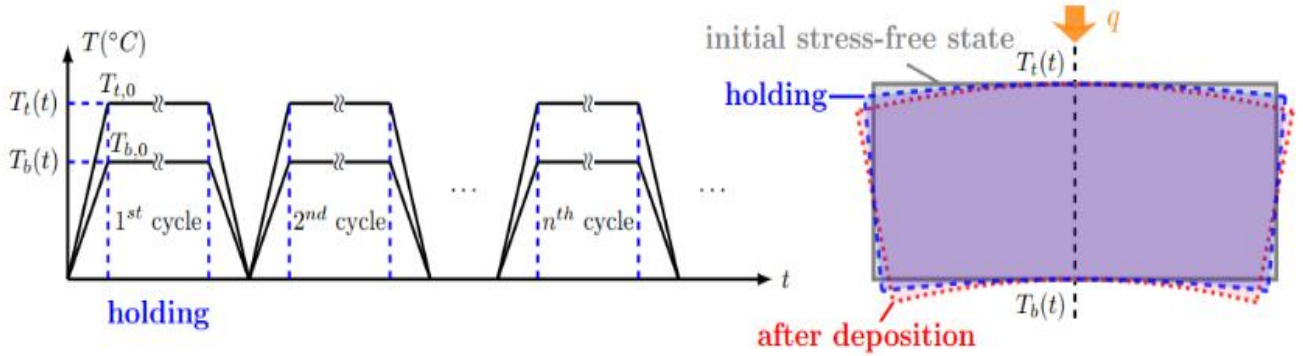


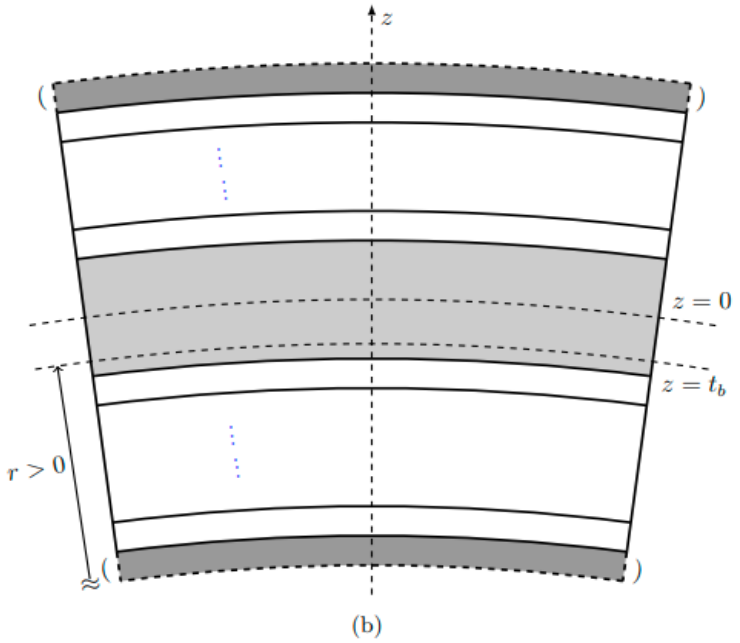
- **Coating layer:** Cubic Silicon carbide (SiC)
  - **HT-CVD** (High-Temperature Chemical Vapor Deposition)
  - at **1200 °C** : SiH_4 and C_3H_8
  - Oxidation resistance
  - High Solar absorptivity ~80%
- **Oxidation of SiC into SiO_2 during thermal cycling**
  - Growing protective oxide layer

Properties	Fe-Cr-Al-Mo	Al_2O_3	3C-SiC	SiO_2
Young ModulusE(GPa)	220	379	430	50-60
Poisson ratio ν	0.3	0.25	0.16	0.17
Density ($g.cm^{-3}$)	7.25	3.87	3.21	2.65
Thermal conductivity ($W\ m^{-1}\ K^{-1}$) à 1000 °C	27	10	21	1.6-1.2
Thermal expansion ($10^{-6}\ K^{-1}$)	15.5	8	5	0.55-0.6

❑ 1D Model in MATLAB

- Simulates thermal aging through cycling (**room temperature ↔ 1000 °C**)
- Calculates:
  - ✓ **Temperature through layers**
  - ✓ **Different strains**
  - ✓ **Stresses in different layers**





❑ Base on Hsueh Model: calculates the strain $\varepsilon(z) = c + \frac{z - t_B}{r}$

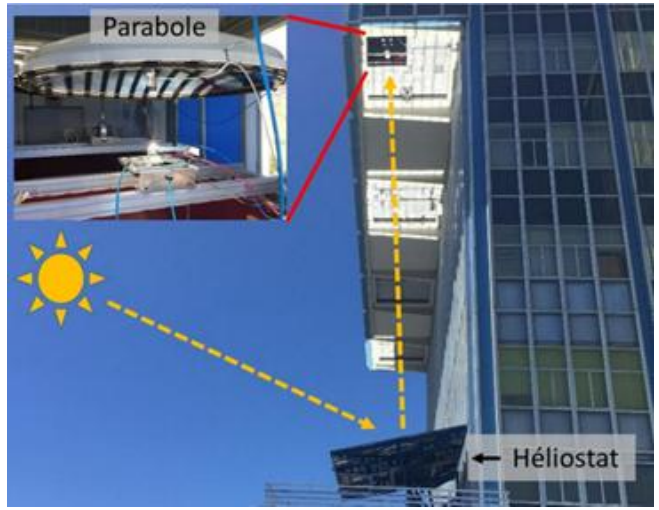
- c: uniform strain component
- $\frac{z - t_b}{r}$: bending strain component where t_b is the bending axis position,
- $\frac{1}{r}$: the curvature and z is the position in layers

❑ Stress in layers

- Stress in substrate: $\sigma_s(z) = \frac{E_s}{1-\nu_s}\left(c + \frac{z-t_b}{r} - \varepsilon_{s,thermal} - \varepsilon_{s,coating} - \varepsilon_{s,thermal} - \varepsilon_{s,creep}\right)$
- Stress in other layers: $\sigma_{layer}(z) = \frac{E_{layer}}{1-\nu_{layer}}\left(c + \frac{z-t_b}{r} - \varepsilon_{layer,coating} - \varepsilon_{layer,thermal} - \varepsilon_{layer,creep}\right)$
  - ✓ Coating : due to deposition
  - ✓ Thermal: due to thermal expansion
  - ✓ Creep: due to temperature holding

