EXFAN

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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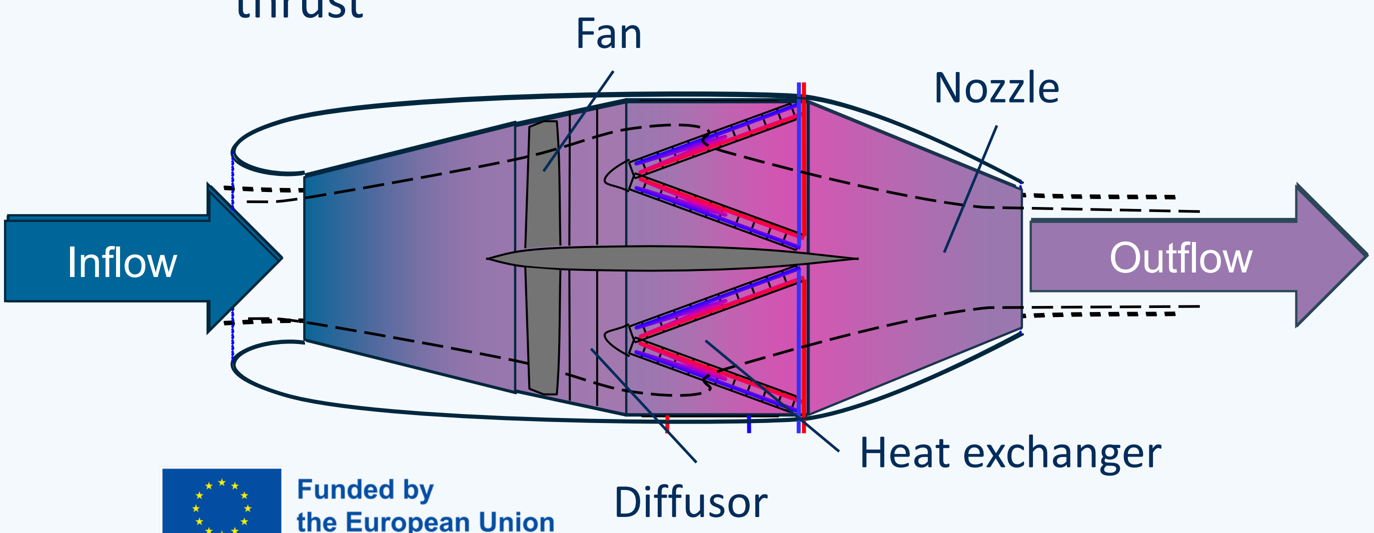
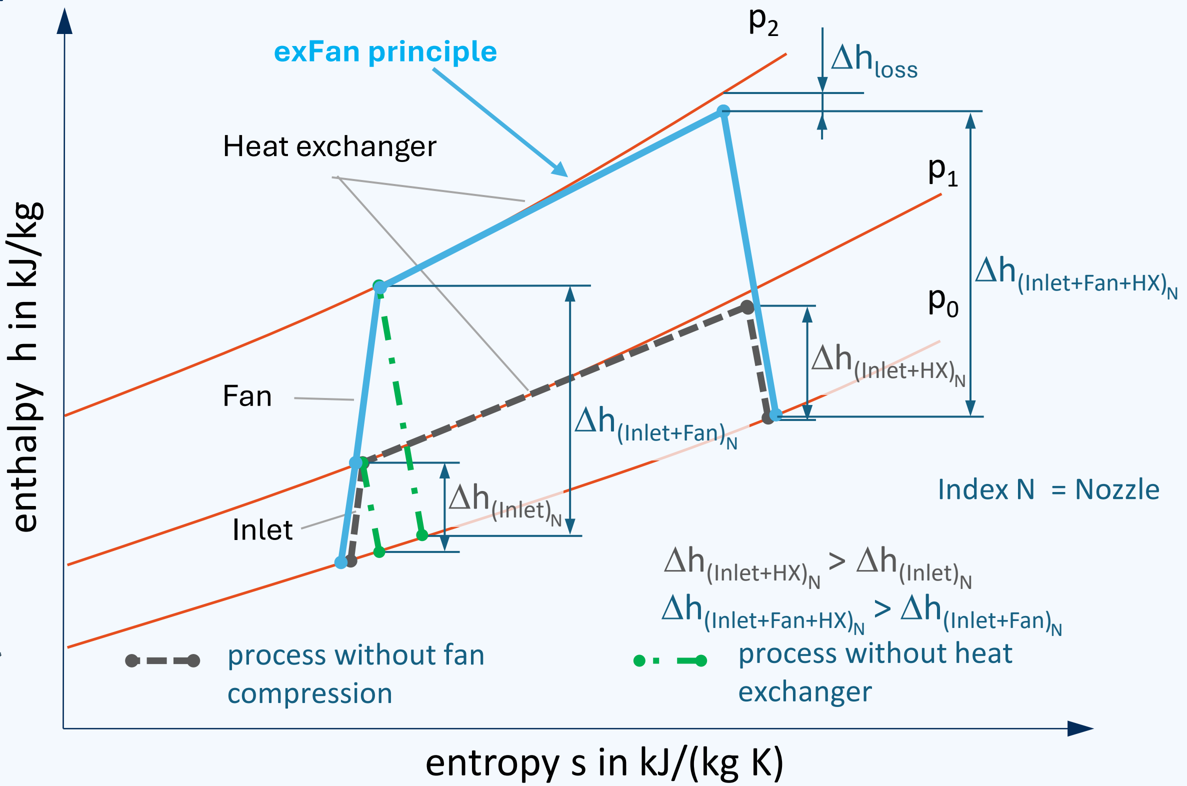
Basic Concepts

- 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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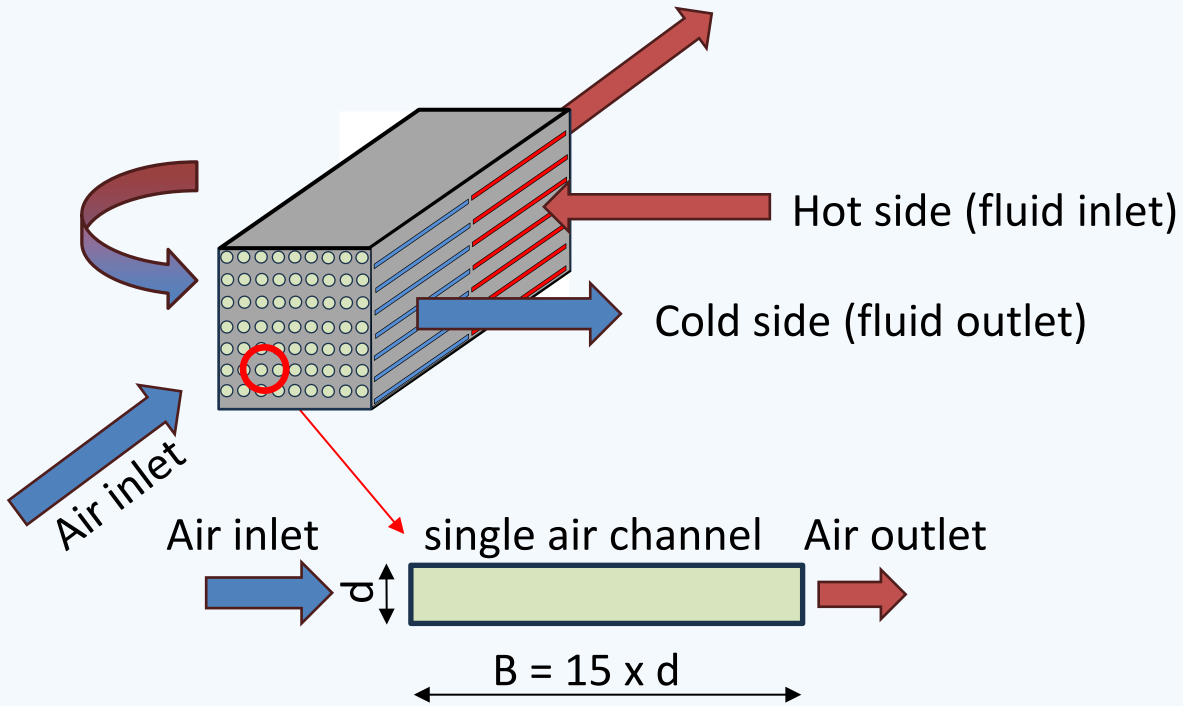
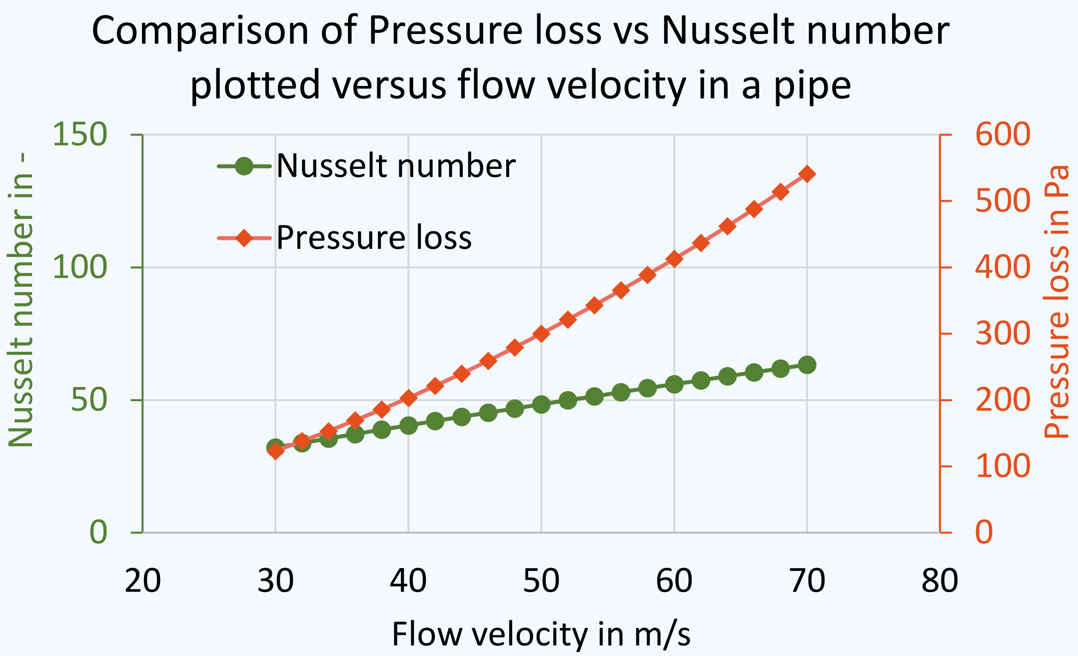
Basic Concepts





