A Novel Turbomachine: The Technological Revolution Towards Clean and Sustainable Hydrocarbon Cracking

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Abstract

Field: Steam cracking of hydrocarbon feedstocks for light olefin production through high-temperature pyrolysis of primarily naphtha feedstock

Relevance: Light olefins (ethylene and propylene) are the basic building blocks for numerous indispensable materials and their production is rapidly growing

Problem: Highly energy intensive (high enthalpy of formation and endothermic reactions), high fossil fuel consumption, and substantial CO_2 emissions

Specific limitations with conventional technology:

- Limited scope in reducing the residence time and increasing the process temperature due to restrictions of the tube metallurgy and intense thermal boundary layers adjacent to the walls (tubular coils much be at a much higher temperature than the working fluid to achieve a good heat transfer rate)
- Long residence times means olefins produced in the early stages undergo secondary reactions which reduces the primary product yield
- Lack of control of hydrocarbon partial pressure leads to condensation into secondary products and coke (reducing primary product yield)
- Decoking occurs fortnightly for 48 h which has a significant impact on the plant operating expenditure

Policy: European Council's target of reducing greenhouse gas (GHG) emissions by 80–95 % by 2050 (relative to emissions in 1990)

Needed: A clean and sustainable production process that is capable of meeting the large-scale demand but with lower GHG emissions and energy costs

Promising solution: Replacing the radiant section of a conventional plant with a **low-volume** turbomachine – **The Roto-Dynamic Reactor (RDR)**

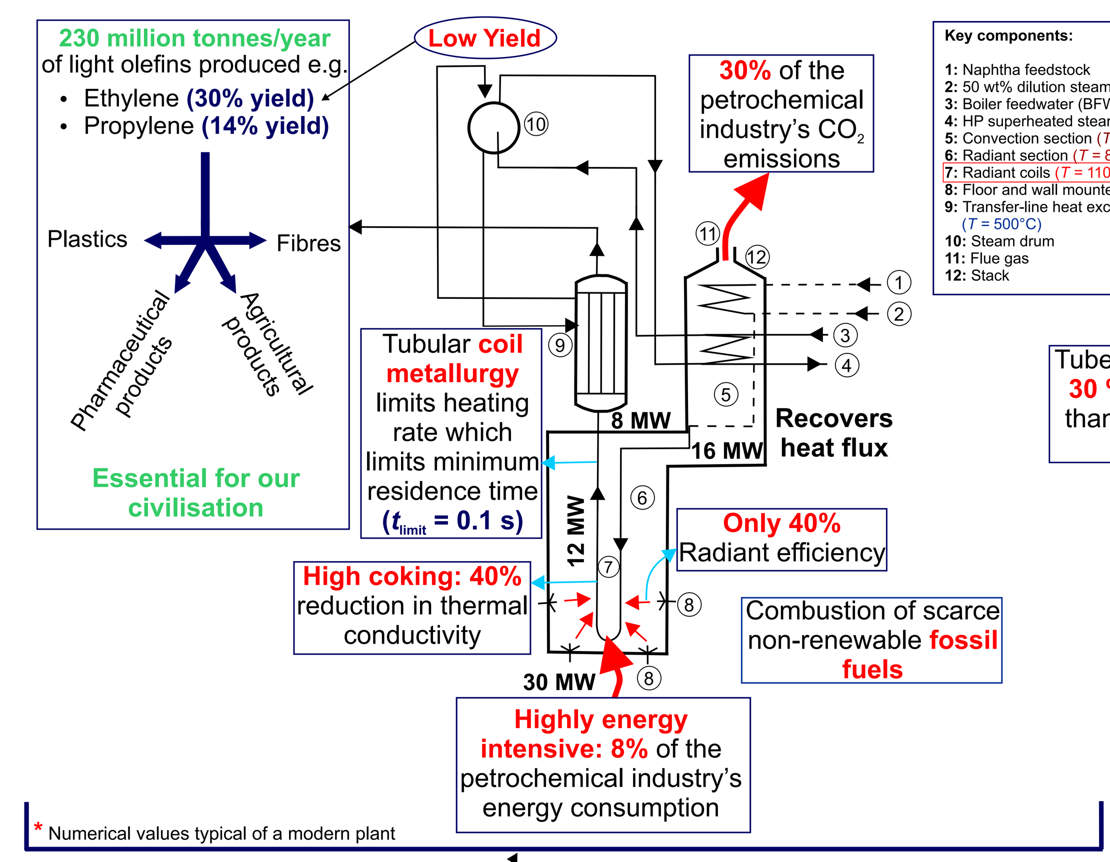
Advantages:

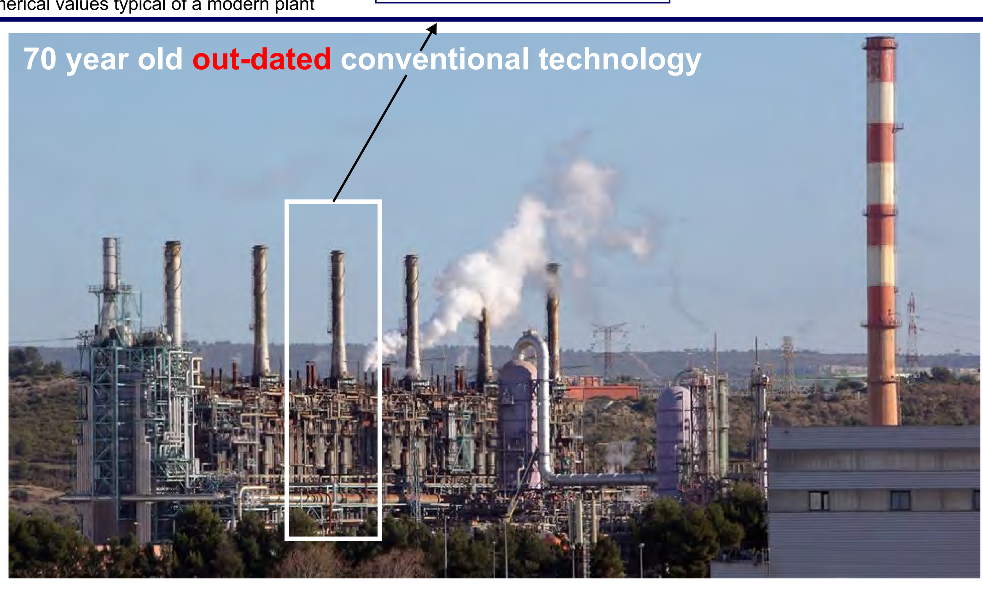
- **Primary product yield is increased** by: lowering the hydrocarbon partial pressure and residence time which minimises secondary reactions
- Mechanical energy transferred *directly* to the working fluid which maximises the use of the system's exergy
- Lower thermal gradients and wall temperatures reduces coking and enables higher temperatures. At higher temperatures, the optimum residence reduces and the rate of primary product conversion increases at a greater rate than secondary products. This **increases the primary product yield**
- Significantly reduces fossil fuel consumption and CO_2 emissions
- Reduction in the plant size, and lower energy consumption and operating costs per tonne of ethylene
- Controllable: energy input, hydrocarbon partial pressure and mixing of species. This results in a highly selective process

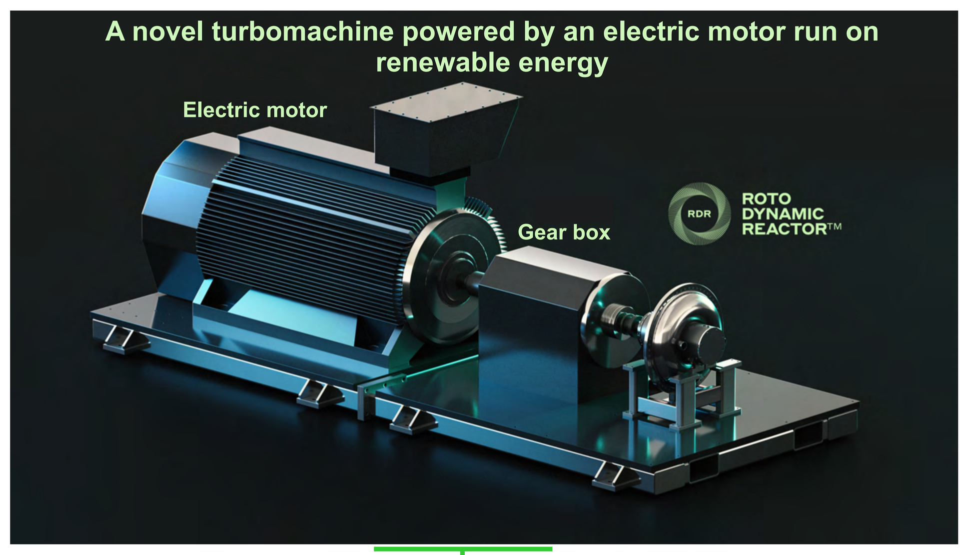
Auxiliary applications: Applicability to *any* industry where pyrolysis of long-chain hydrocarbons into higher value short-chain molecular structures is required