- In order to obtain **the stresses**, one must solve a system of equations involving three unknowns **(c, t_b, and r):**
  - ✓ The sum of the forces due to the uniform deformation **equal to zero**
  - ✓ The sum of the forces due to the bending experienced by the sample **equal to zero**
  - ✓ The resultant moment with respect to the axis of curvature **equal to zero**

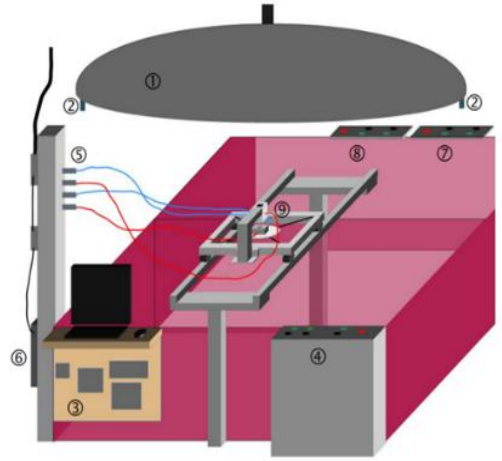
❑ Experimental Setup: SAAF (Solar Accelerated Aging Facility)



➢ Main Components

- **Solar concentration system:**
  - ✓ Mobile heliostat (6 m × 4.5 m) → tracks the sun
  - ✓ Fixed parabolic mirror (Ø 1.5 m, 900 W power, concentrates 15,000 times)
  - ✓ Focal point: Ø ~20 mm at 635 mm from center
- **Kaleidoscope**: homogenizes the flux on the sample
- **Movable shutters** (blades): control the solar flux
- **Cooling**: water (kaleidoscope) and compressed air (sample holder)
- **Control system and data acquisition**

➢ Usage: Simulate multilayer aging through controlled thermal cycling



1. Parabolic dish reflector
2. Laser
3. Control panel
4. Control console (S/E trapdoor)
5. Cooling ball valves
6. Air flowmeter
7. Control console (tracking)
8. Control console (S/W trapdoor)
9. Experimental cart

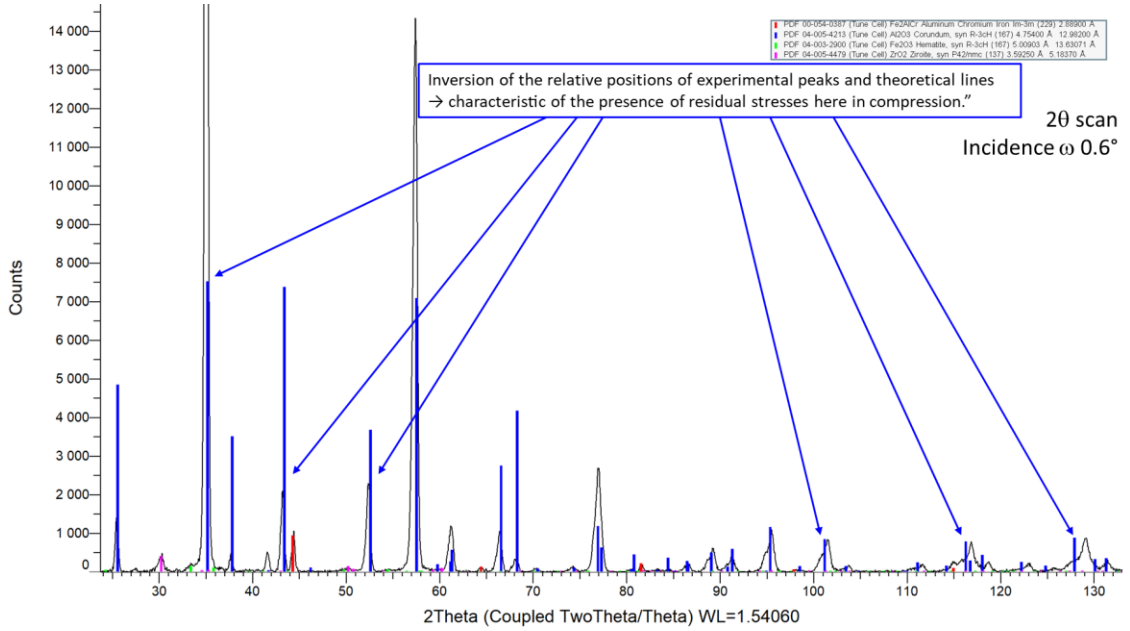
❑ Residual Stress Measurement by X-ray Diffraction (XRD)

➢ XRD $\sin^2\psi$ Method:

- Uses crystalline planes as strain gauges
- **Measures d-spacing at different ψ angles**
- Linear plot (ε vs $\sin^2\psi$) → slope gives residual stress

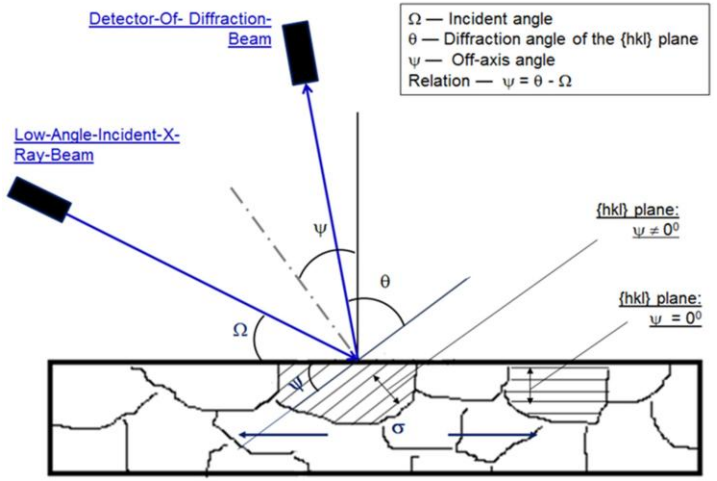
➢ Limitations of Conventional Method:

- High diffraction angles ($2\theta > 125°$) usually required
- Problematic for thin films: weak and broadened peaks



