Novel recuperation system to maximize EXergy From ANergy for fuel cell powered geared electric aircraft propulsion system

Opportunities to move from heat rejection to heat utilization in hydrogen electric aircraft - exFan

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BMK Endowed Professorship for Innovative Aviation Technologies

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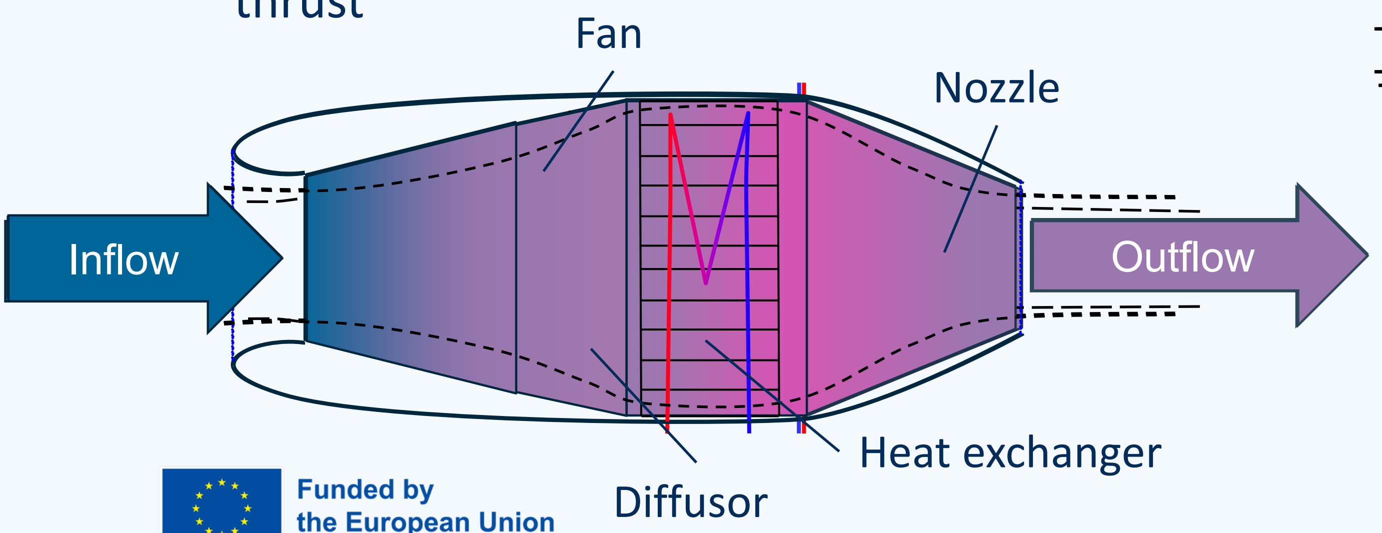
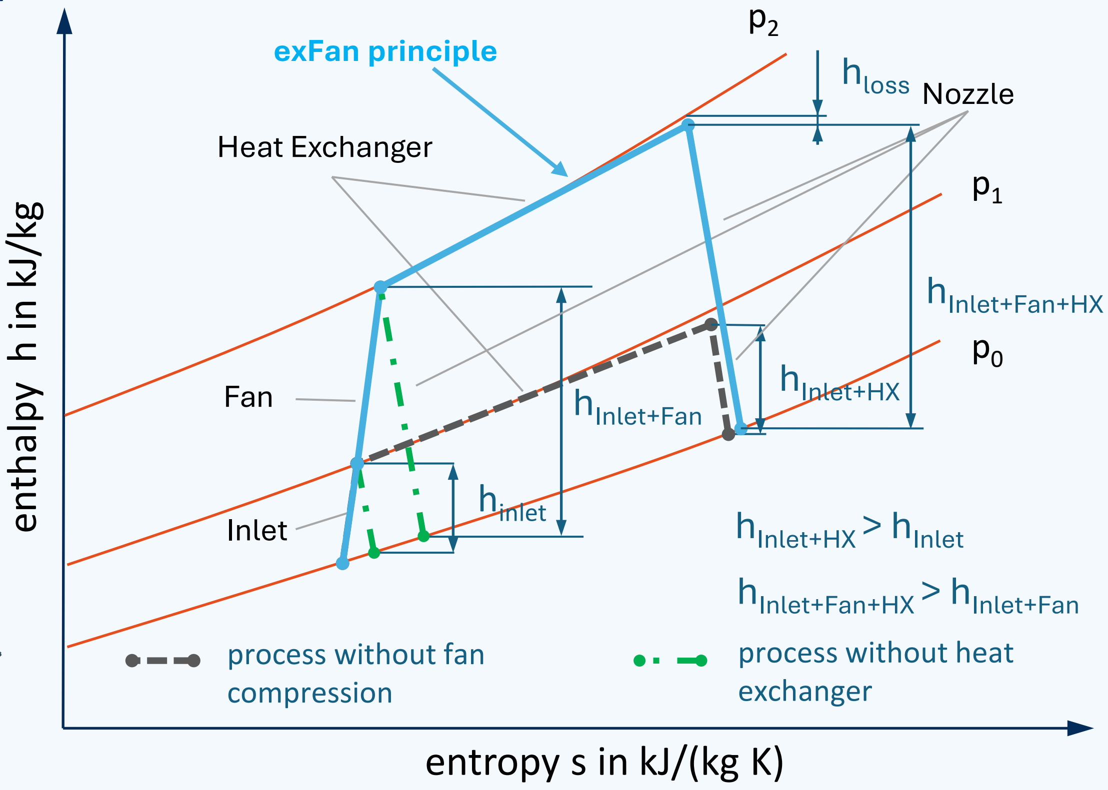
Basic Concepts

- Heat exchanger air duct and propulsor are combined
- The fan compression increases the efficiency of the Brayton cycle
- By heating the air flow, the volumetric flowrate increases and so does the jet velocity and the net thrust