Objective : **The first ever high-fidelity numerical investigation proving the concept's feasability and validating the design requirements**

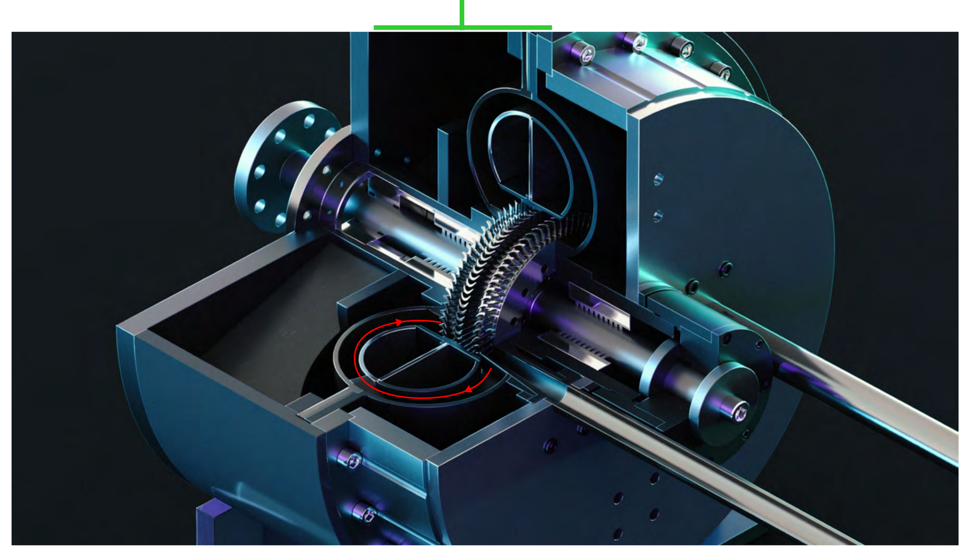
Deficiencies of conventional steam cracking plant