➢ Alternative: GIXRD (Glancing Incident XRD):

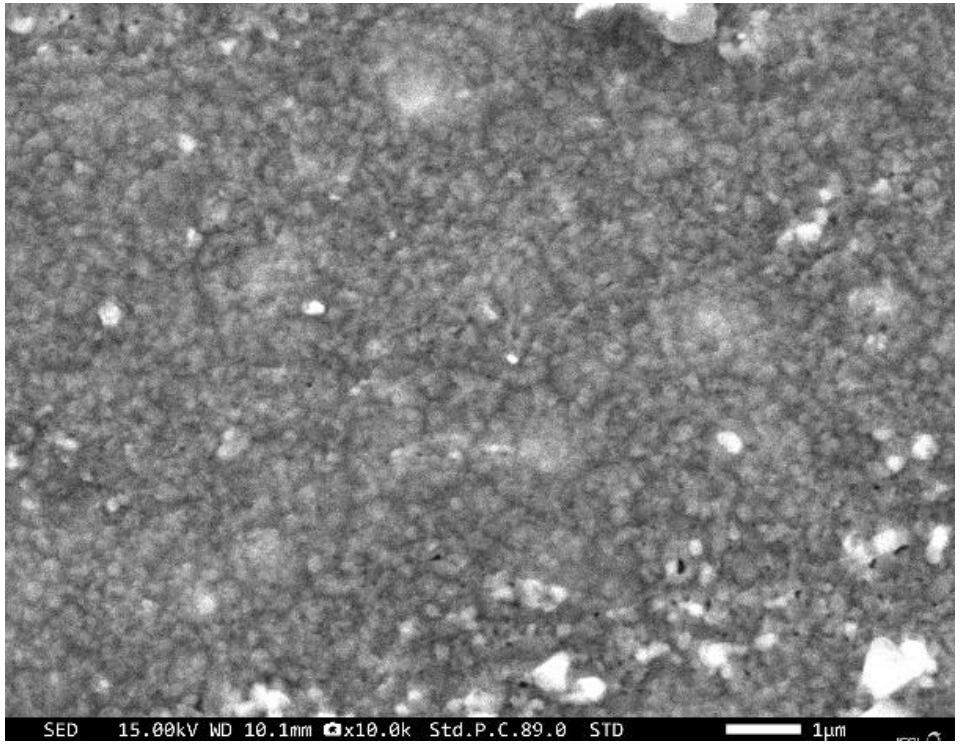
- Employs a constant, low incident angle Ω
- Different ψ angles obtained via $\psi = \theta - \Omega$
- Especially suited for thin films and surface layers
- Effective for cubic crystalline materials



❑ After oxidation : stresses in Al_2O_3/APMT sample

- Treatment: **50 hours at 1100 °C in air**
- Aluminum oxide formed : **α-Al_2O_3**
- Homogeneous surface
- No cracking observed

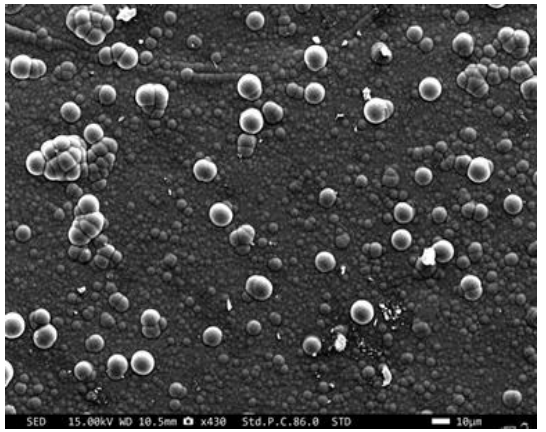
Layer	Numerical (MPa)	Experimental (MPa)	Limit compressive strength (MPa)
Al_2O_3	-2489.7	-2760	-2000 to -4000

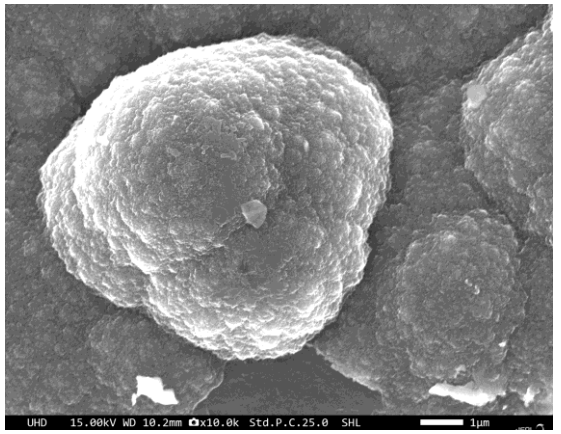


- Compressive in both methods
- Values very close (<10%)
- The model accurately represents the oxidation process

❑ After SiC deposition : stresses in SiC/Al2O3/APMT simple

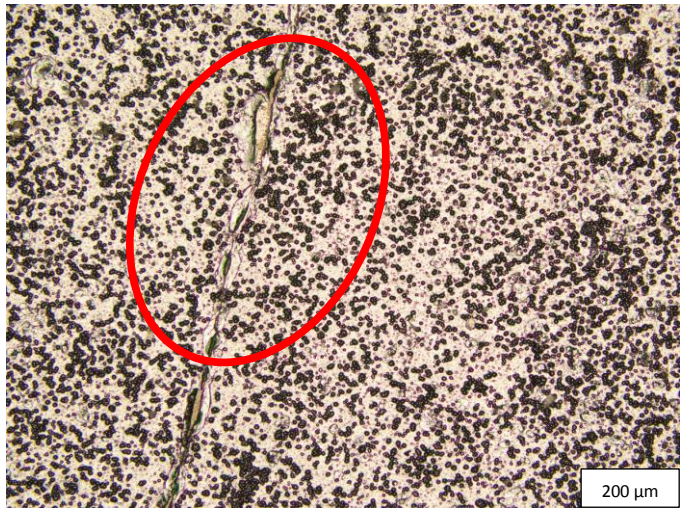
- **SEM image:** “Cauliflower” morphology, typical of HTCVD 3-SiC
- Some coating delamination observed along the existing scratches in the substrate.





