

PREVENTION OF CONTRAIL FORMATION IN HYDROGEN FUEL CELL AIRCRAFT

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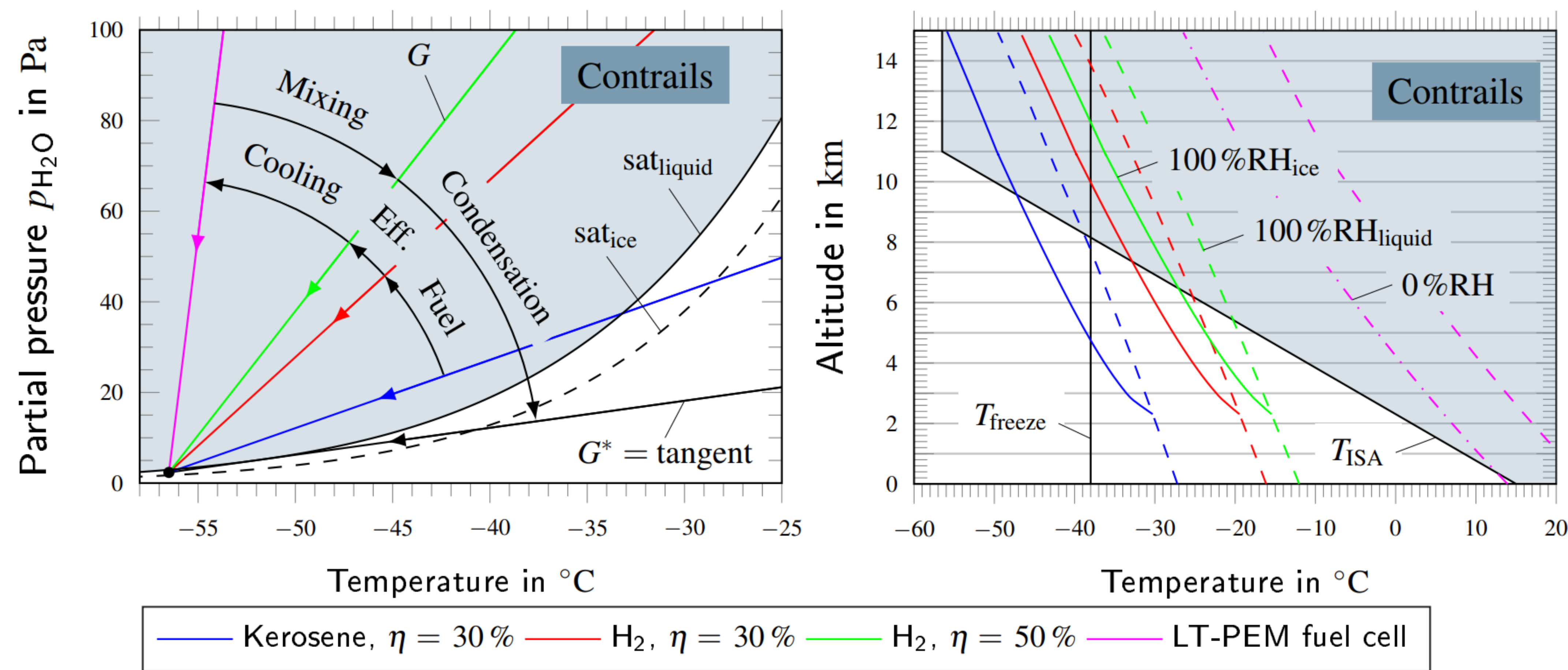
Contact information