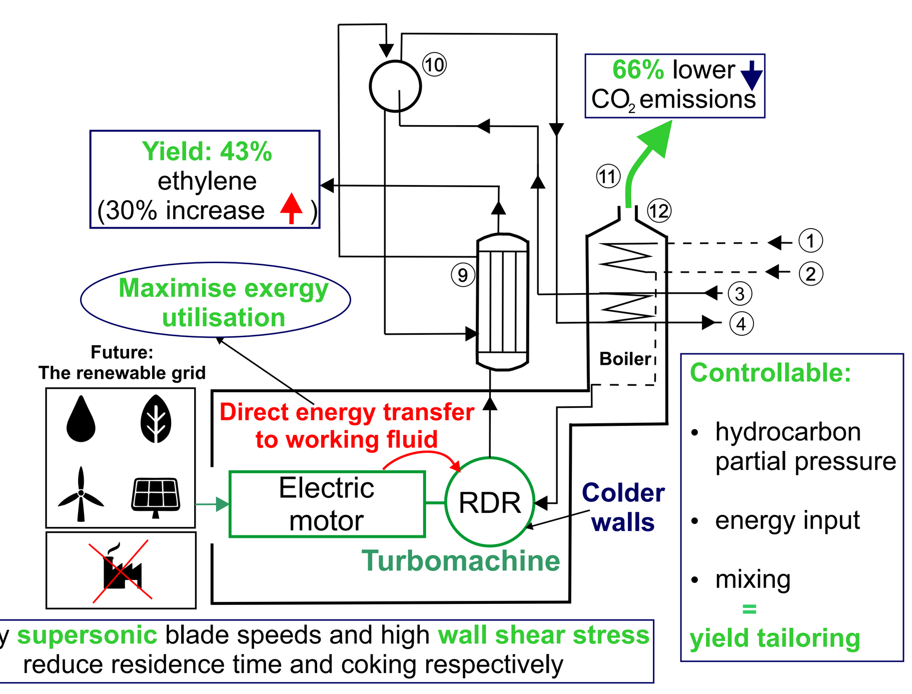


Innovation

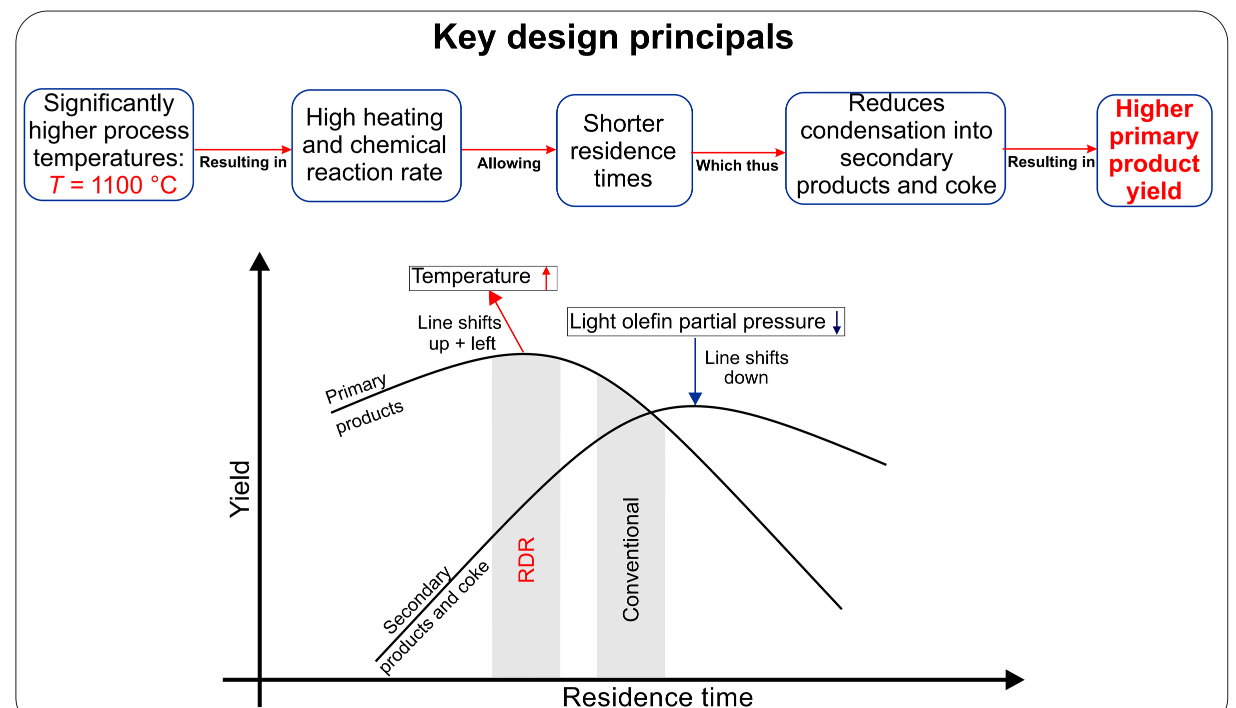


Cut-away of the Roto-Dynamic Reactor

Novel turbomachine: The Roto-Dynamic Reactor



Key design principals



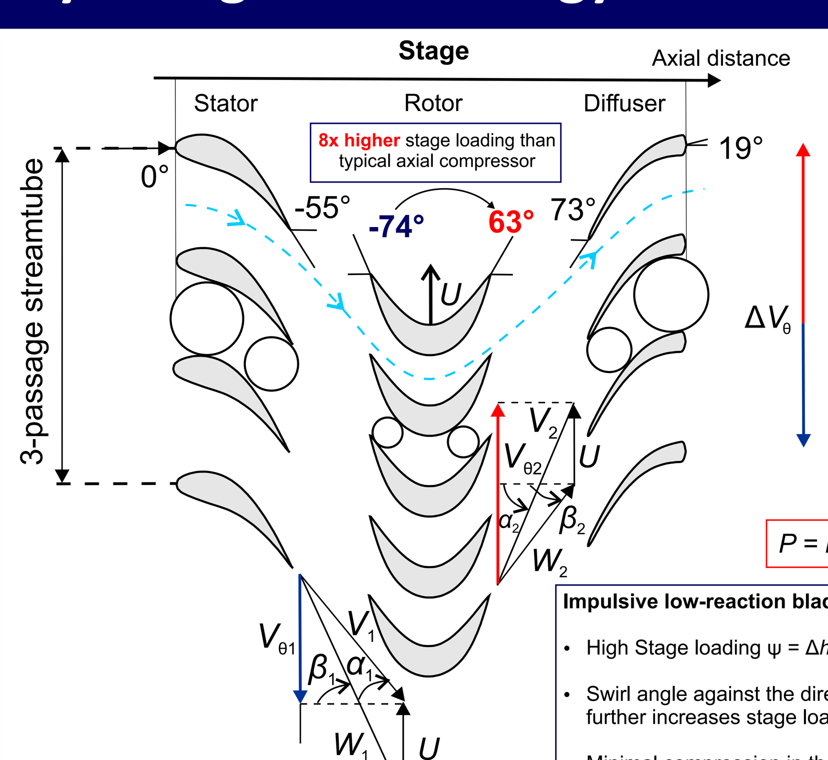
Single pass: velocity triangles and energy transformation