- 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 is transferred to a fluid via a heat transfer surface.

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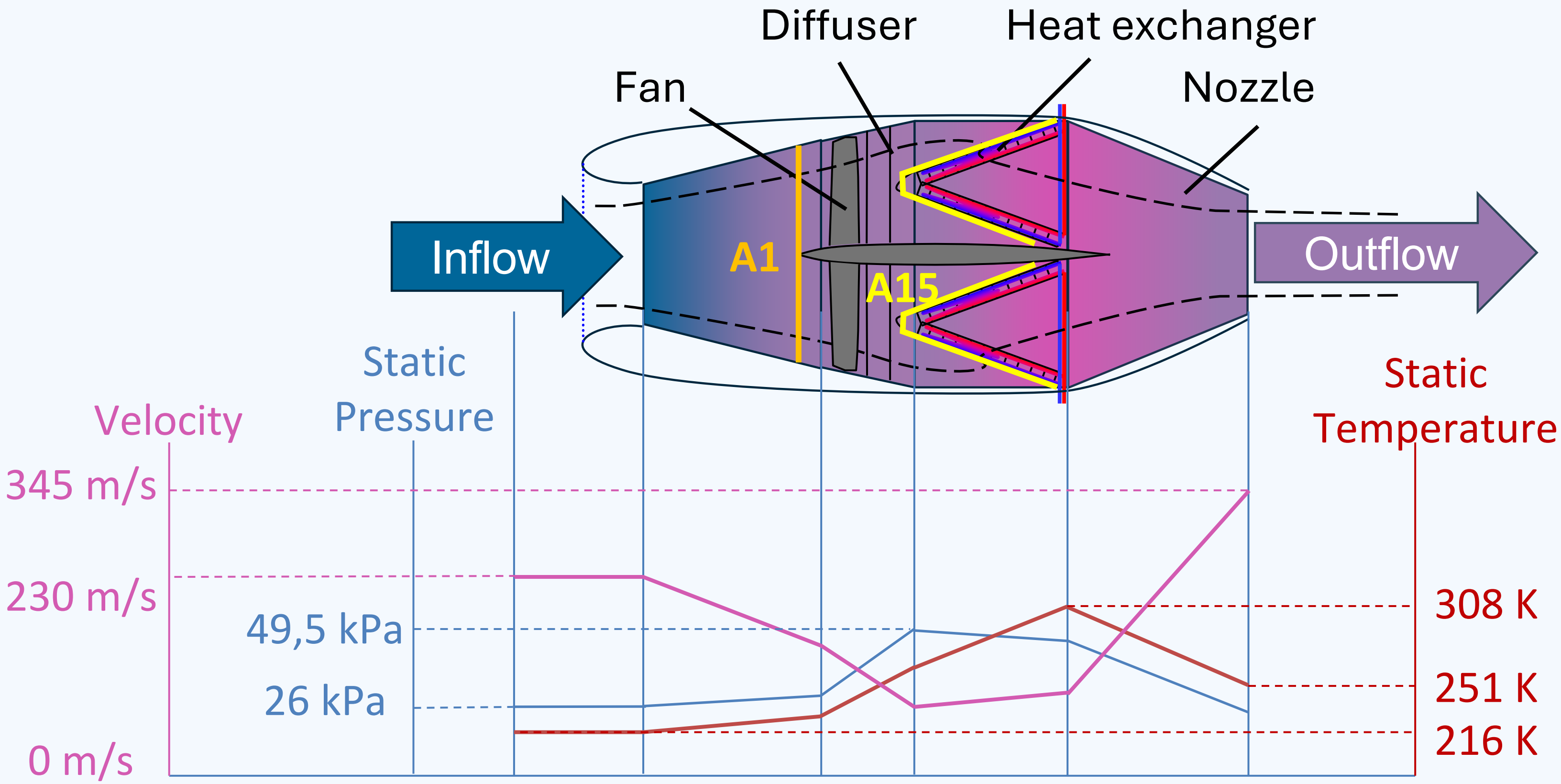
Basic Concepts

- 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

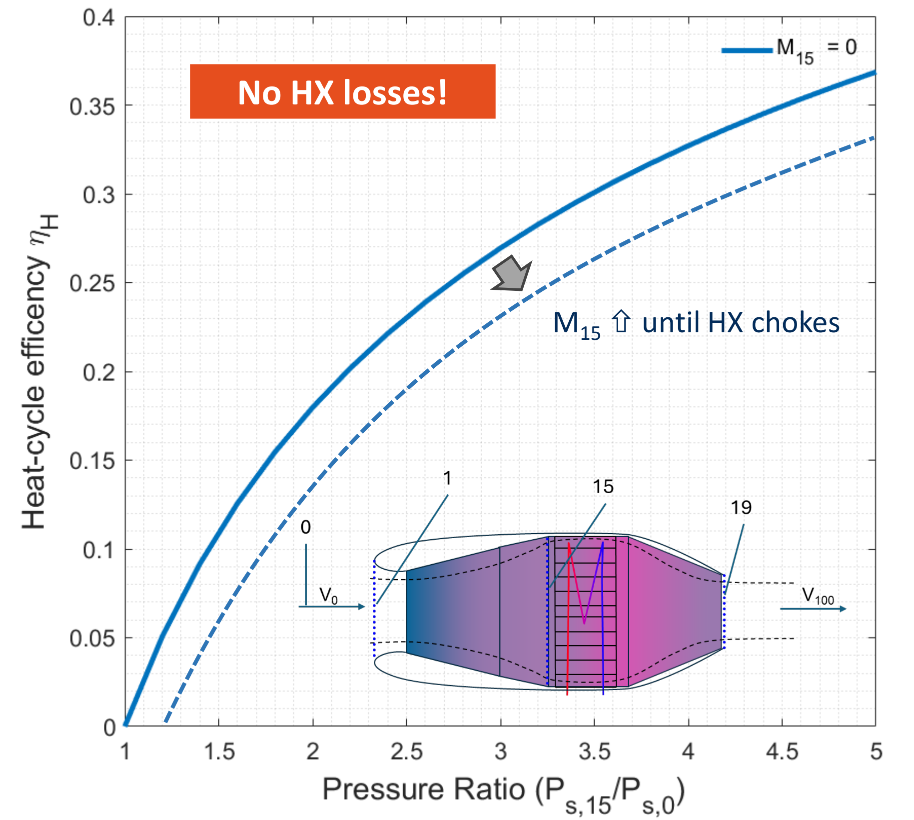
- Model of an installed HX with no losses, low M_{15} compared with M_0 and simplifications:

$$\eta_H = \frac{Kinetic\ power\ recovered}{Total\ heat\ added} = 1 - \left(\frac{P_{s,15}}{P_{s,0}}\right)^{\frac{1-\gamma}{\gamma}}$$

- Effectiveness of rejected heat conversion into kinetic jet power depends on pressure ratio $\left(\frac{P_{s,15}}{P_{s,0}}\right)$!
- Recuperated kinetic jet power depends on heat rate $\dot{Q}_{PEMFC}$, not on temperature.