Layer	Numerical (MPa)	Experimental (MPa)	Limit compressive strength (MPa)
SiC	-1845	-2393	2500-3500
Al_2O_3	-2967	-3120	2000-4000

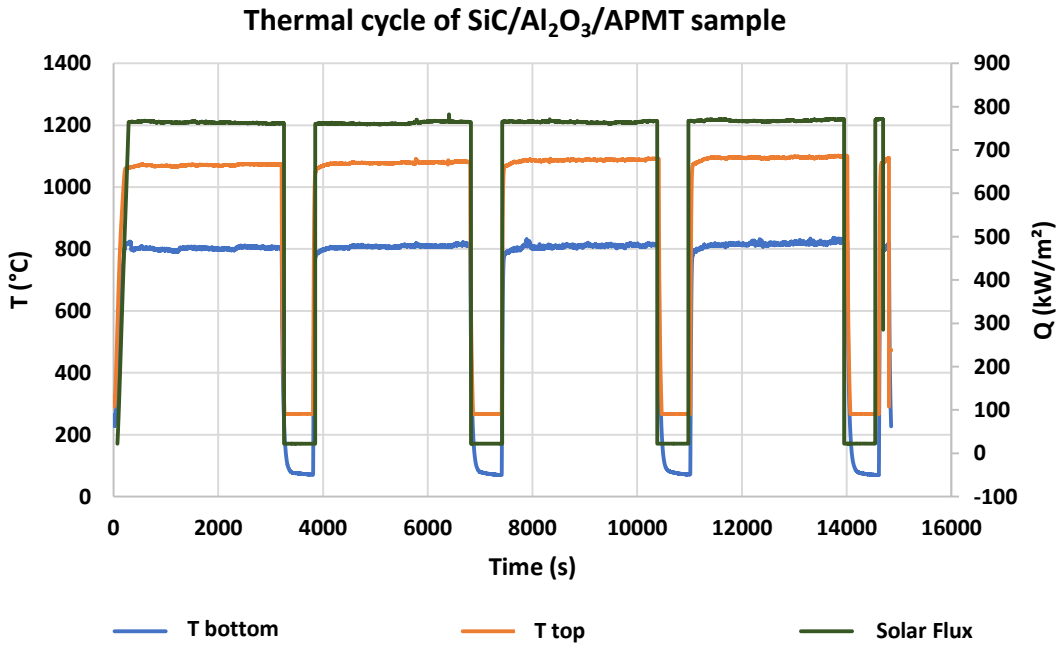
- Compressive stresses in both layers and methods
- **Numerical value of SiC is 23% lower than experimental value**
- For alumina the two values are very close (<5%)
- **Comparison with compression limits**
  - Observed cracks probably originate in alumina
  - Consequentially affect the SiC layer



❑ After thermal cycle : SiC/Al2O3/APMT simple

➢ Simulation Parameters:

- Number of simulated cycles: **4**
- **1 hour** duration (**50 min** at high temperature and **10 min** rapid cooling)
- Incident solar flux: **800 kW/m²** → temperature reached at sample Top: ~**1100 °C**
- Geometry and materials (multilayer):
  - ✓ Substrate: thickness: **2 mm**
  - ✓ Alumina (Al_2O_3) layer: **1 µm**
  - ✓ SiC layer: **10 µm**
- High SiC absorptivity: **81%**

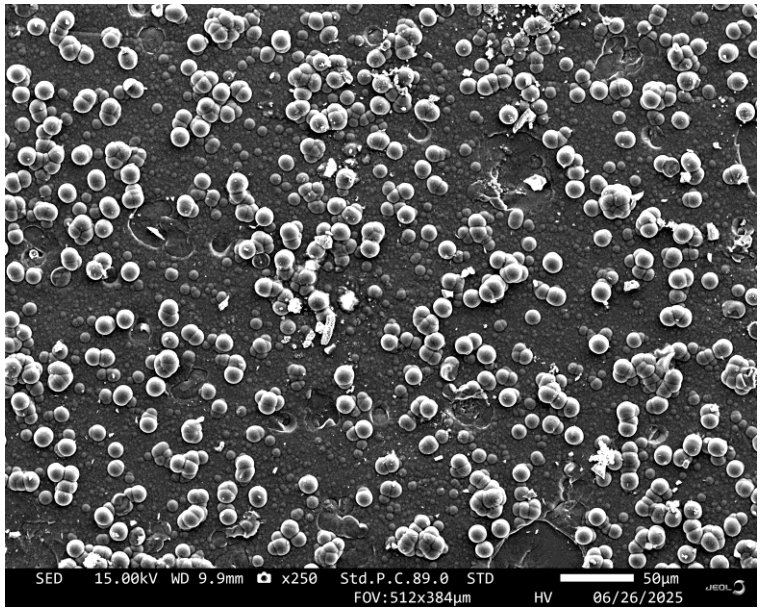


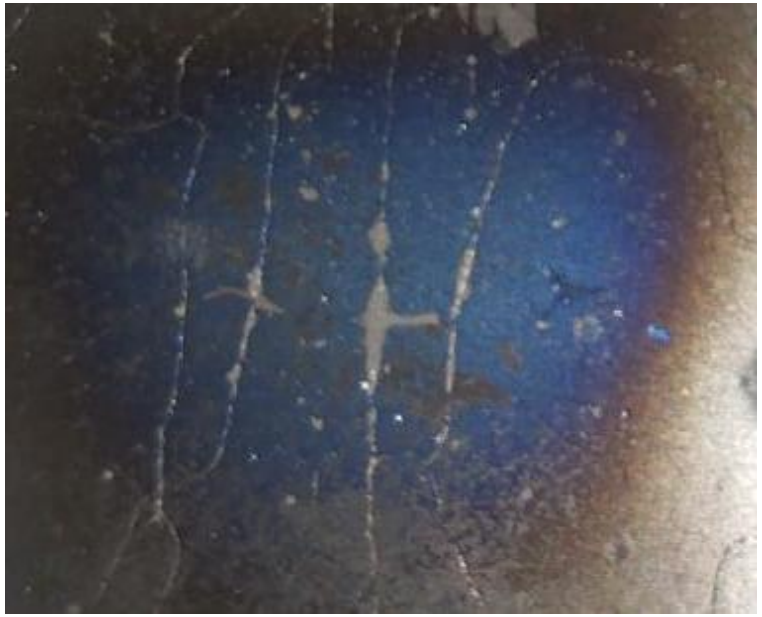
❑ After thermal cycle : SiC/Al_2O_3/APMT sample

- **Oxidation observed**: confirmed by EDS and XRD analysis
- **Propagation of existing cracks**.