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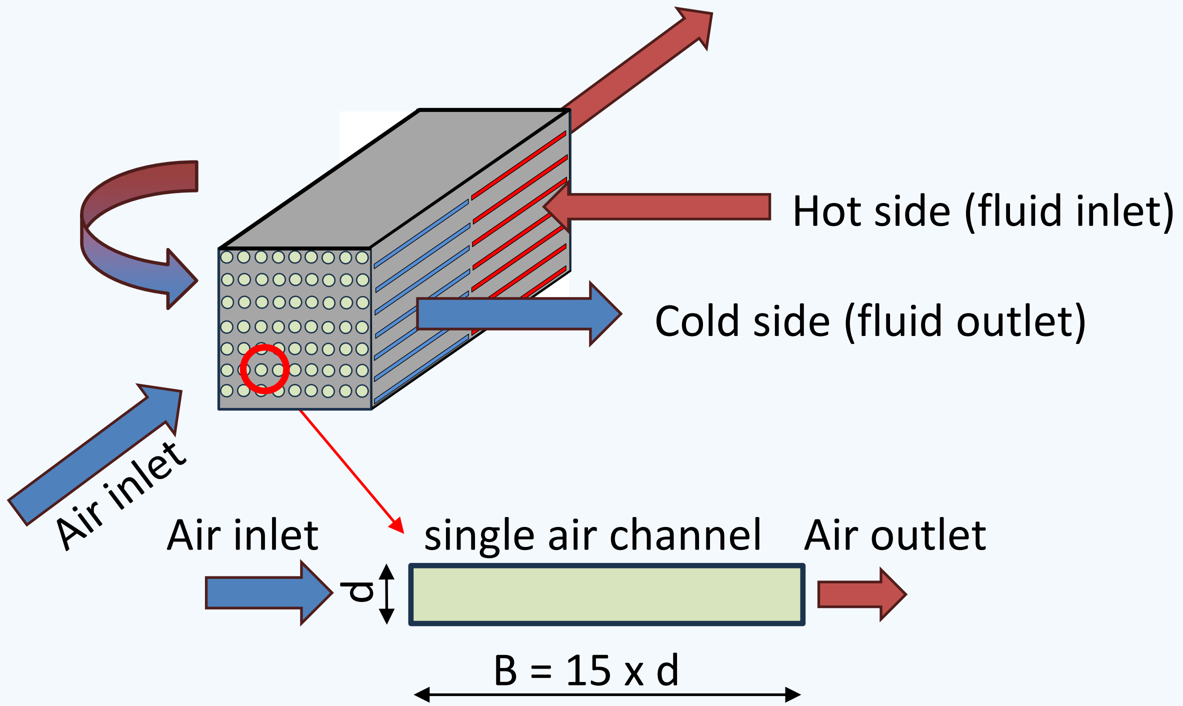
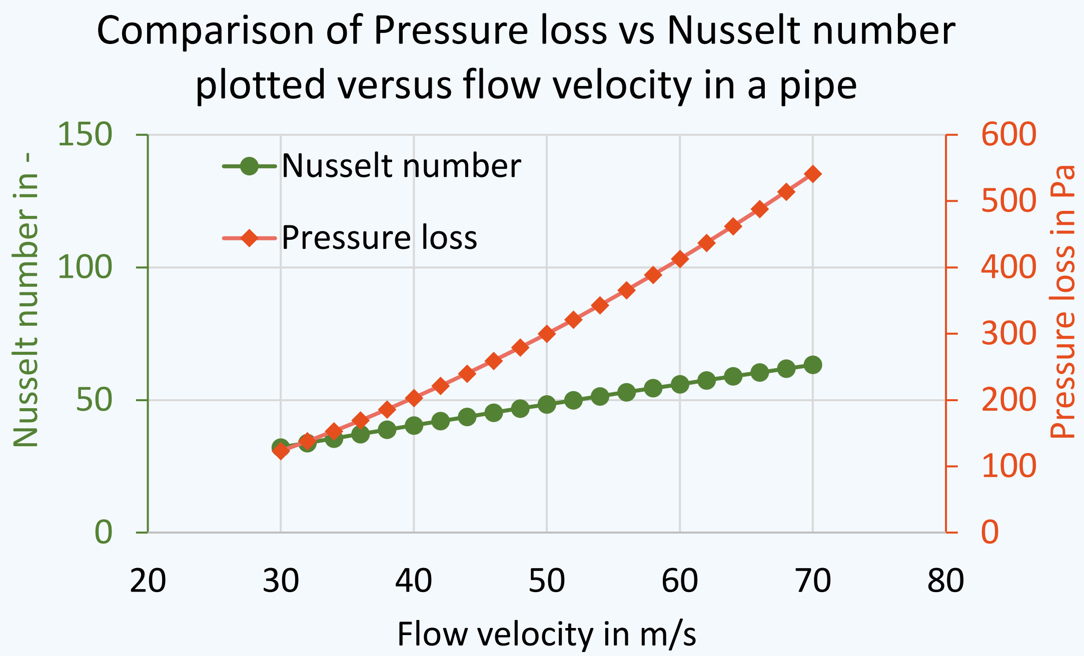
Basic Concepts





- Pressure losses outgrow the advantage of the increased Nusselt numbers with increasing flow velocity.
- It is advantageous to decrease the flow velocity and increase the HX air side surface area instead.

Nusselt number: Indicates how much heat that can be exchanged over a specific surface.