$$\eta_T = \frac{Added\ useful\ thrust\ power}{Total\ heat\ added} = \eta_H \cdot \eta_j$$

$$\eta_j = \frac{Propulsive\ power}{Kinetic\ jet\ power}$$



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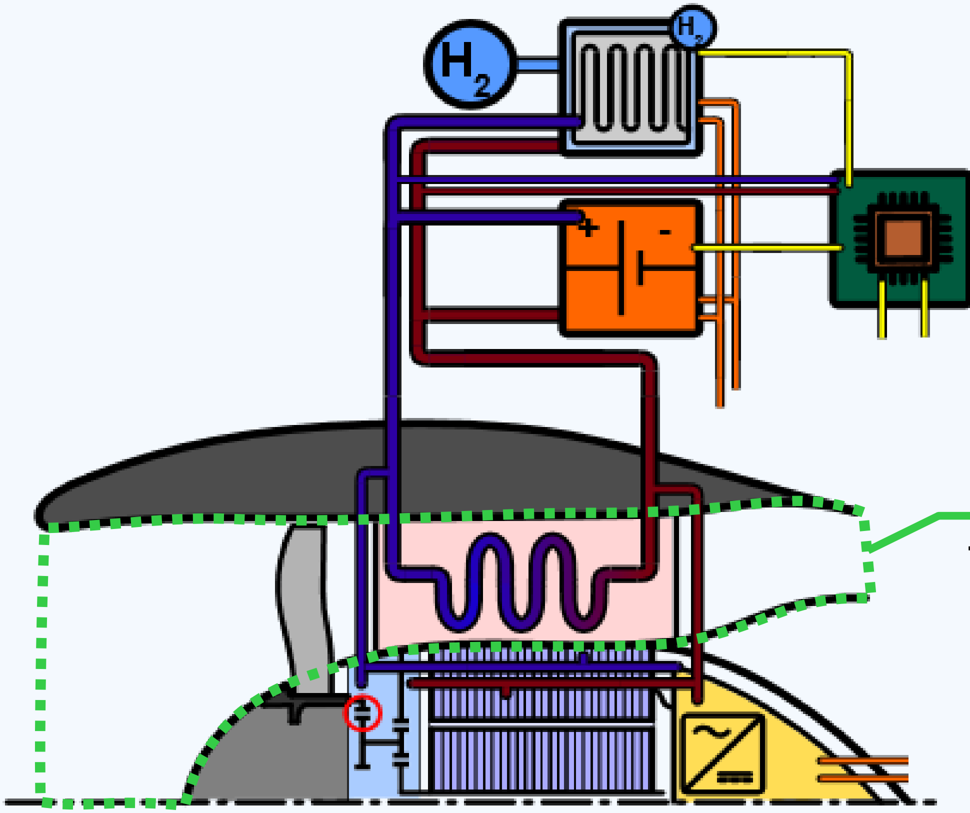
Source: J. V. BECKER und D. D. BAALS, „The Aerodynamic Effects of Heat and Compressibility in Internal Flow Systems, and High-Speed Tests of a Ram-jet System.“, NACA Rept. 773, 1943.

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 altitude, flight Mach, etc.
  - Nacelle external drag
  - System masses
- Engine of a twin engine SMR-a/c (A320 size)
- Sizing mode study: Component sizes are adapted to operating conditions ⇨ “Rubberized”
- Fixed fan inlet Mach number
  ⇨ Variable area nozzle / Fixed pitch fan rotor
- All fuel power that is not converted into mechanical shaft power is rejected as heat by HX



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

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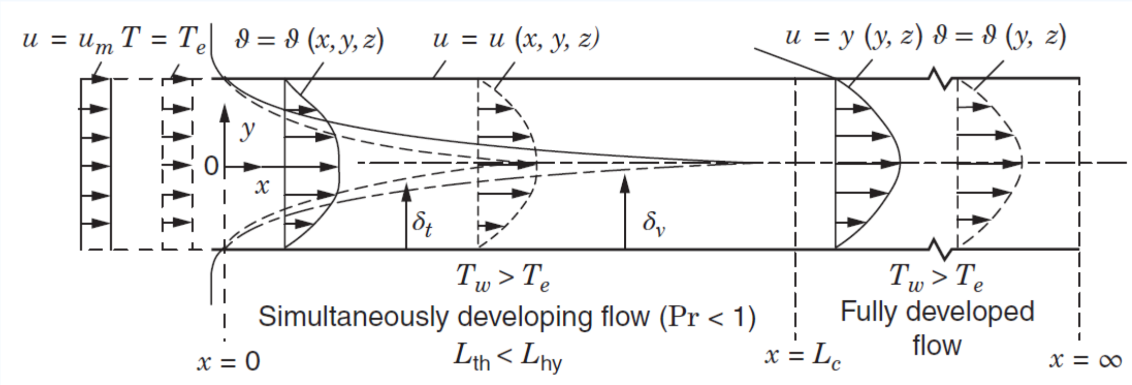
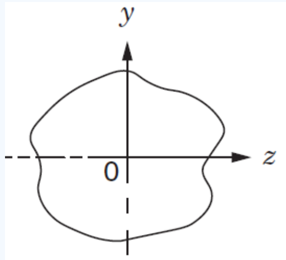
Parameter Study - Assumptions



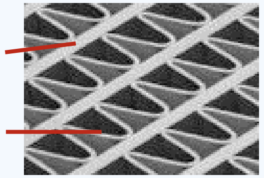


Present parameter study

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

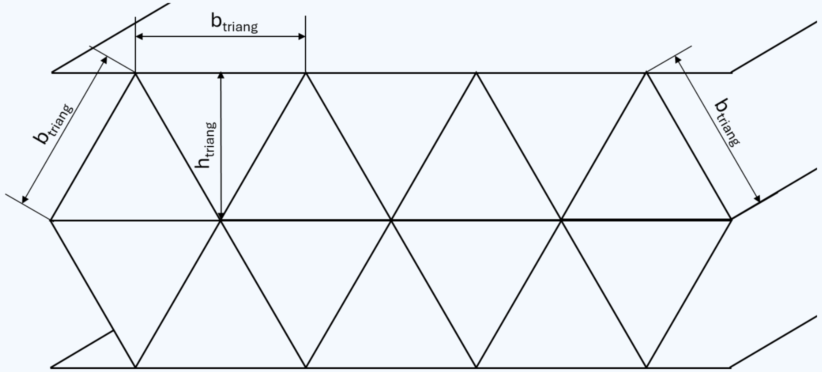
plate (aka tubes => liquid coolant channels)

fins form air flow path



HX air side settings

- Friction losses in the HX
- 1D-Modelling (based on hydraulic diameter)
- Counter flow compact plate and fin HX (real HX may be of crossflow type)
- Two fluid, direct transfer, single pass
- Blockage due to coolant plate/tubes is neglected
- Fully developed turbulent flow, Prandtl number Pr = 0.72



b_{triang} = 10 mm

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Parameter Study - Results

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

ISA temperature deviation (K)	0.0
Freestream Mach number	0.78
Fan inlet Mach number	0.5
Fan polytropic efficiency	0.85
Fuel cell and electric drive combined efficiency	0.5
Ratio of HX air inlet to fan inlet areas	3.0
Hot side inflow temperature (°C)	80
Net thrust (kN)	23.020

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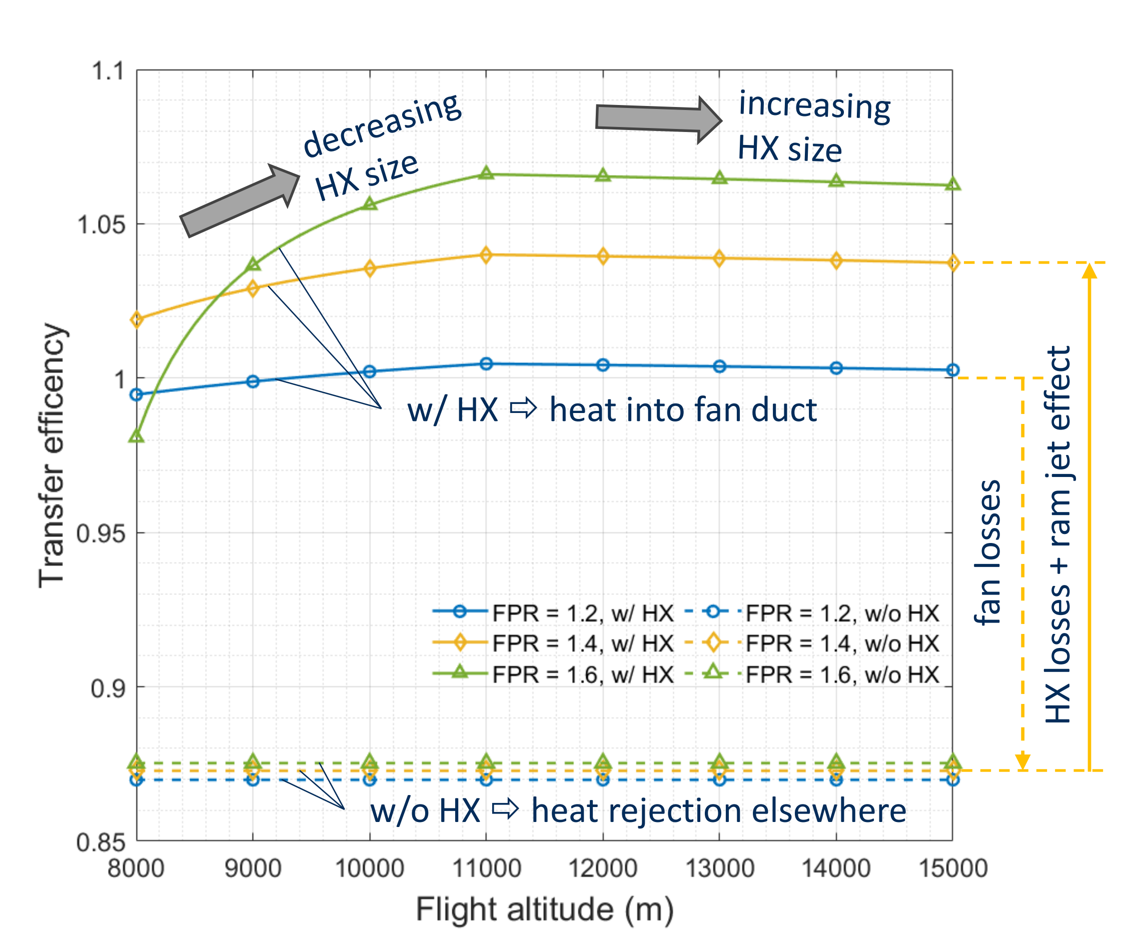
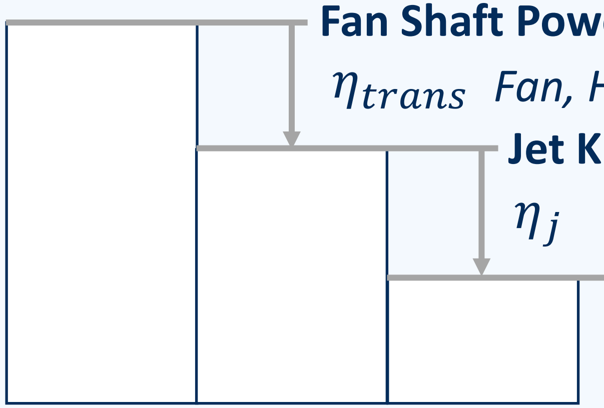