Layer	Numerical (MPa)	Experimental (MPa)	Limit compressive strength (MPa)
SiC	-2530	-1113	-2500 to -3500

- **Experimental stress is 50% lower than numerical stress**
  - DRX method is highly dispersive
- **Based on the results:** Numerical value reflects observations better (cracks and delamination)
- **Ongoing work: other methods**
  - Photoluminescence
  - Curvature measurement (Stoney)
- **Comparison of different methods**





- ❑ Simulations and experiments are very close for alumina but need correction for SiC layer
- ❑ Linear dependence between stress and deformation
- ❑ Some issues observed: delamination and crack propagation from alumina
- ❑ Promising concept, but needs **further optimization** for long-term stability

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Thank you for your attention

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UPR CNRS en convention avec l'UPVD

Annex 8: Residual Stress Measurement by X-ray Diffraction (XRD)

$$d_{hkl} = \frac{1+\nu}{E} \times \sigma \times d_0 \times \sin^2\psi + \frac{-2\times\nu}{E} \times \sigma \times d_0 + d_0$$

$$\frac{d_{hkl}-d_0}{d_0} = \frac{1+\nu}{E} \times \sigma \times \sin^2\psi + \frac{-2\times\nu}{E} \times \sigma$$

$$\varepsilon = \frac{d_{hkl}-d_0}{d_0} = \frac{1+\nu}{E} \times \sigma \times \sin^2\psi + \frac{-2\times\nu}{E} \times \sigma$$

$$\varepsilon = C\sin^2\psi + D = f(\sin^2\psi) \text{ where}$$

$$C = \frac{1+\nu}{E} \times \sigma \text{ and } D = \frac{-2\times\nu}{E} \times \sigma$$