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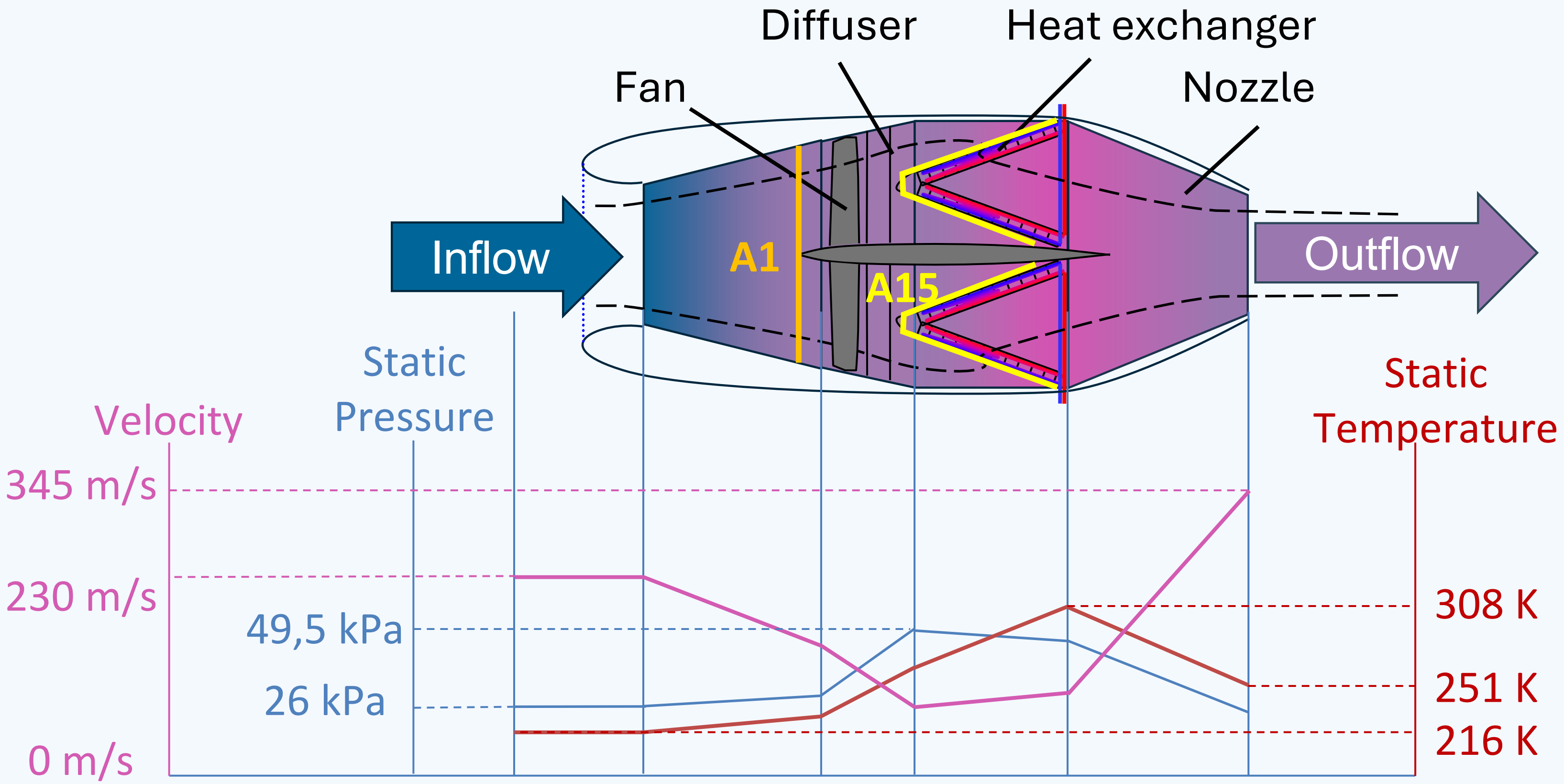
Basic Concepts

- Heat exchanger inclined arrangement following F1 example
- Flow cross section area is increased in order to reduce local flow velocities while large frontal areas are avoided.



Data curves show development of average annular duct properties.

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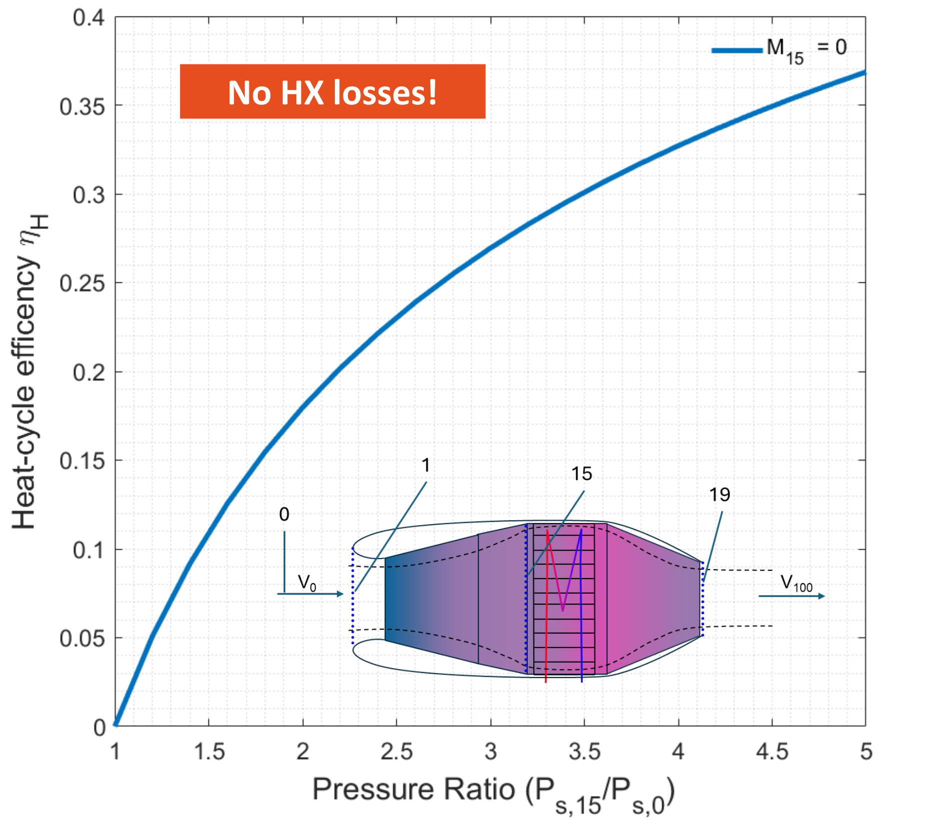
Basic Concepts

- Model of an installed HX with no losses and simplifications:

$$\varepsilon_H = \frac{Kin.power\ recov.}{Total\ heat\ added} = 1 - \left(\frac{P_{s,15}}{P_{s,0}}\right)^{\frac{1-\gamma}{\gamma}}$$

- Effectiveness of rejected heat conversion into kinetic jet power depends on nozzle pressure ratio!
- Recuperated kinetic jet power depends on heat rate $\dot{Q}_{PEMFC}$, not on temperature