$$\eta_{trans} = \frac{P_{kin,j}}{P_{br}} = \frac{Kinetic\ jet\ power}{Power\ at\ fan\ shaft}$$

Parameter Study - Results

- Higher jet velocities with increased FPR's
  ⇨ Jet propulsive efficiency decreases
- Ram jet effect further adds to jet velocities and jet kinetic power P_j
  ⇨ Jet propulsive efficiency w/ HX is always lower than w/o HX for a fixed FPR



Fan Shaft Power P_{br}

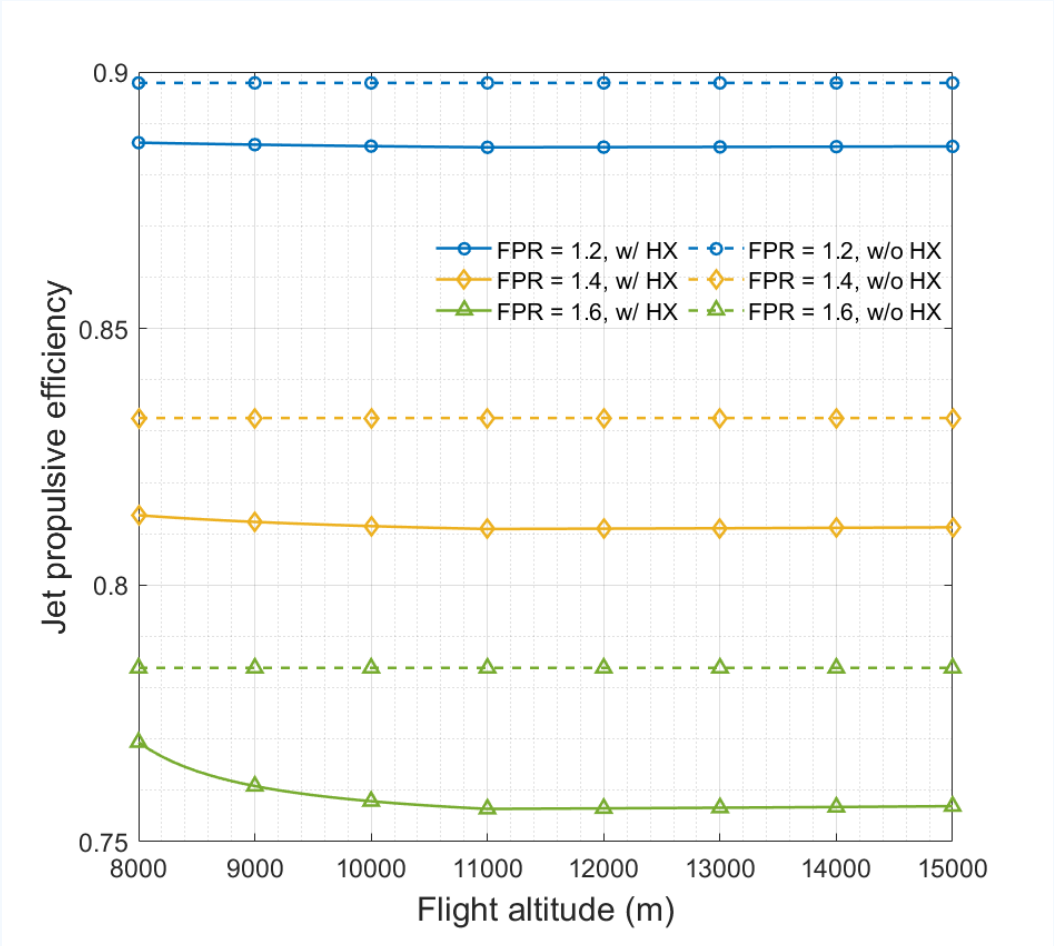
η_{trans} *Fan, HX, Nozzle, (Ram Jet Effect)*

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

η_j

Propulsive Power

$\boldsymbol{P_{av} = \dot{m}(v_j - v_0) \cdot v_0}$



$$\eta_j = \frac{P_{av}}{P_j} = \frac{Propulsive\ power}{Jet\ kinetic\ power}$$

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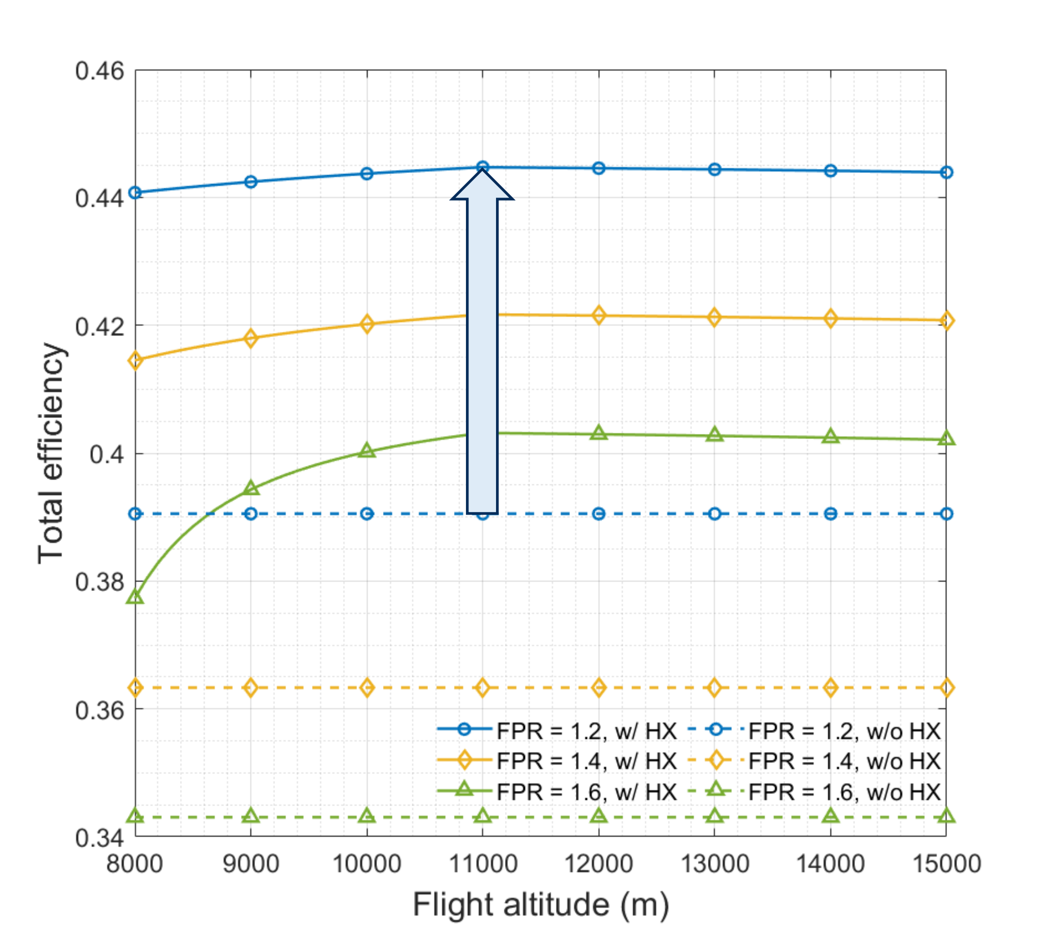
Parameter Study - Results