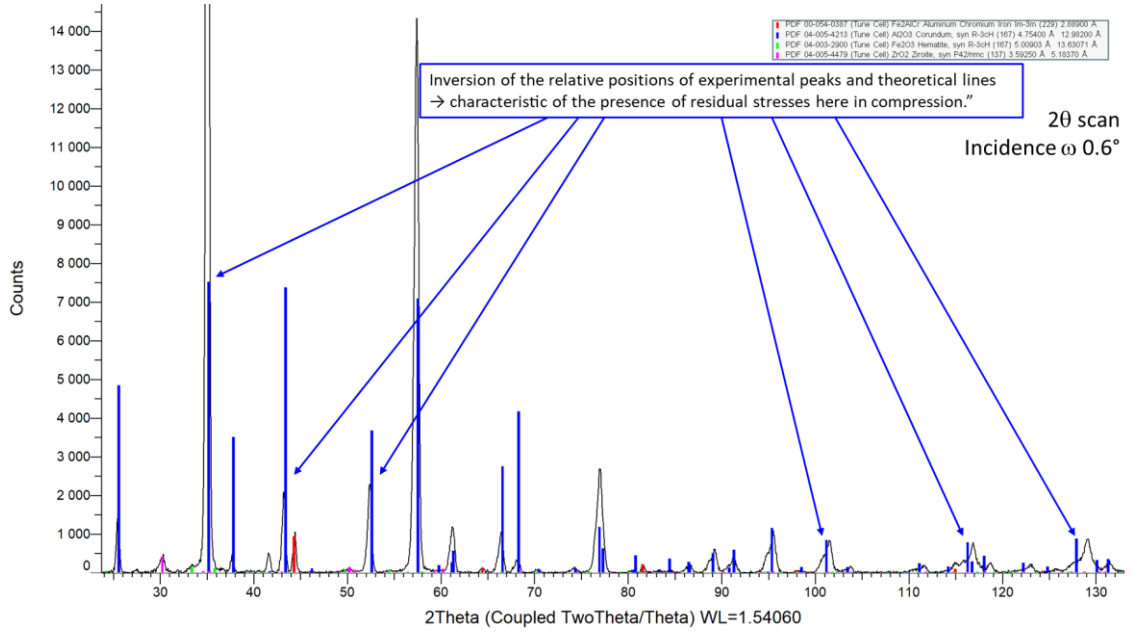
$$\sigma = \frac{E}{1+\nu} \times C$$

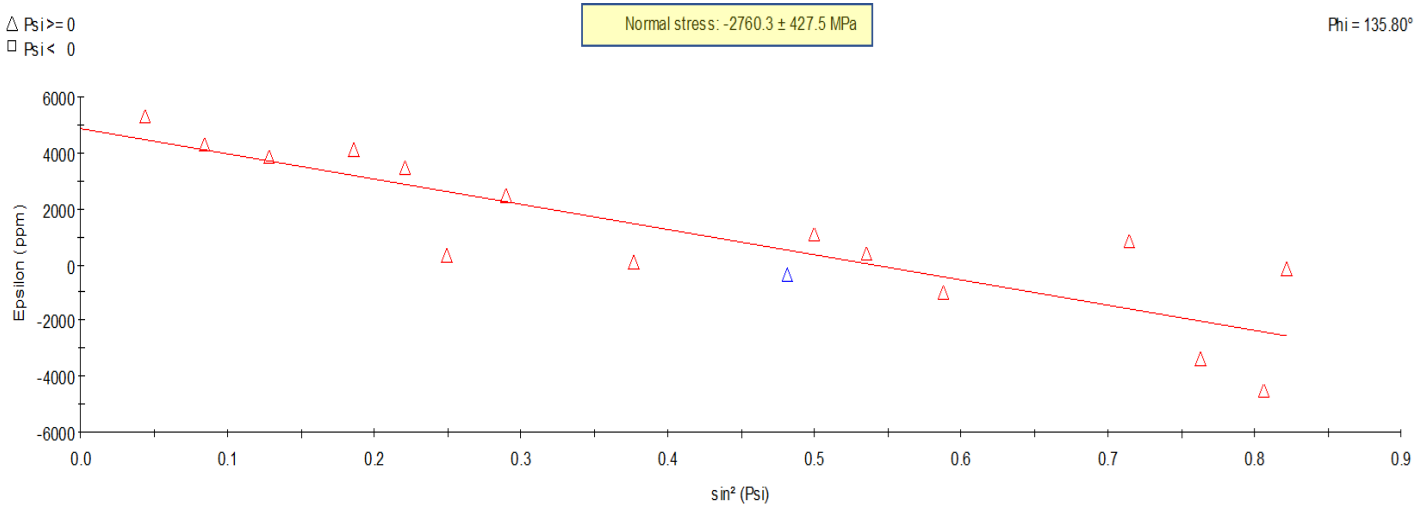
ε in the strain depending on ψ

E is the Young Modulus

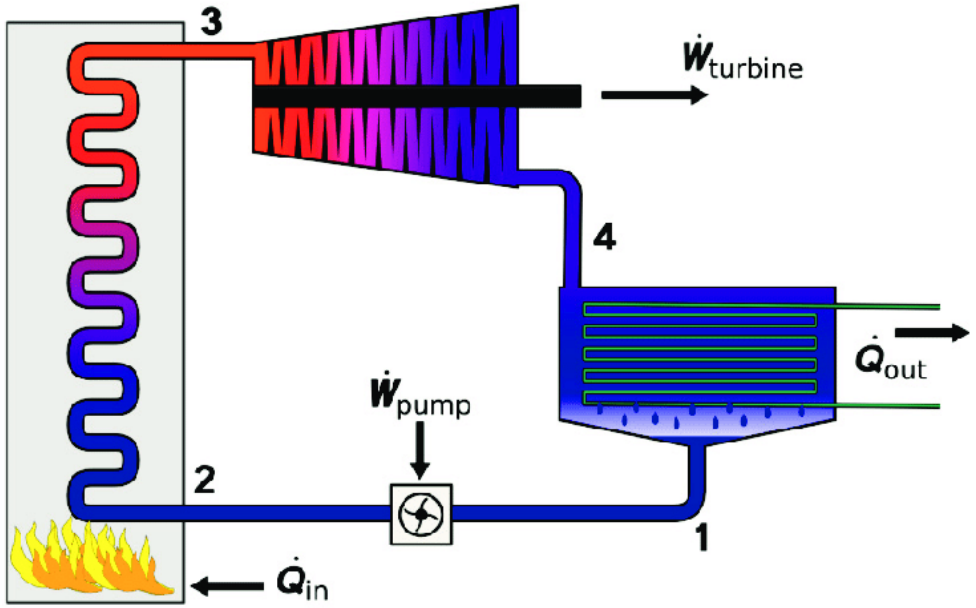
ν is the Poisson ratio

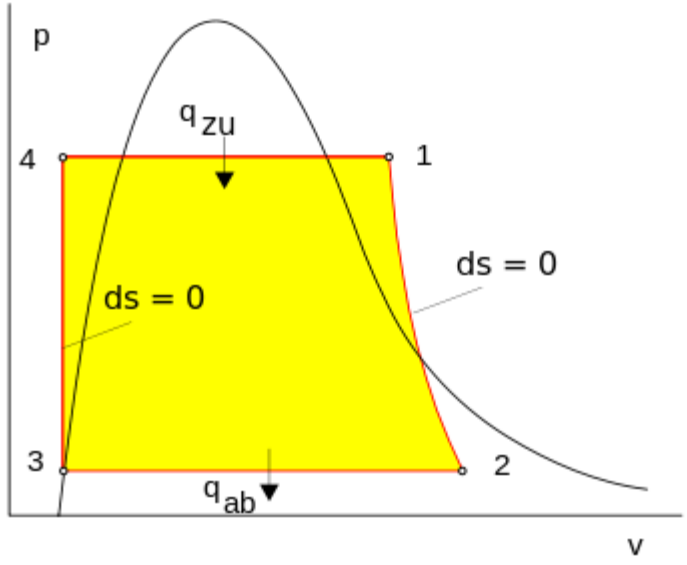
σ is the residual stress





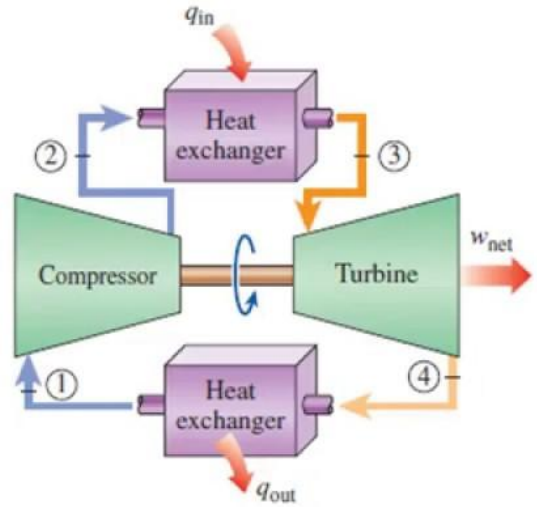