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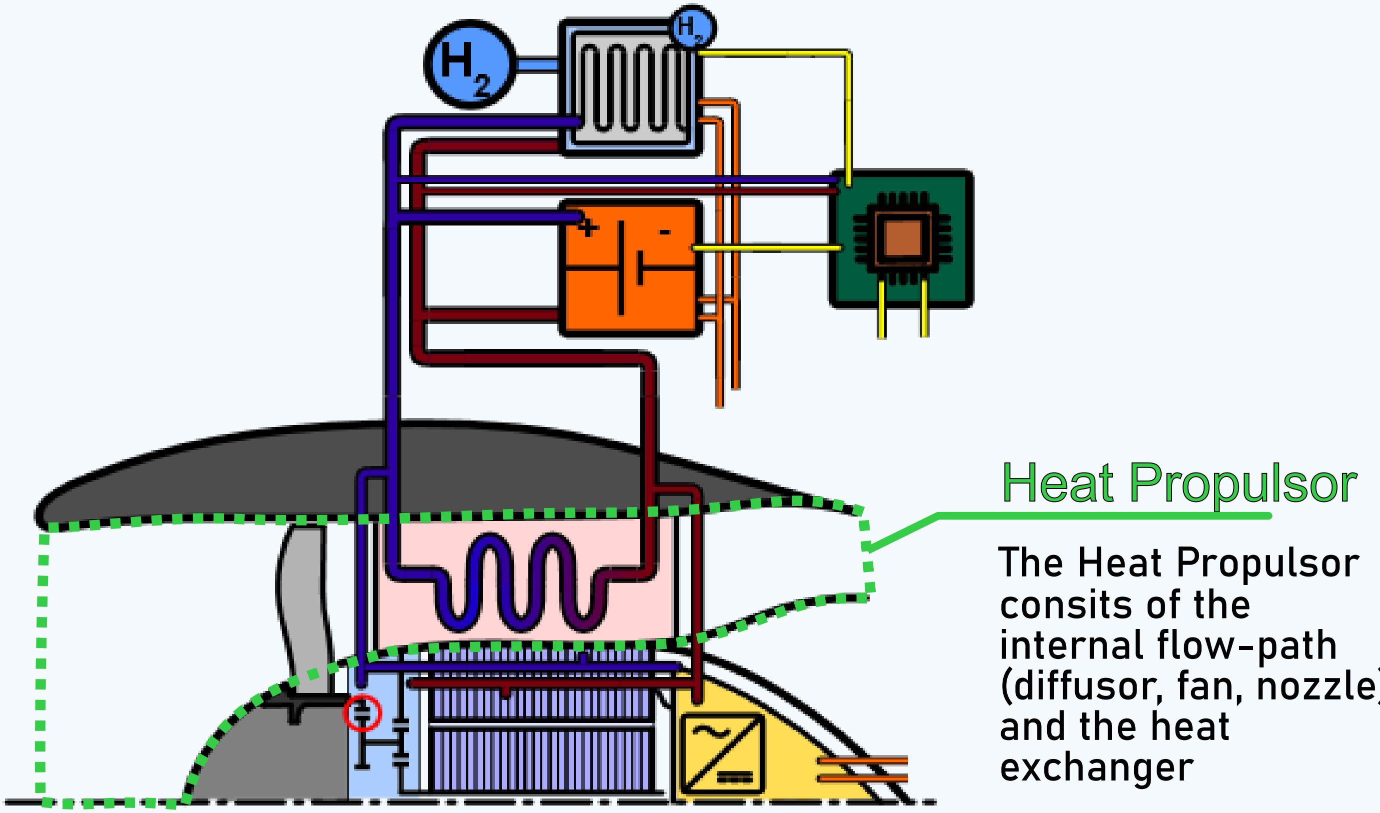
Source: J. V. BECKER und D. D. BAALS, „The Aerodynamic Effects of Heat and Compressibility in Internal Flow Systems, and High-Speed Tests of a Ram-jet System.“, NACA Rept. 773, 1943.

Parameter Study - Assumptions

General settings

- Focus on thermodynamics of heat propulsor!
- 0D-Modell for the heat propulsor except HX
- Not considered yet:
  - Fuel cell system ancillaries power variation with height, flight Mach, etc.
  - Nacelle external drag
  - System masses
- Single engine of a twin engine SMR-aircraft (A320 size)
- Sizing mode study:
  - Component sizes are adapted to operating conditions
  - “Rubberized” model



The Heat Propulsor consits of the internal flow-path (diffusor, fan, nozzle) and the heat exchanger

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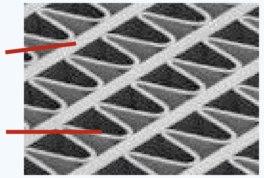
Parameter Study - Assumptions

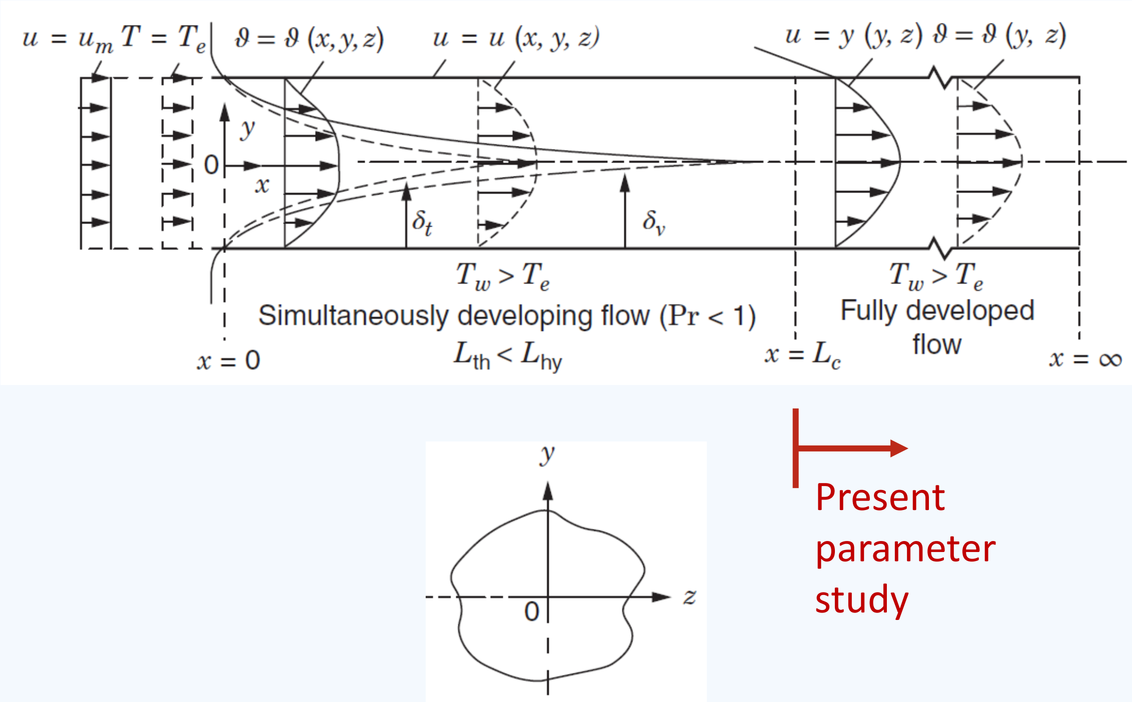
plate (aka tubes => liquid coolant channels)