Efficiency gains

- Diagram example:
  - FPR = 1.2
  - H = 11 km
- Ram jet potential considering losses in terms of total efficiency:
  - Net gain: + 5.4%
  - + 13.9% w. r. t. “w/o HX” case



$$\eta_{tot} = \frac{P_{av}}{P_{Fuel}} = \frac{Propulsive\ power}{Fuel\ power}$$

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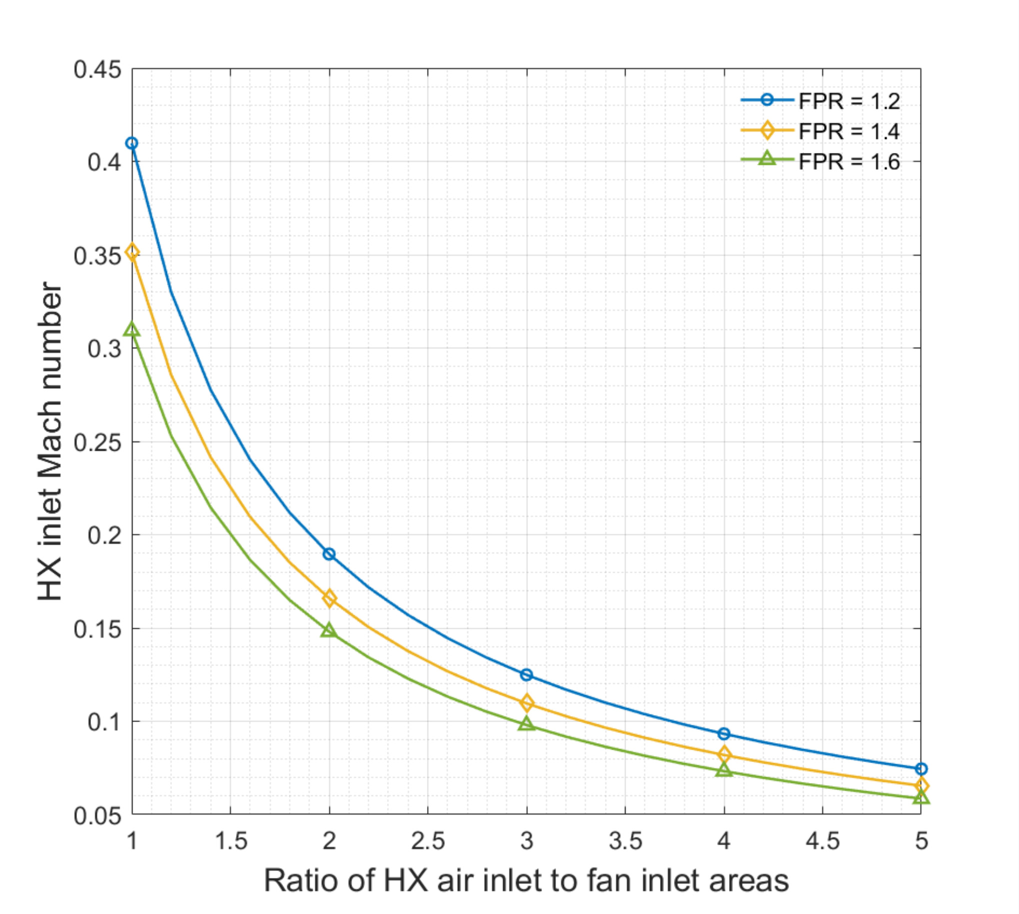
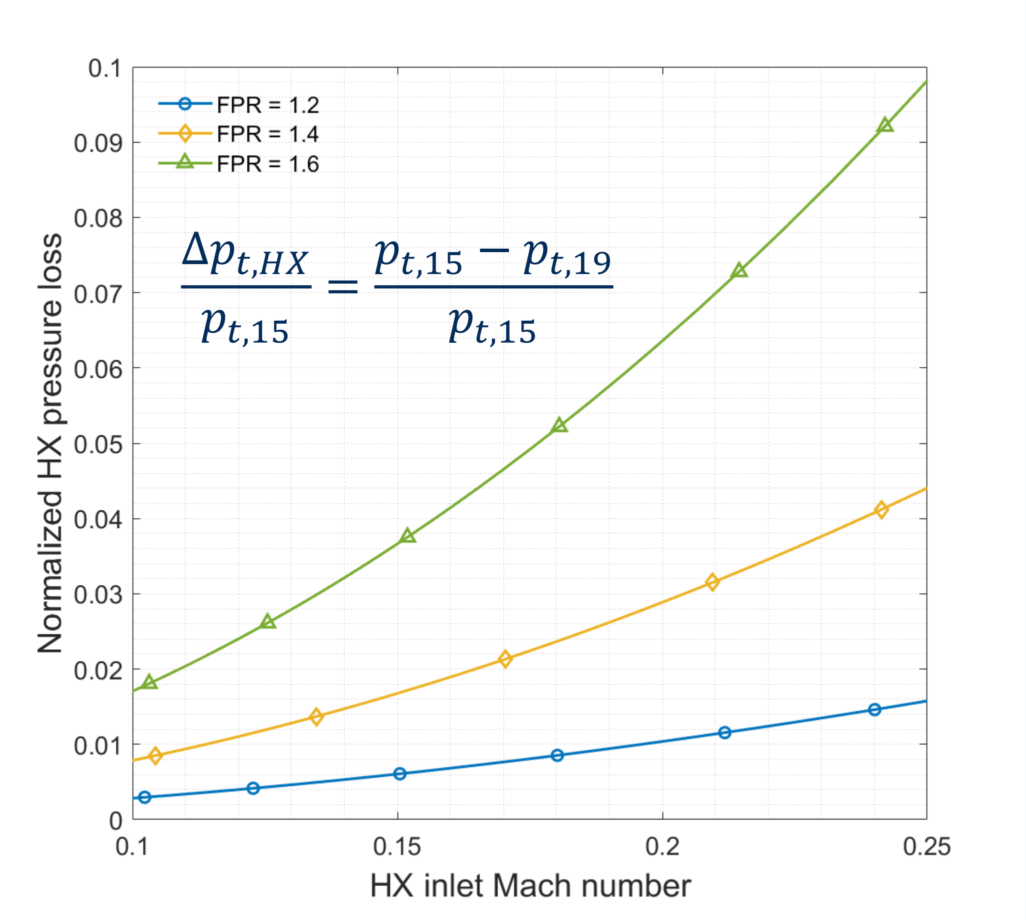
Parameter Study - Results