Roto-Dynamic Reactor design aims:

- Maximise static **temperature** rise
- Minimise static **pressure** rise

Solution

- A novel turbomachine that is a blend between a compressor and a turbine and can neither be categorised as a radial, axial or mixed-flow machine
- A 1.5 stage turbomachine consisting of: stator, rotor and diffuser
- Highly accelerating stator blades similar to nozzle guide vanes (NGV) in a turbine stage
- Impulsive low-reaction rotor blades characteristic of an impulse compressor stage
- A diffuser that promotes flow separation and mixing (similar to a combustor) whilst transforming kinetic energy into internal energy



Energy input:

Work is added to the fluid by turning the flow to increase the circumferential velocity component rather than decelerating the flow in the relative frame of reference

Euler's equation:

translates changes in swirl velocity into work consumed by working fluid through conservation of angular momentum and energy principals

$$P = \dot{m}U\,\Delta V_\theta = \dot{m}\Delta h_0 = \dot{m}\Delta T_0$$

Impulsive low-reaction blading advantages:

- High Stage loading $\psi = \Delta h_0/U^2$ (measure of work addition)
- Swirl angle against the direction of shaft rotation which further increases stage loading
- Minimal compression in the rotor (low stage reaction coefficient $\Lambda \approx \Delta p_{rotor}/\Delta p_{stage}$)
- Fewer stages required – low-volume reactor

Multi-pass: regenerative heating concept

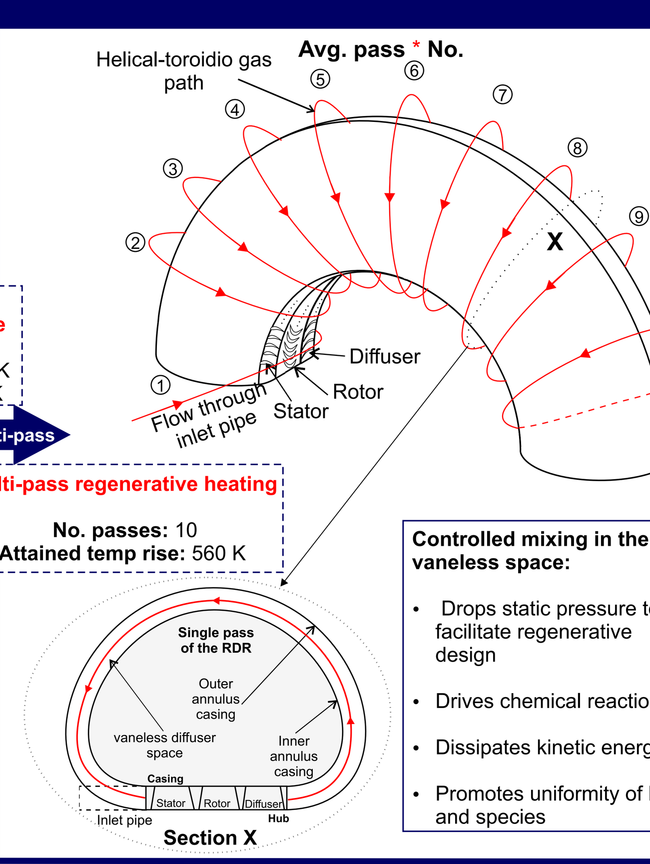
Total temperature rise

Single pass: 56 K
Required: 560 K

Multi-pass

Multi-pass regenerative heating

No. passes: 10
Attained temp rise: 560 K



Controlled mixing in the vaneless space:

- Drops static pressure to facilitate regenerative design
- Drives chemical reactions
- Dissipates kinetic energy
- Promotes uniformity of heat and species

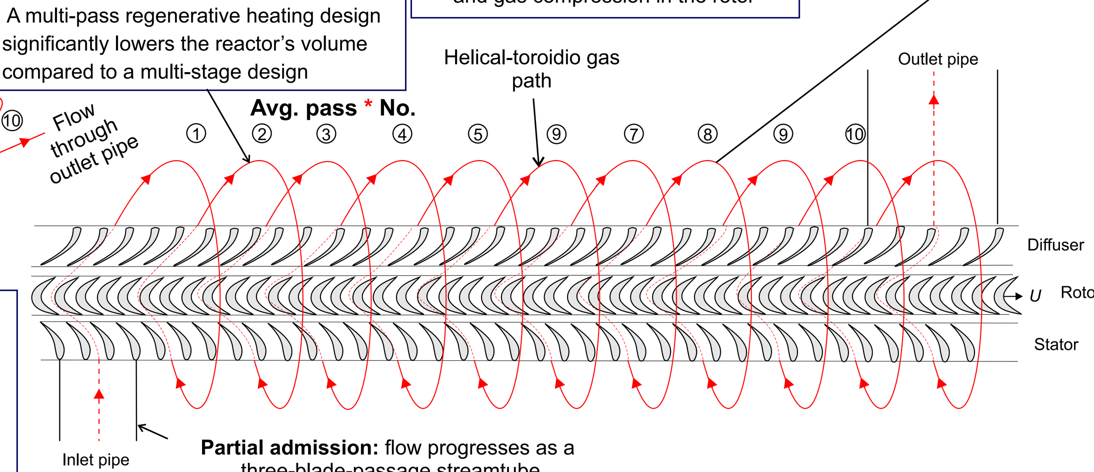
Regenerative design:

- Toroidal-shaped vaneless diffuser space connects the outlet of the diffuser of one stage to the inlet of the stator of the next adjacent stage.
- A multi-pass regenerative heating design significantly reduces the reactor's volume compared to a multi-stage design

Regenerative design through mixing:

The mixing process in the diffuser vaneless space drops the static pressure to ensure that the flow begins each regenerative pass at the same inlet pressure despite upstream diffusion and gas compression in the rotor

Helical-toroidio gas path has just enough **swirl velocity** at the diffuser TE to progress the flow regeneratively to the next stator passages



* *Regenerative pass* = average particle traversing: stator → rotor → diffuser → vaneless space → repeat

Similar effect to having multiple turbomachinery stages in series

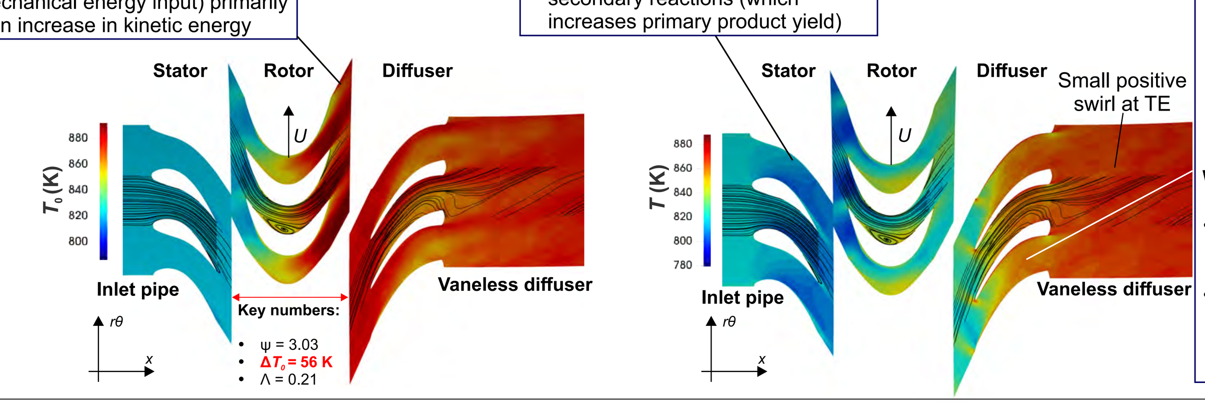
Numerical simulations: energy transformation

Static and stagnation temperature contours at mid-span (LES)