fins form air flow path

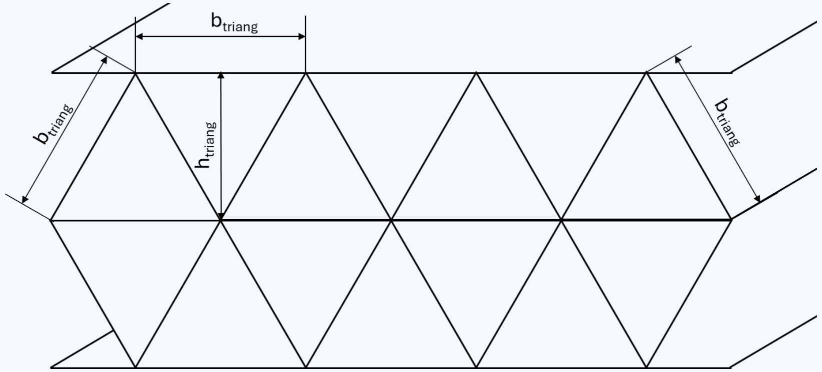


HX air side settings

- Friction losses in the HX, Polytropic efficiency of fan stage
- 1D model
- HX assumptions
  - Counter flow compact plate and fin HX (real HX may be crossflow)
  - Two fluid, direct transfer, single pass
  - Blockage due to coolant plate/tubes is neglected
  - 1D-Modelling of the air side flow (based on hydr. diameter)
  - Fully developed turbulent flow



Present parameter study



Source: Sekulic D.P., Shah R.K.: Fundamentals of heat exchanger design, Wiley, 2003

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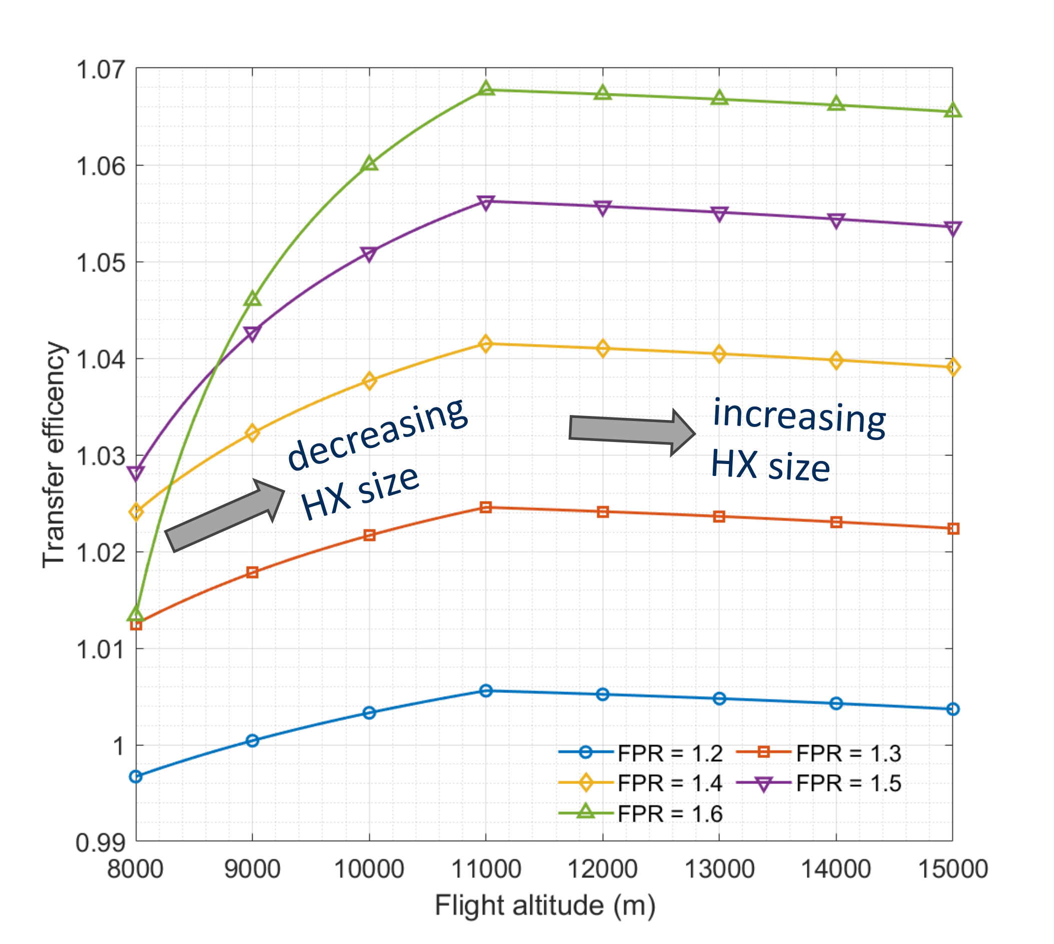
Parameter Study - Results

- Transfer efficiency
  - contains fan and HX losses as well as ram jet effect
  - can be > 1 due to ram jet effect of the HX
- Best ram jet performance at high fan pressure ratios (FPR's)
- Above 11km
  - T_{amb} = const.; pressure further decreases according to ISA
  - no further reduction in HX size due to decreasing temperature difference (HX coolant entry and ambient)

ISA temperature deviation in K	0.0
Freestream Mach number	0.78
Fan polytropic efficiency	0.85
Fuel cell and electric drive combined efficiency	0.5
Net thrust in kN	23.020
Fan inlet Mach number	0.5
Ratio of HX air inlet to fan inlet areas	3.0



$$\eta_{trans} = \frac{P_{kin,j}}{P_{br}} = \frac{Kinetic\ jet\ power}{Power\ at\ fan\ shaft}$$