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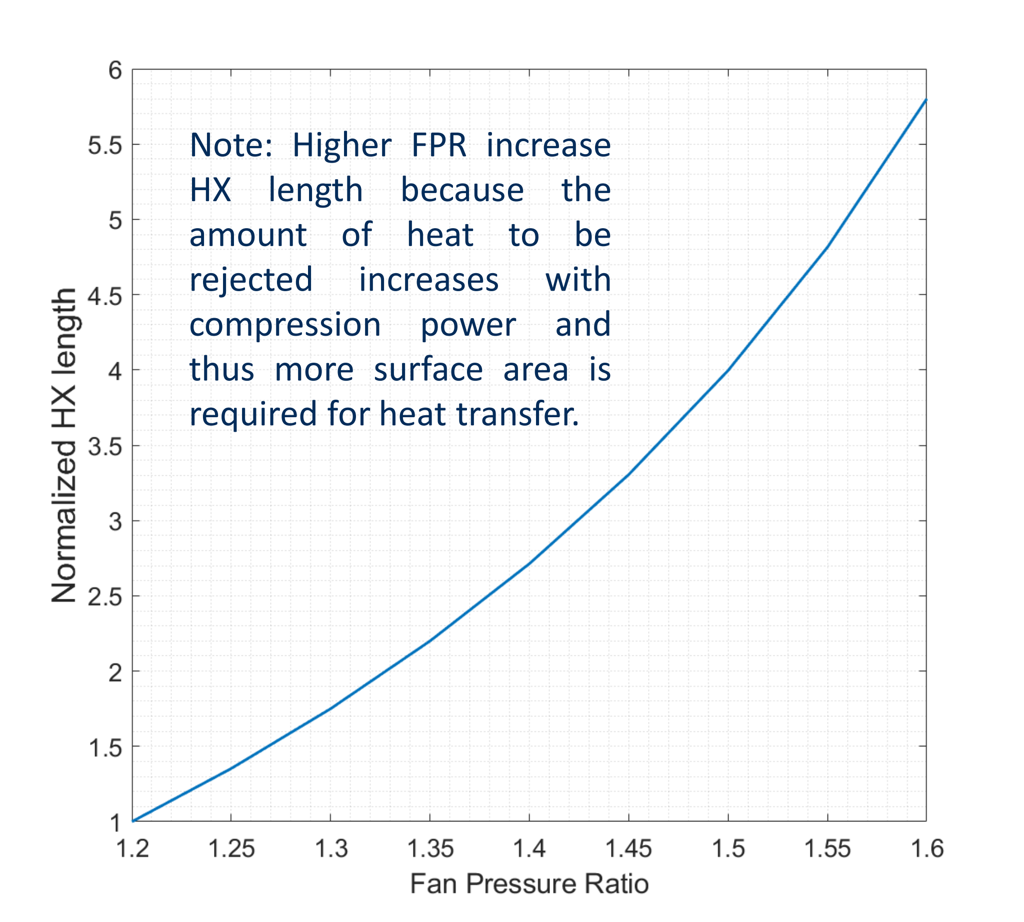
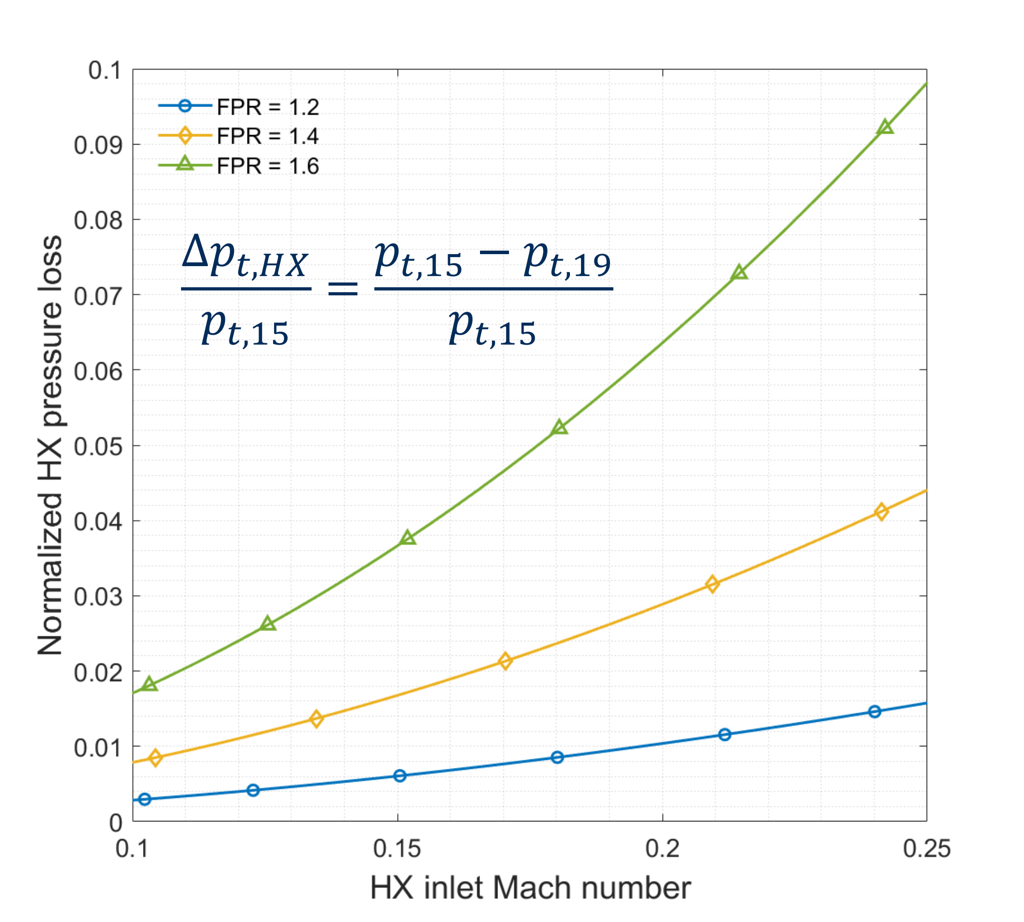
Parameter Study - Results





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Parameter Study - Results

- HX losses decrease with hot side inflow temperature because of reduced HX size ⇨ Efficiency increases

	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	
Ratio of HX air inlet to fan inlet areas	3.0	

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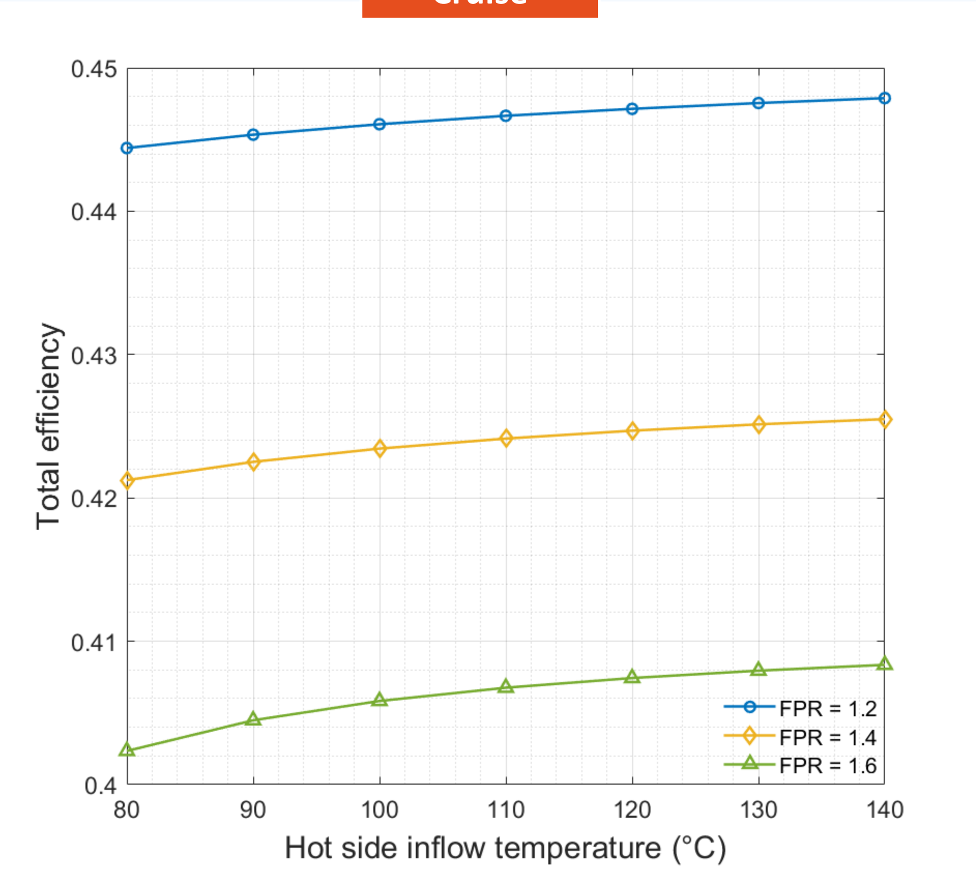
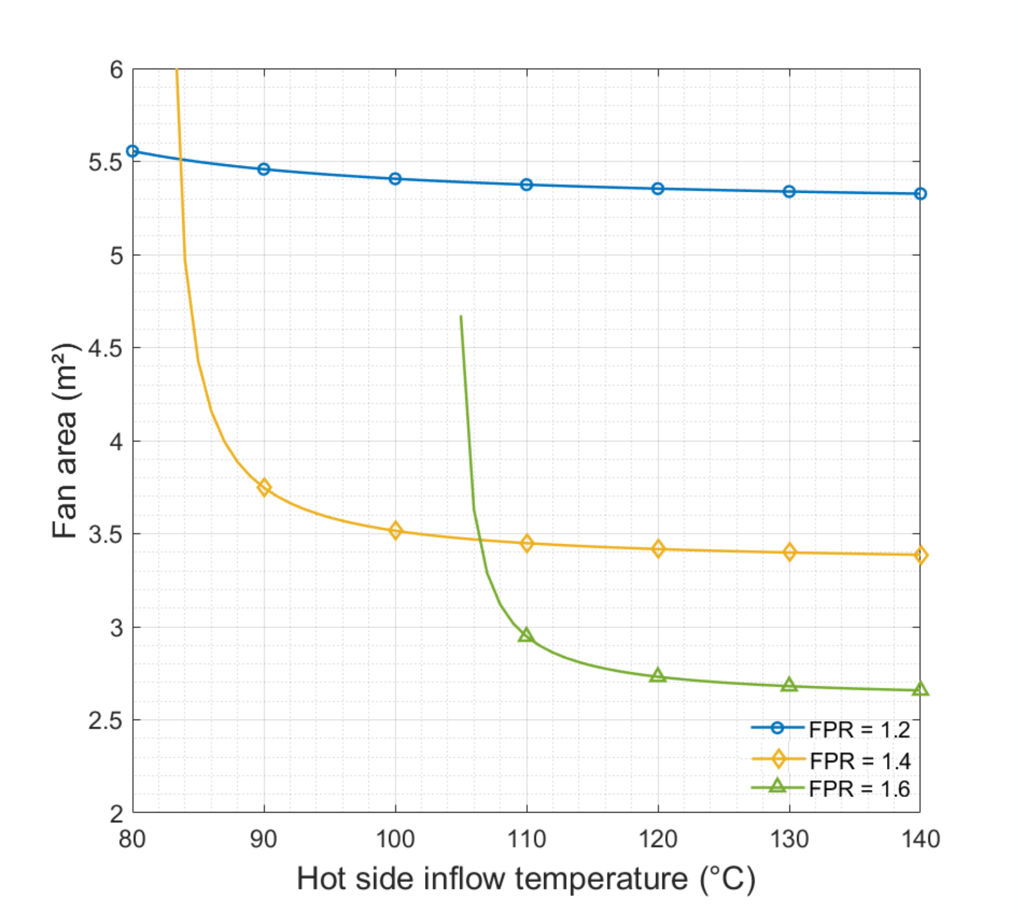
Cruise