Saturation → Droplets → Freezing → Persistence → Radiative forcing

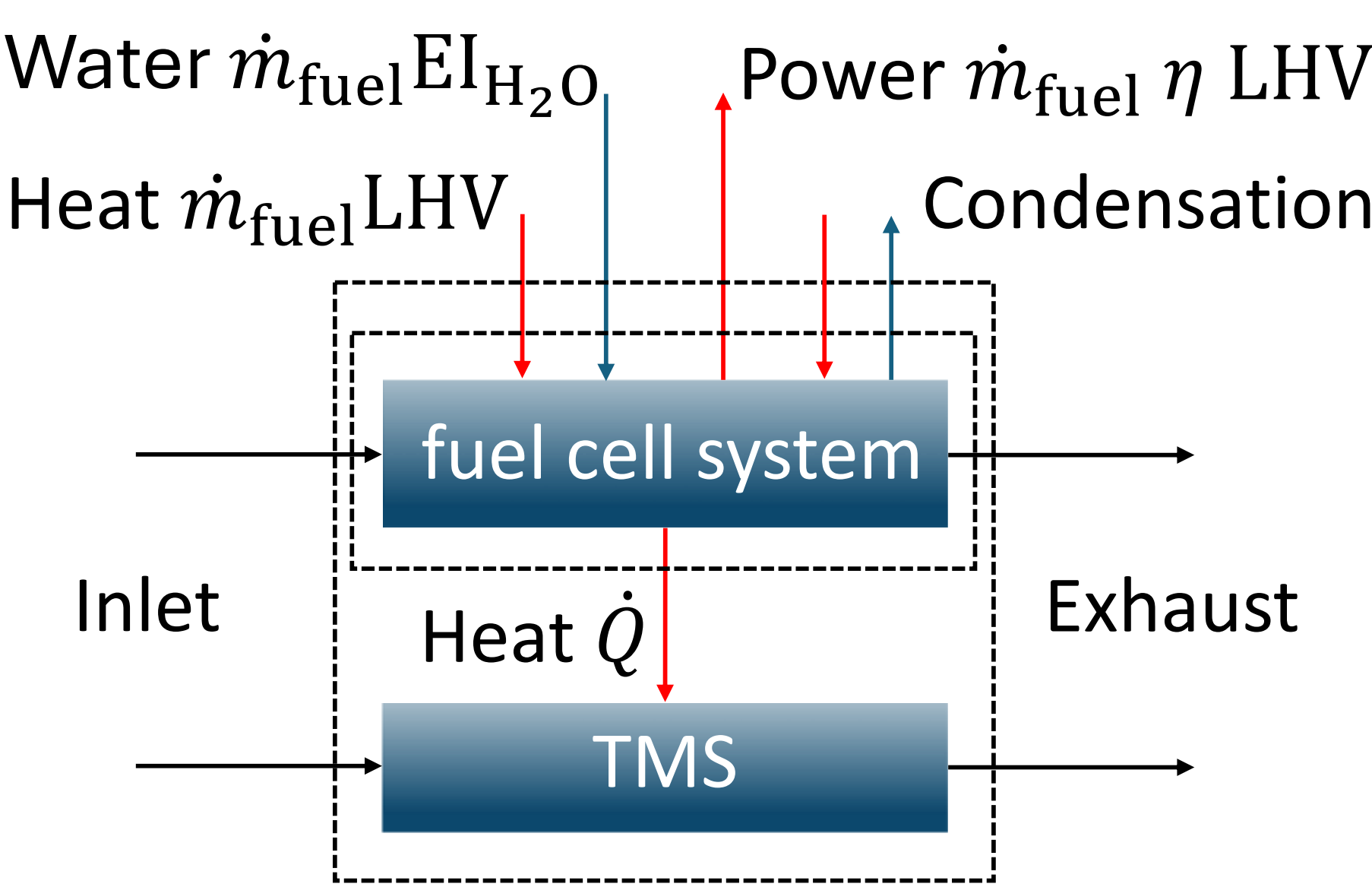


Challenge Potentially increased contrail formation

- Contrails are the largest non-CO₂ climate impact of aviation
- Fuel cell propulsion can increase contrail formation:
 - Hydrogen **fuel** → more water produced per energy released (factor ~ 2.6)
 - Higher **efficiency** → cooler exhaust (factor ~ 1.4)
 - External **cooling** → even lower temperatures (factor ~ 6.5)



$$G = \frac{\Delta p_{H_2O}}{\Delta T} \approx \frac{pEI_{H_2O}c_{p,air}}{0.622LHV(1-\eta)} \xrightarrow{\text{Condensation}} G^* = \frac{\Delta p_{H_2O}^*}{\Delta T^*} \approx \frac{pEI_{H_2O}(1-f_{cond})c_{p,air}}{0.622(LHV(1-\eta) + f_{cond}\Delta h_vEI_{H_2O})}$$