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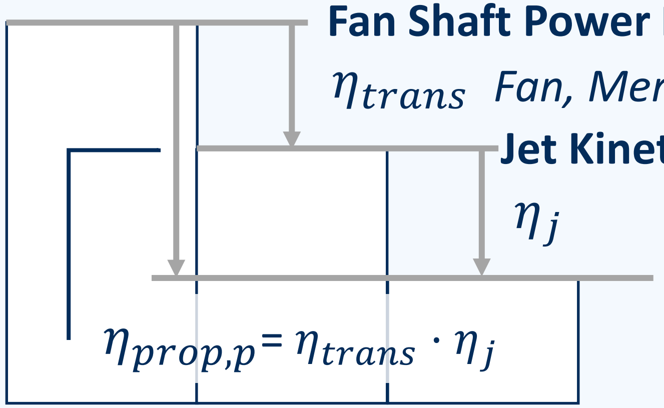
Parameter Study - Results

- Ram jet effect is improved with FPR but overall propulsive efficiency decreases

→ Lower FPR better for the performance of the heat propulsor

→ Heat propulsor performs best close to the tropopause (11km)



Fan Shaft Power P_{br}

η_{trans} *Fan, Meredith Effect, Nozzle*

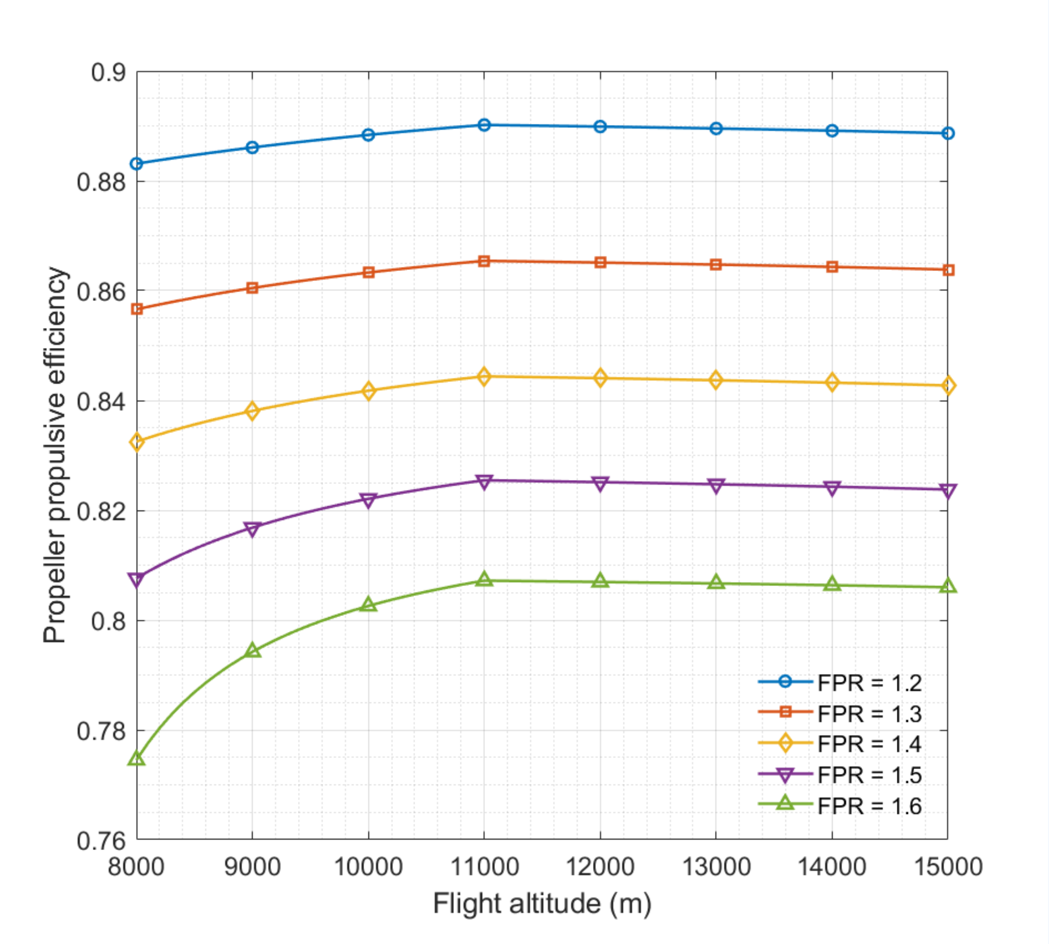
Jet Kinetic Power $P_j = \frac{1}{2}\dot{m}(v_j^2 - v_0^2)$

η_j

Propulsive Power

$P_{av} = \frac{1}{2}\dot{m}(v_j - v_0) \cdot v_0$

$\eta_{prop,p} = \eta_{trans} \cdot \eta_j$



$$\eta_{prop,p} = \frac{P_{av}}{P_{br}} = \frac{Propulsive\ power}{Power\ at\ fan\ shaft}$$