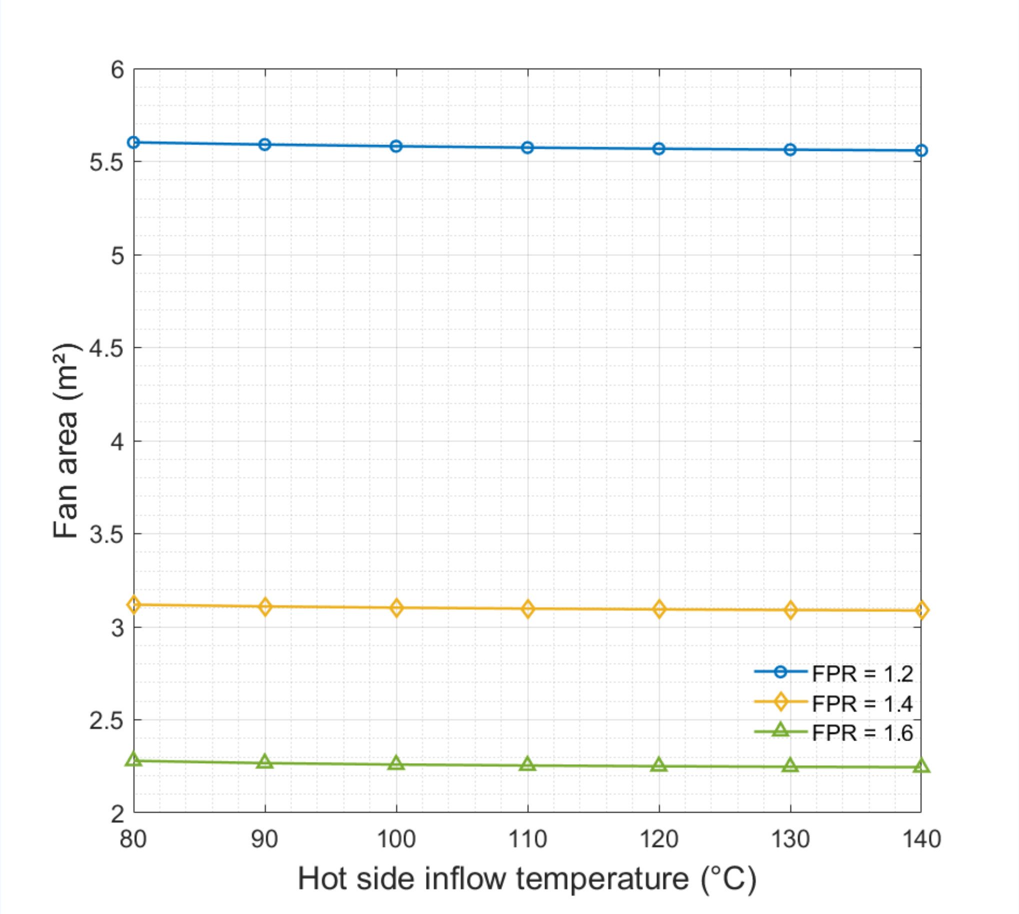
$$\eta_{tot} = \frac{P_{av}}{P_{Fuel}} = \frac{Propulsive\ power}{Fuel\ power}$$

Parameter Study - Results

Take Off



Cruise



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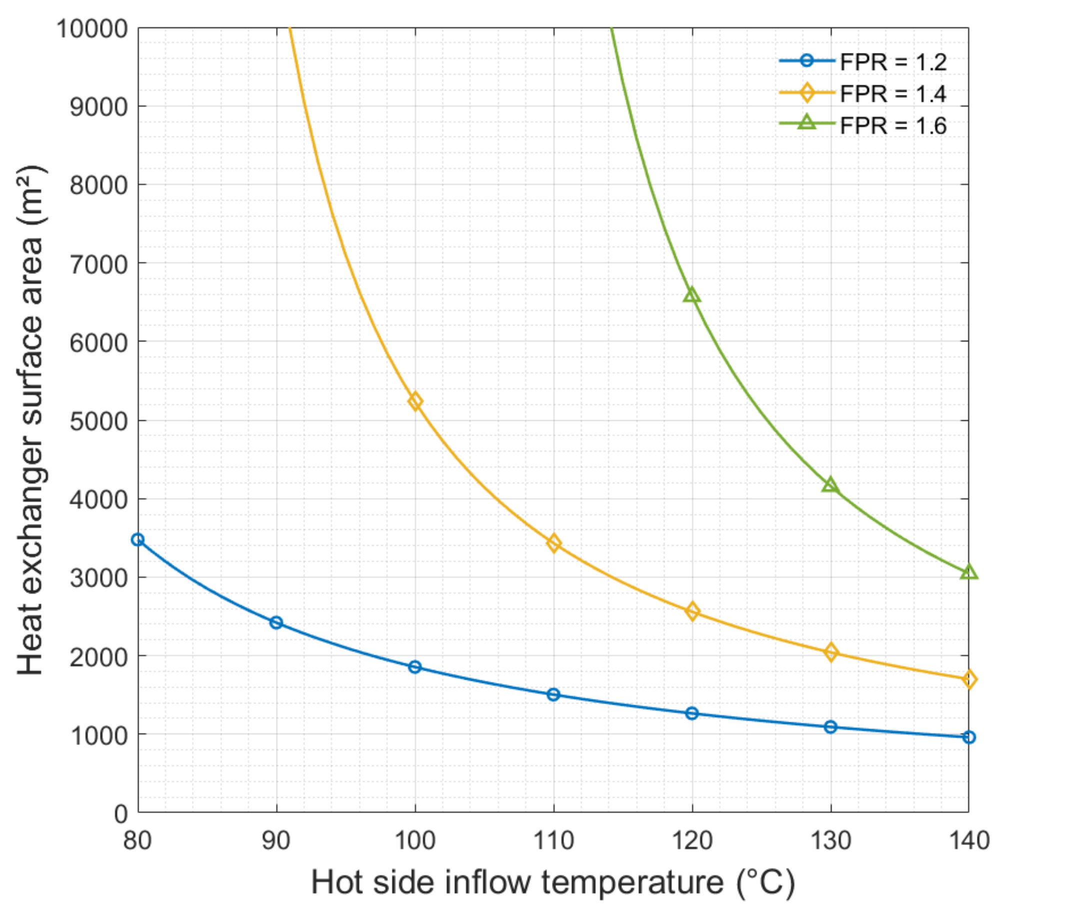
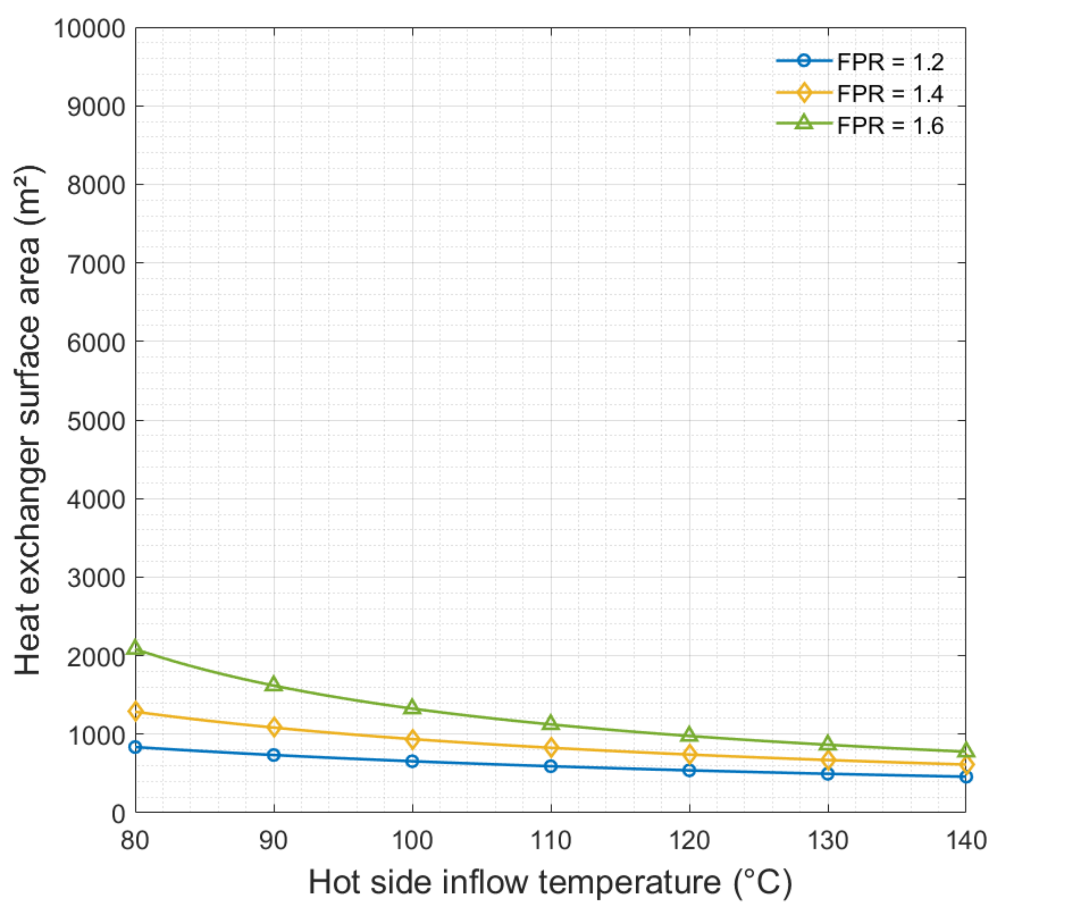
Parameter Study - Results