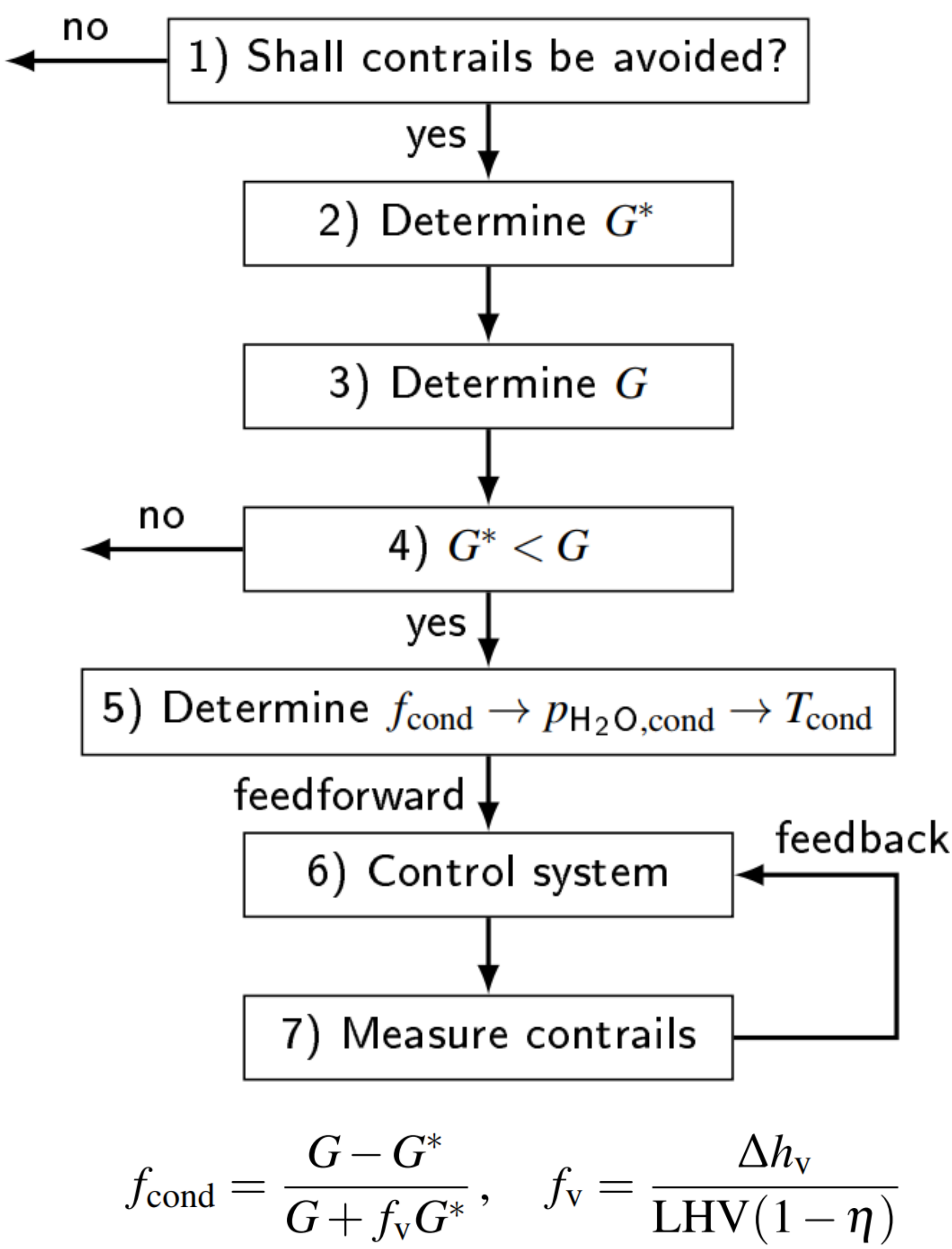
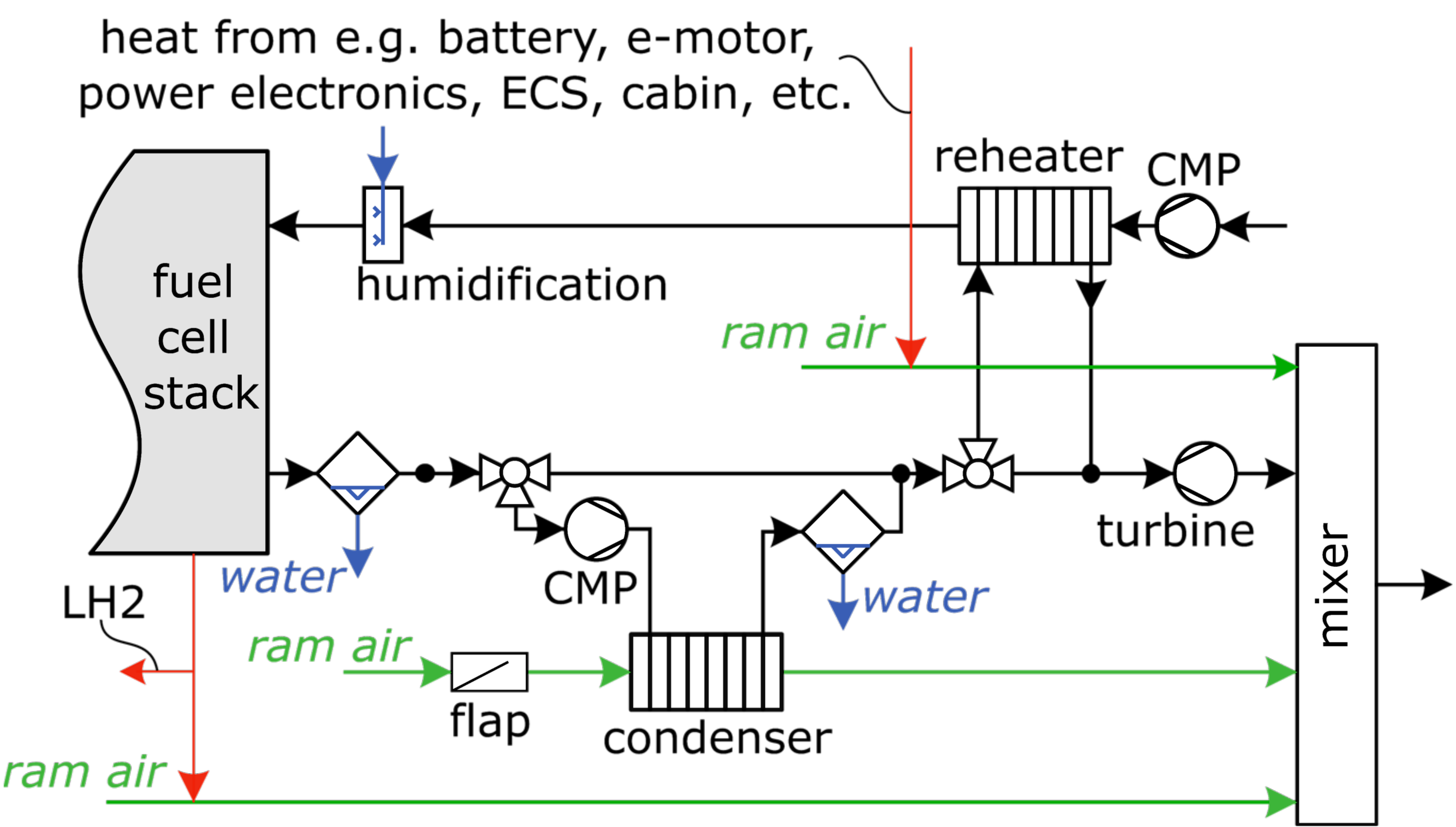


G – mixing slope in $\frac{Pa}{K}$
 EI_{H_2O} – emission index in $\frac{kg_{H_2O}}{kg_{fuel}}$
 LHV – lower heating value in $\frac{MJ}{kg_{fuel}}$
 Δh_v – enthalpy of vaporization in $\frac{MJ}{kg_{H_2O}}$
 f_{cond} – condensation ratio



Proposed Solution Mixing and condensation

- Condense** water vapor in exhaust
- Mix** fuel cell exhaust with dry cooling air
- Control** to minimize drag while still preventing contrail formation



Impact Potential to fully eliminate contrails

- Theoretically great reduction in aviation's climate impact possible
- Minimal drag penalty while avoiding contrail conditions
- Major advantage for hydrogen fuel cell aircraft adoption



Methological Approach

- Apply **Schmidt-Appleman** criterion to fuel cell exhaust
- Derive influence of **mixing** process
- Extend theory to take **condensation** into account
- Derive **minimum required condensation** for contrail avoidance



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