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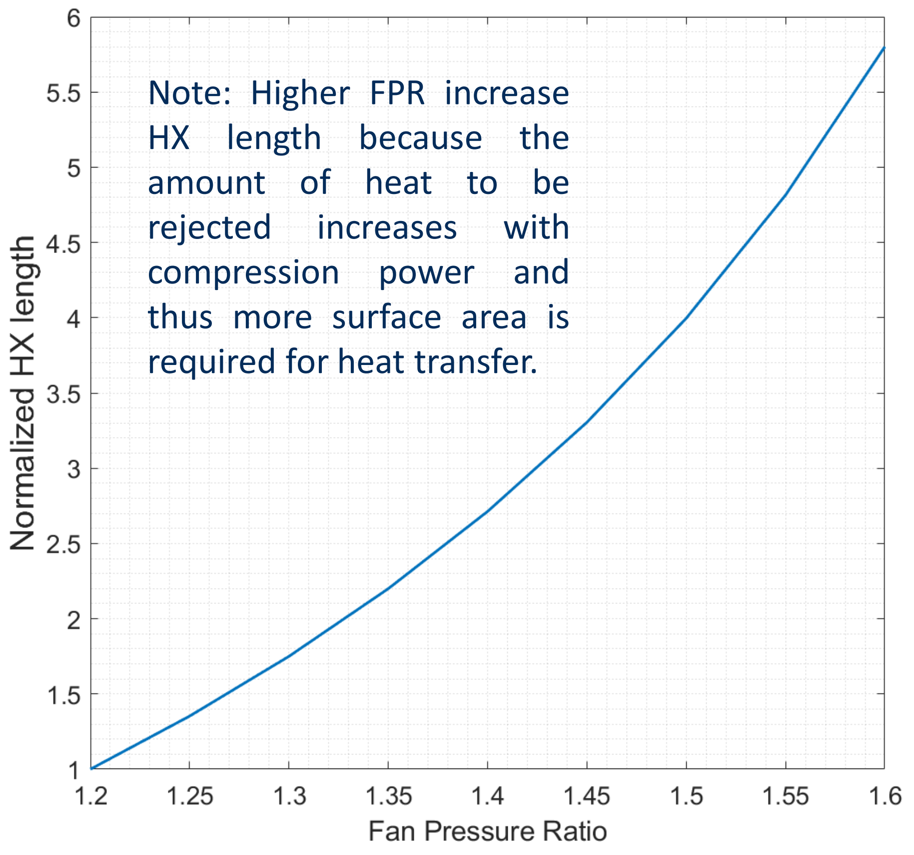
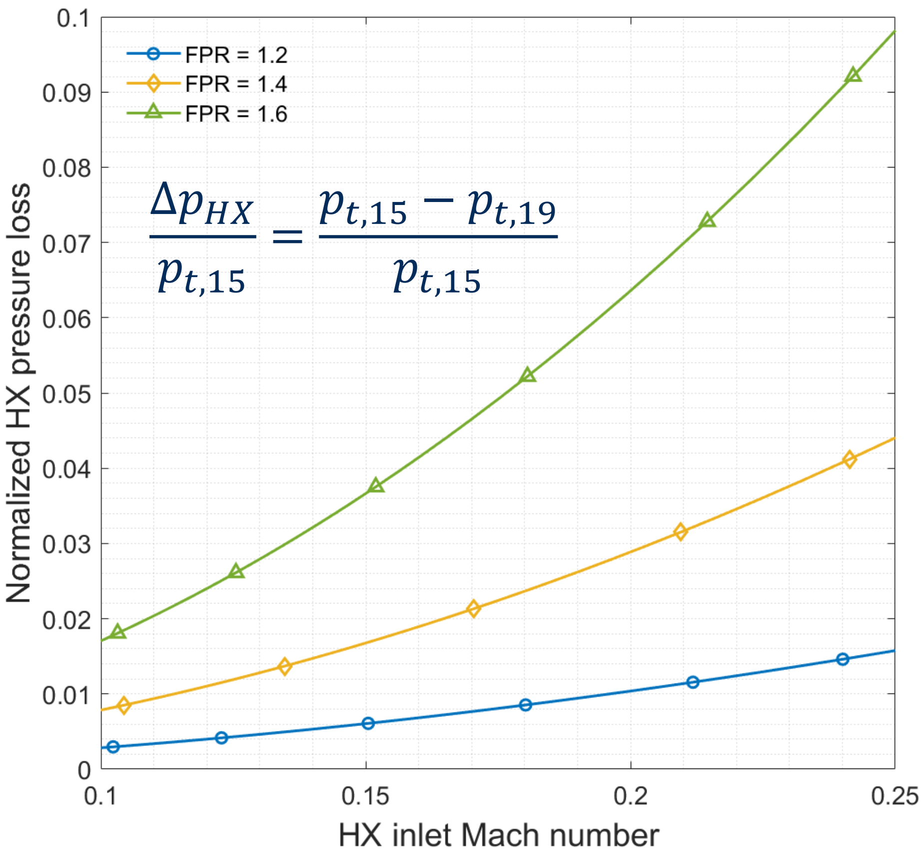
Parameter Study - Results





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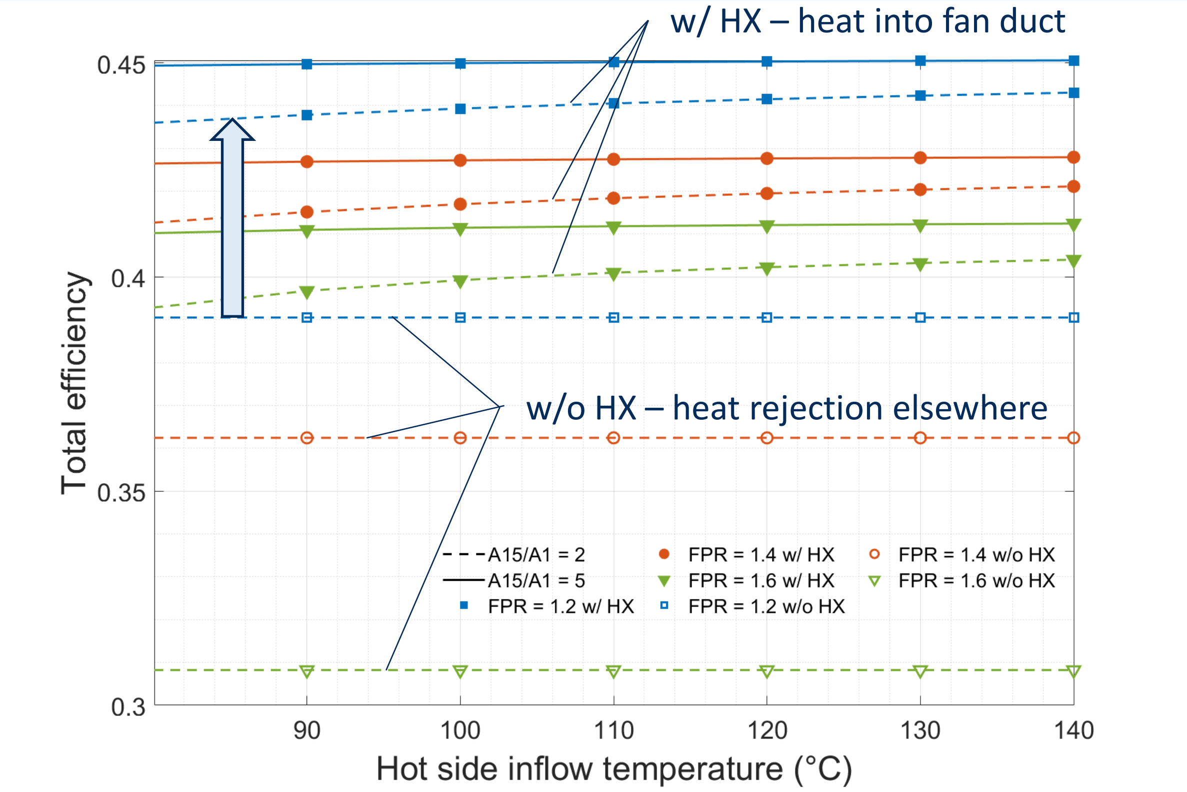
Parameter Study - Results