Annex 1: Rankine cycle

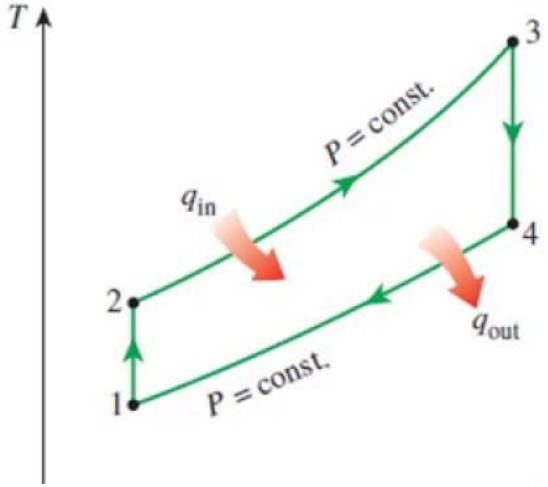


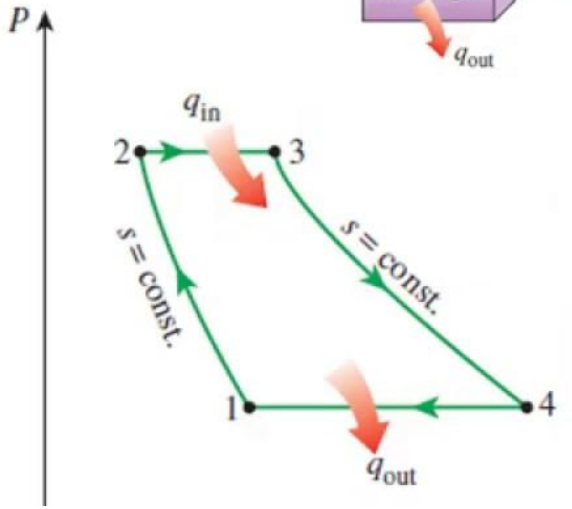


Annex 2: Brayton cycle

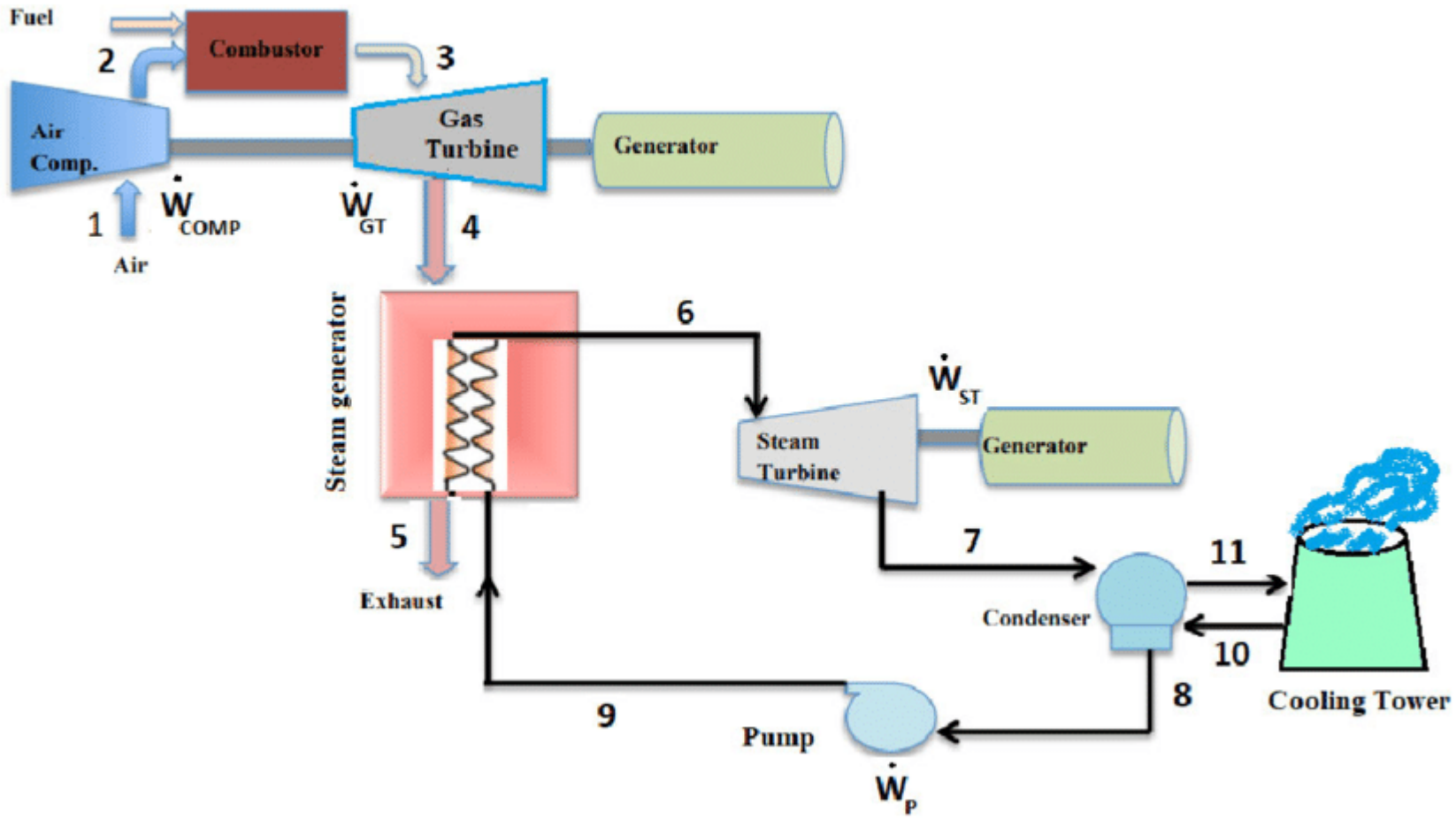
1-2 Isentropic compression (in a compressor)
2-3 Constant-**pressure** heat addition
3-4 Isentropic expansion (in a turbine)
4-1 Constant-**pressure** heat rejection