Take Off



Cruise



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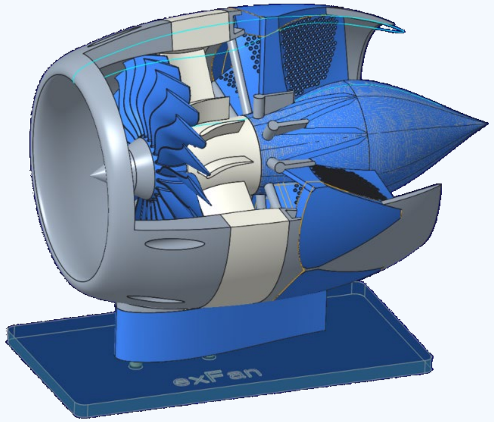
Conclusions and Outlook

Conclusions

- Ram jet effect increases with flight Mach number
- Heat exchanger size depends
  - on coolant temperature (“heat quality”) and
  - installed system power / heat load
- 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
  - Tropopause altitude
- Net benefits by ram jet effect even when pressure losses taken into account
- Nacelle integration is principally possible!

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
- Challenges:
  - Match sea level take off and cruise req.’s
  - Hot day take off

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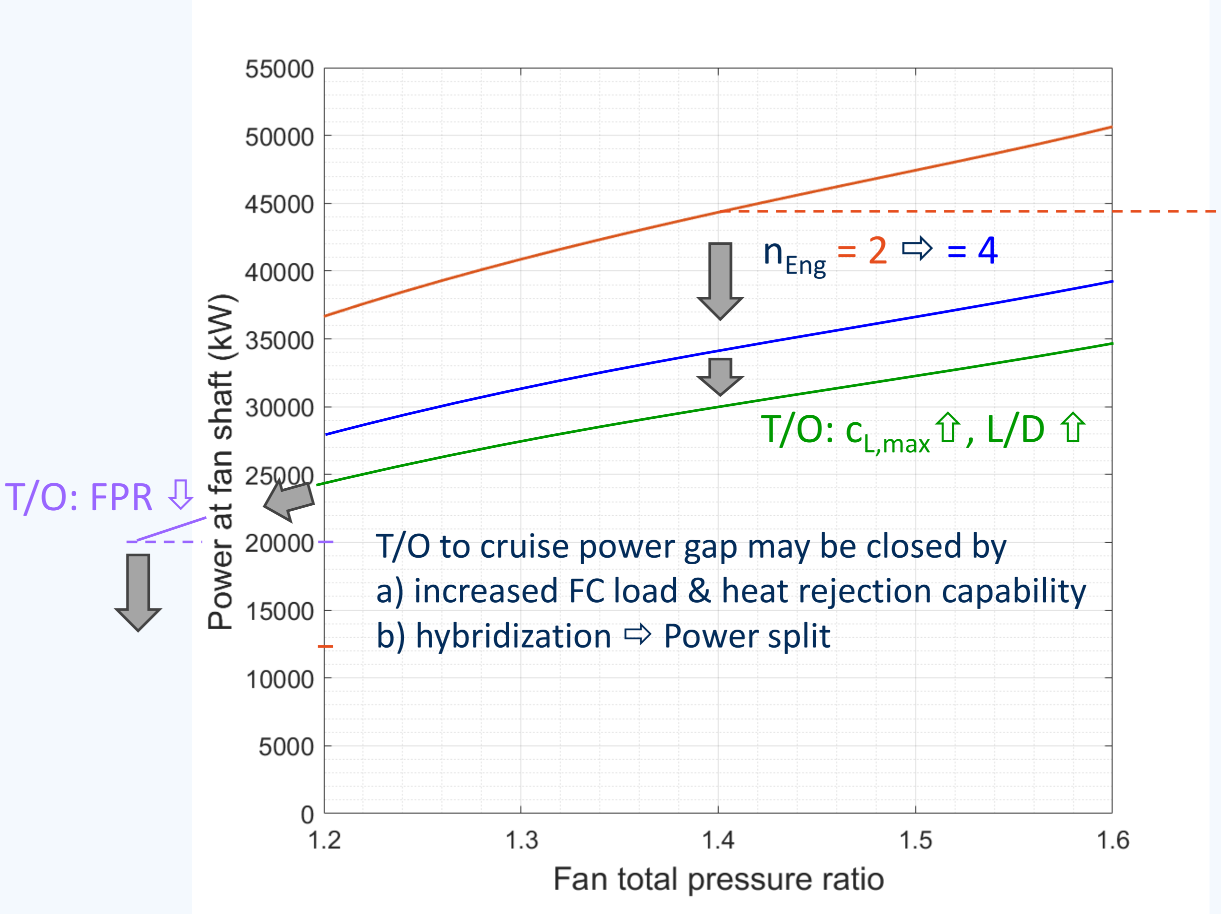
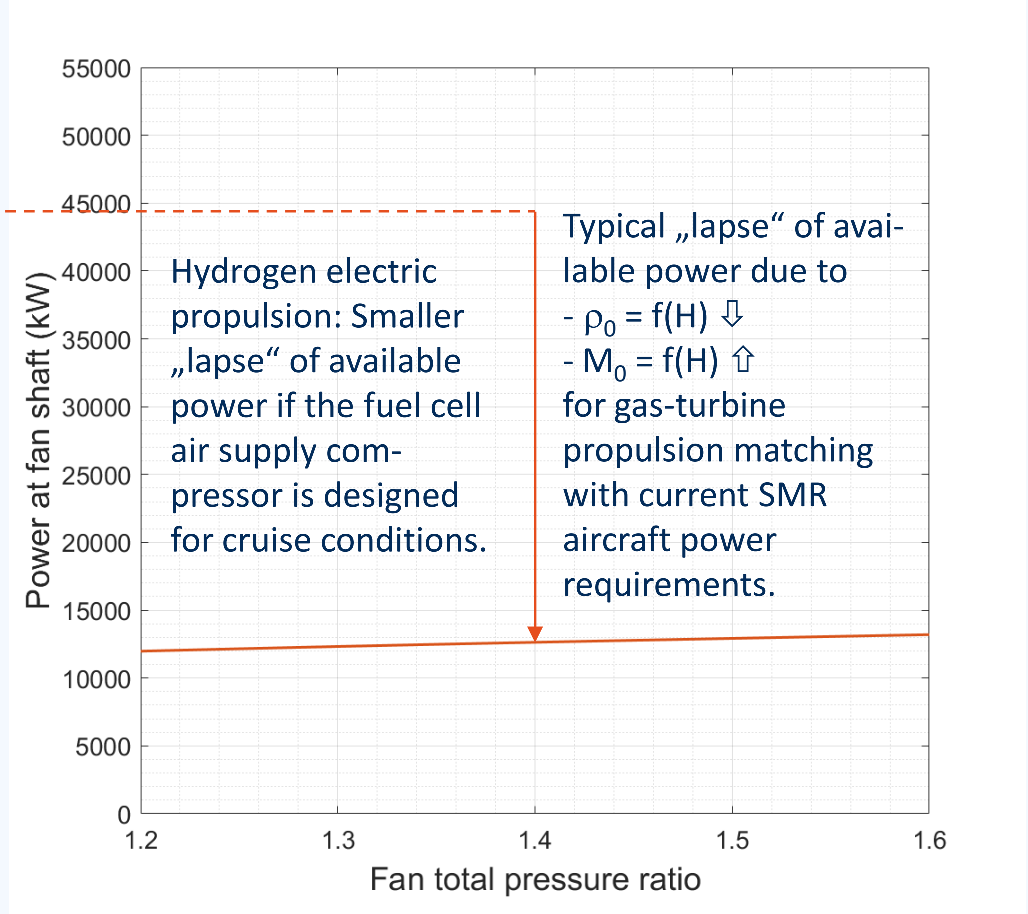
Conclusions and Outlook

Take Off



Cruise



Coolant temperature 120°C!

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EXFAN

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

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