- HX losses decrease with hot side inflow temperature because of reduced HX size
- Efficiency gains (A15/A1 = 2, FPR = 1.2, 85°C):
  - 14.5% w.r.t. “w/o HX” case or
  - 5.5% points w.r.t. total efficiency

	Take Off	Cruise
Flight altitude in ft	0.0	35000
ISA temperature deviation in K	0.0	
Freestream Mach number	0.22	0.78
Fan polytropic efficiency	0.85	
Fuel cell and electric drive combined efficiency	0.5	
Fan total pressure ratio (FPR)	1.2 – 1.6	
Net thrust in kN	120.143	23.020
Fan Inlet Mach number	0.5	



Cruise

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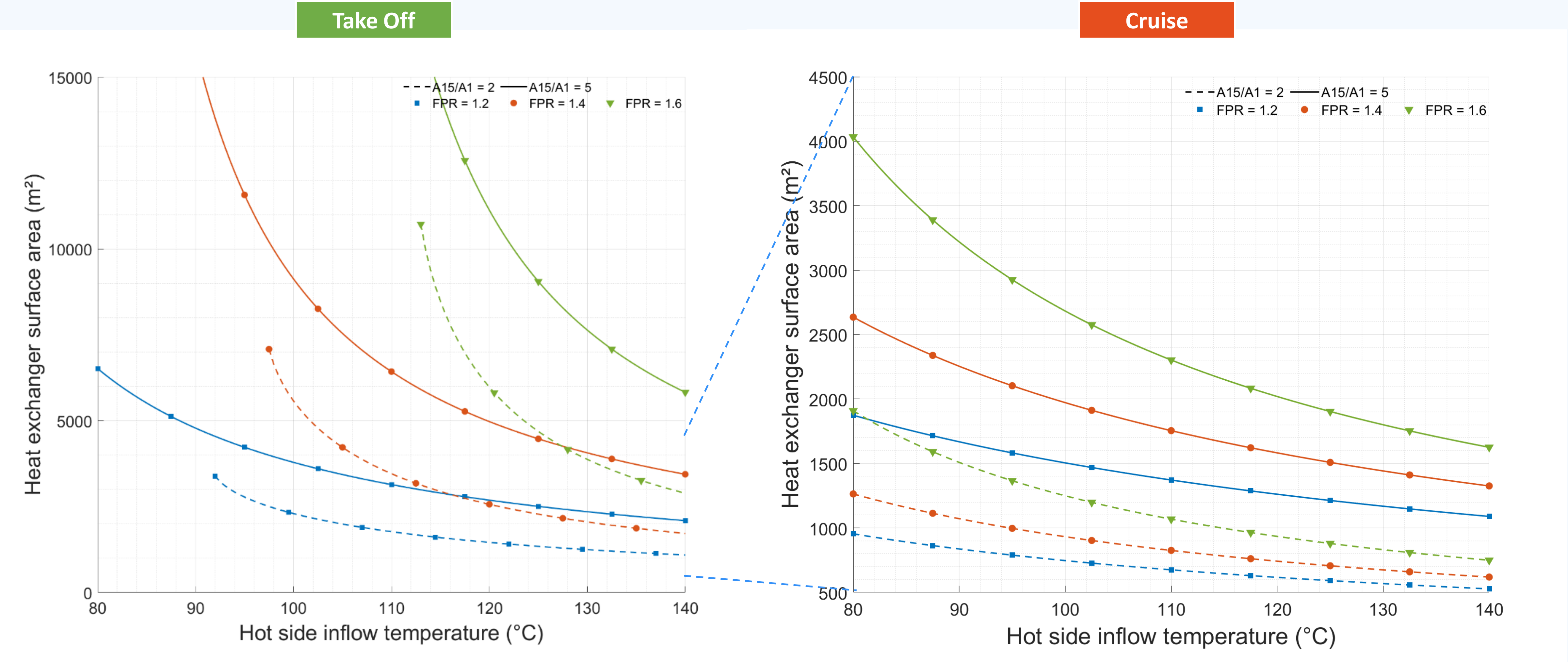
Parameter Study - Results



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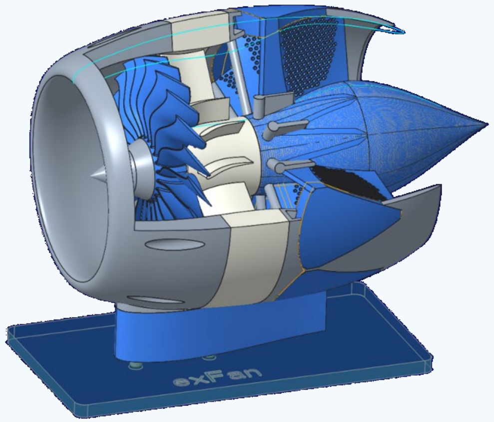
Conclusions and Outlook

Conclusions

- Thermodynamic sweet spot
  - Heat in fan flow and ram jet effect reward increased FNPR's (and hence FPR's for fixed M_0)
  - This partially offsets the trend towards lower FNPR's for increased propulsive efficiency
  - Operation at tropopause altitude
- Nacelle integration: Principally possible!
- Net benefits by ram jet effect even when pressure losses have been taken into account
- Challenge: Match sea level take off and cruise requirements

This is an "artists impression" of a nacelle type integration



Outlook

- Enhanced models include
  - Advanced compact HX features (offset strip fin, louvers, bionic designs)
  - Fuel cell system ancillaries power variation
  - Nacelle external drag and system masses
  - Aircraft performance (fuel mileage, costs, LCA)
  - Propulsion system airframe integration and snowball effects

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EXFAN

„The challenges of the industry are huge, but so are the opportunities.“

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