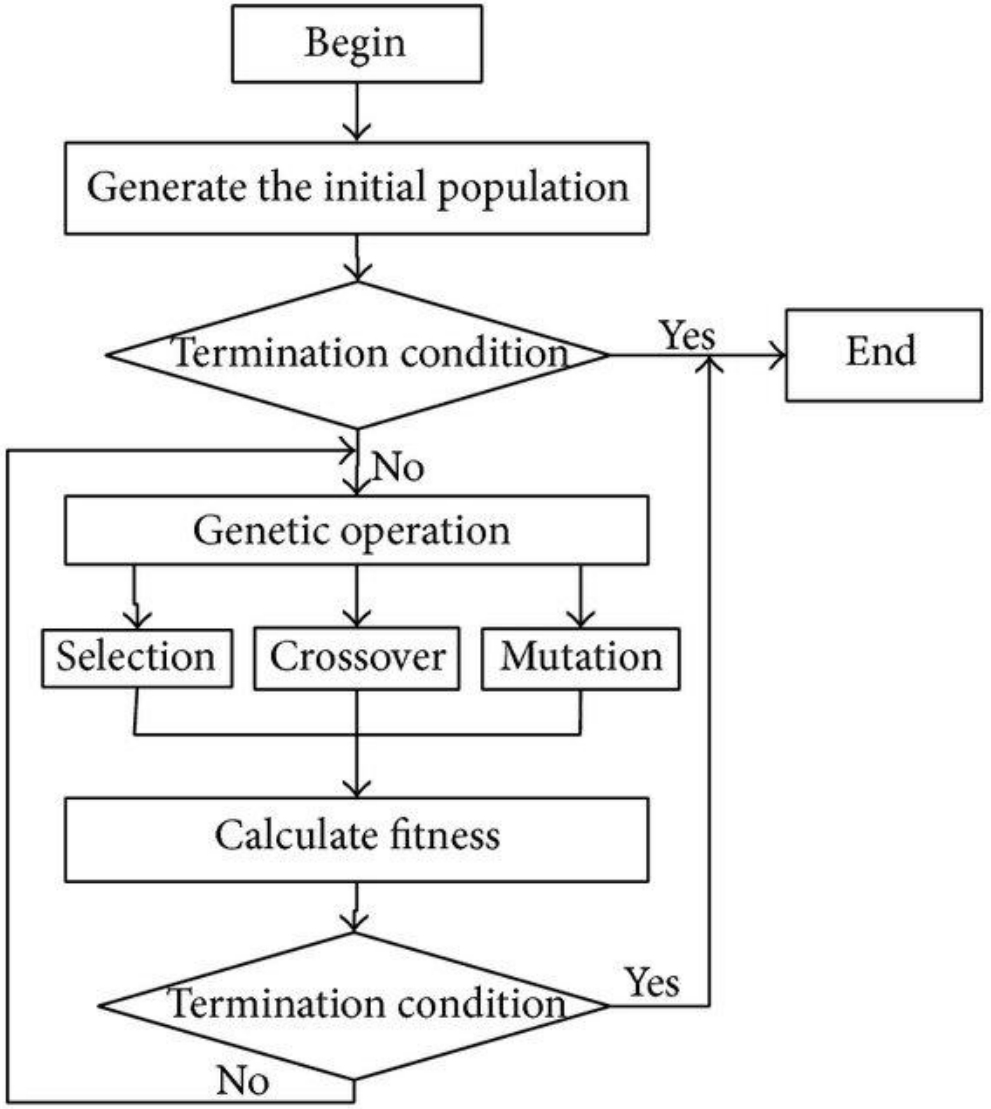




Annex 3: Combined cycle



Annex 4: Genetic algorithm



The resultant force due to the uniform strain component is zero

$$\int_{z_{o,b}(t)}^{z_{c,bm}(t)} \frac{E_{o,b}}{1-\nu_{o,b}} \left[c(z,t) - \varepsilon_{o,th,b}(z,t) - \varepsilon_{o,cr,b}(z,t) - \varepsilon_{o,l,b}(z,t)\right] dz$$

$$+ \sum_{i=1}^{m} \int_{z_{c,b_i}(t)}^{z_{c,b_{i-1}}(t)} \frac{E_{c,b_i}}{1-\nu_{c,b_i}} \left[c(z,t) - \varepsilon_{c,th,b_i}(z,t) - \varepsilon_{c,cr,b_i}(z,t) - \varepsilon_{o,g,b_i}(z,t)\right] dz$$

$$+ \int_{-t_s\frac{t}{2}}^{\frac{t_s(t)}{2}} \frac{E_s}{1-\nu_s} \left[c(z,t) - \varepsilon_{s,th}(z,t) - \varepsilon_{s,cr}(z,t)\right] dz$$

$$+ \sum_{i=1}^{m} \int_{z_{c,t_{i-1}}(t)}^{z_{c,t_i}(t)} \frac{E_{c,t_i}}{1-\nu_{c,t_i}} \left[c(z,t) - \varepsilon_{c,th,t_i}(z,t) - \varepsilon_{c,cr,t_i}(z,t) - \varepsilon_{o,g,t_i}(z,t)\right] dz$$

$$+ \int_{z_{c,t_n}(t)}^{z_{o,t}(t)} \frac{E_{o,t}}{1-\nu_{o,t}} \left[c(z,t) - \varepsilon_{o,th,t}(z,t) - \varepsilon_{o,cr,t}(z,t) - \varepsilon_{o,l,t}(z,t)\right] dz = 0$$

The sum of bending component with respect to the bending axis is zero

$$\int_{z_{o,b}(t)}^{z_{c,bm}(t)} \sigma_{o,b}(z,t).[z-t_b(t)]dz + \sum_{i=1}^{m} \int_{z_{c,b_i}(t)}^{z_{c,b_{i-1}}(t)} \sigma_{c,b_i}(z,t).[z-t_b(t)]\,\mathrm{dz}$$
$$+ \int_{-\frac{t_s(t)}{2}}^{\frac{t_s(t)}{2}} \sigma_s(z,t).[z-t_b(t)]dz + \sum_{i=1}^{m} \int_{z_{c,t_i}(t)}^{z_{c,t_i}(t)} \sigma_{c,t_i}(z,t).[z-t_b(t)]\,\mathrm{dz}$$
$$+ \int_{z_{c,t_n}(t)}^{z_{o,t}(t)} \sigma_{o,t}(z,t).[z-t_b(t)]dz = 0$$

The resultant force due to the bending component is zero

$$\int_{z_{o,b}(t)}^{z_{c,b_m}(t)} \frac{E_{o,b}}{1-\nu_{o,b}} \cdot \frac{z-t_b(t)}{r(t)} dz + \sum_{i=1}^{m} \int_{z_{c,b_i}(t)}^{z_{c,b_{i-1}}(t)} \frac{E_{c,b_i}}{1-\nu_{c,b_i}} \cdot \frac{z-t_b(t)}{r(t)} dz$$
$$+ \int_{-\frac{t_s(t)}{2}}^{\frac{t_s(t)}{2}} \frac{E_s}{1-\nu_s} \cdot \frac{z-t_b(t)}{r(t)} dz + \sum_{i=1}^{m} \int_{z_{c,t_{i-1}}(t)}^{z_{c,t_i}(t)} \frac{E_{c,t_i}}{1-\nu_{c,t}} \cdot \frac{z-t_b(t)}{r(t)} dz$$
$$+ \int_{z_{c,t_n}(t)}^{z_{o,t}(t)} \frac{E_{o,t}}{1-\nu_{o,t}} \cdot \frac{z-t_b(t)}{r(t)} dz = 0$$