- High stage loading results in a large increase in stagnation temperature
- The static temperature does not increase significantly across the rotor
- Therefore the stagnation temperature rise (from the mechanical energy input) primarily constitutes an increase in kinetic energy

Highly accelerating flow:

- Kills turbulent fluctuations remnant from mixing in the vaneless space
- Reduces hydrocarbon partial pressure to controllably minimise secondary reactions (which increases primary product yield)



Energy Transformation:

Kinetic energy from rotor → Internal energy

Mechanism:

- Shockwaves
- Flow deceleration (diffusion)

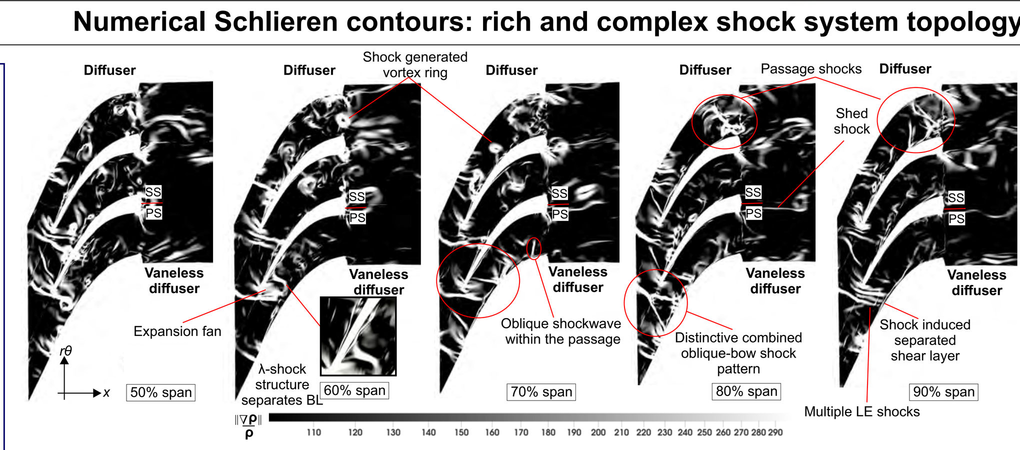
Why?

- Provides thermal energy to break chemical bonds
- Promotes the mixing process that drops the static pressure and drives the chemistry

Numerical Schlieren contours: rich and complex shock system topology (LES)

Shock structure:

- Pre-shock Mach number, incidence and back pressure vary temporally and spatially
- Highly unsteady and 3-D shock system topology
- Combination of oblique, bow, passage, shed and nearly normal shockwaves observed



Shock-induced temperature rise is essential for kinetic to internal energy transformation

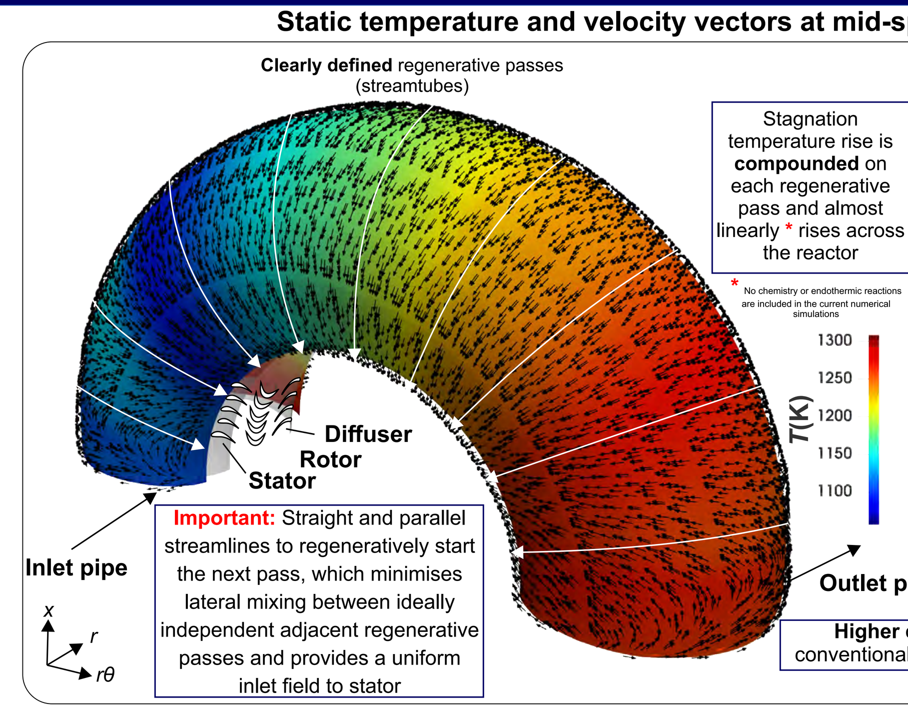
Integral mechanisms for complex mixing profile:

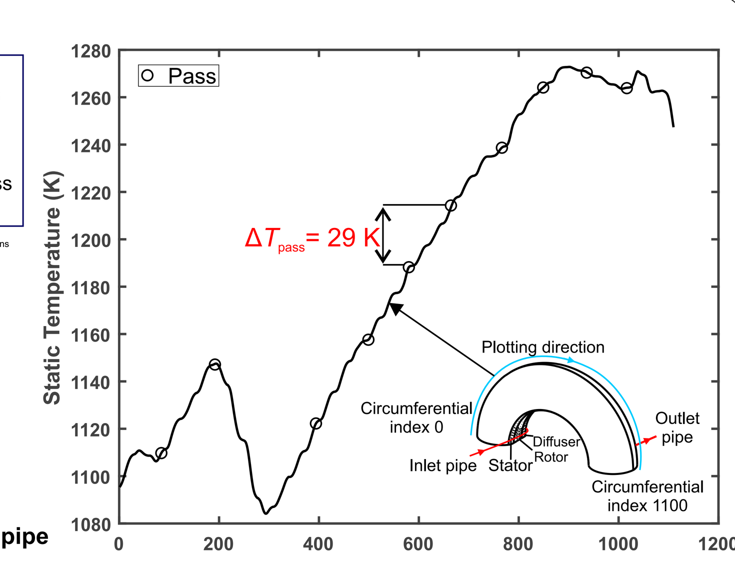
- Shock-induced flow separation and shock/boundary layer interaction
- Interaction between shock and separated free shear layer
- Unsteady shock reflection within the blade passage
- Compressible vortex rings

Controlling the shock topology enables fine-tuning of the mixing profile and yield

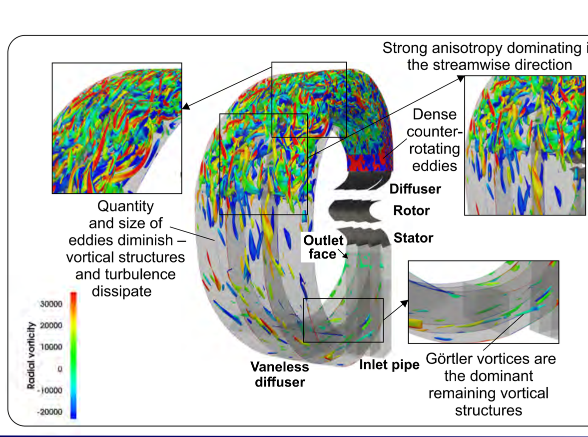
Numerical simulations: regenerative heating and mixing

Static temperature and velocity vectors at mid-span in the vaneless space (URANS)

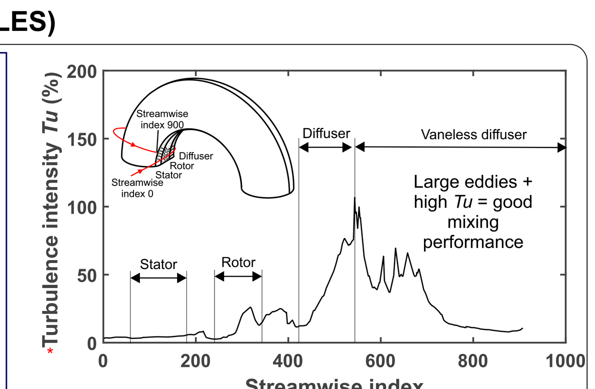




The turbulent mixing process (LES)



- **Mixing mechanism:** turbulence and vortex shedding
- Velocity fluctuations rapidly rise in the diffuser before decaying in the vaneless space such that the mixing process is complete before the start of the next regenerative pass (at the stator inlet)
- Optimising the length, curvature and cross-section of the vaneless space controls the mixing intensity and distribution, and residence time
- Therefore the yield and residence time can be fine-tuned



* measures fluctuations from turbulence and large structures responsible for mixing