KTH ROYAL INSTITUTE
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Flow and heat transfer in a turbocharger radial turbine

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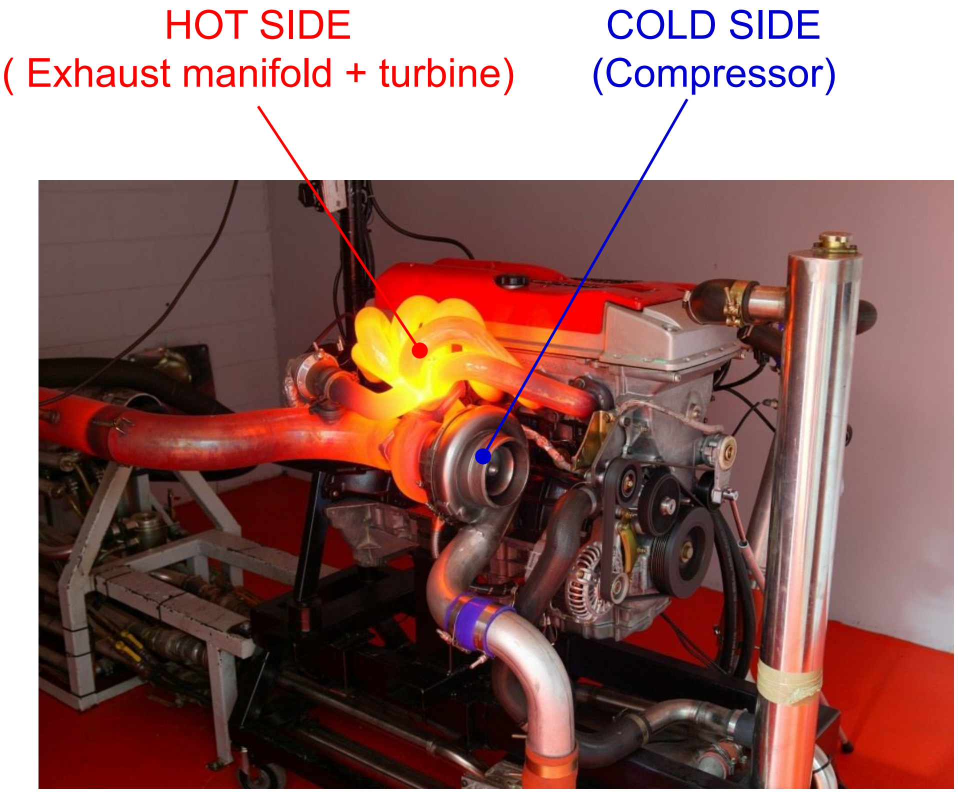
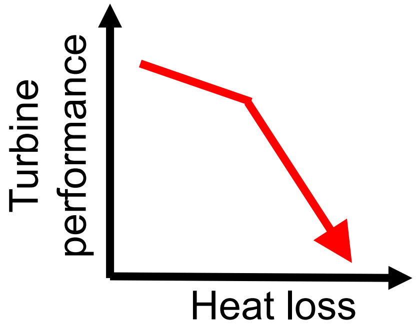
Heat transfer research scope in general

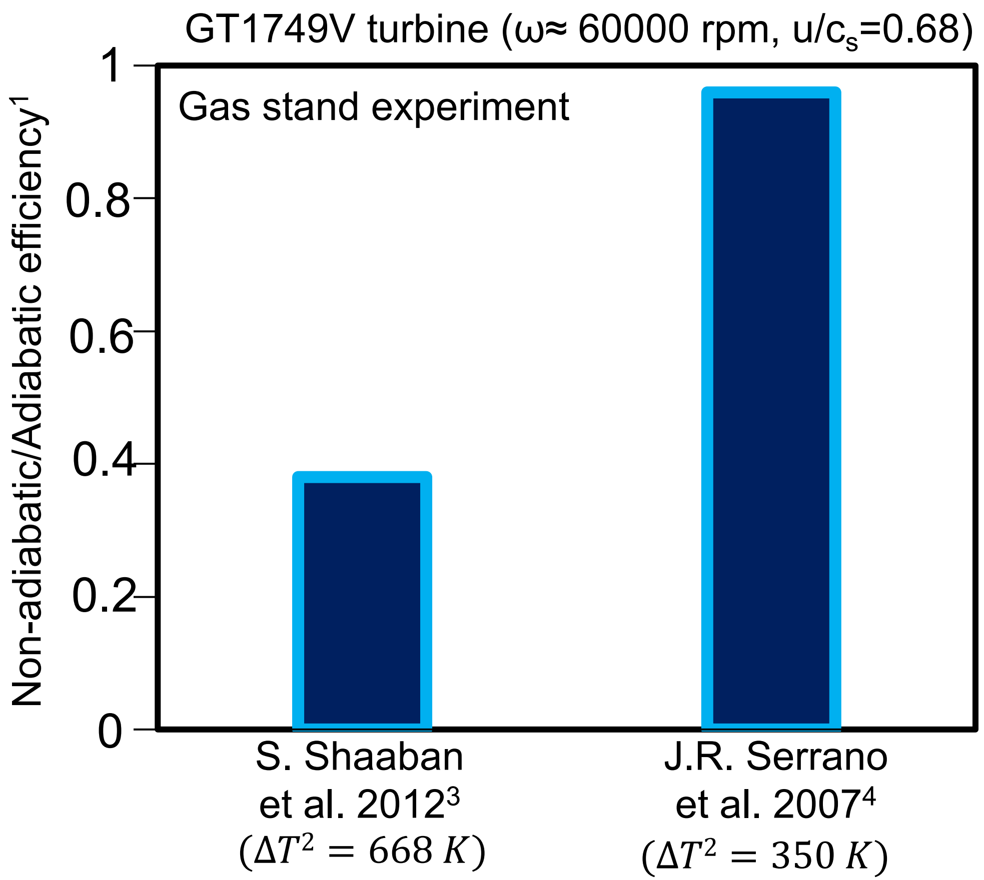


Adapted from Car Throttle (2013)

- Performance maps correction.
- 1-D/reduced order modelling.
- Correlation: turbine performance vs. heat loss.



Research gaps



- First law of thermodynamics based approach.
- Contradicting results.
- Lack of physical understanding.

[1] A value of one means no deviation from adiabatic performance.
[2] ΔT is the difference in turbine inlet gas temperature between cold and hot test.

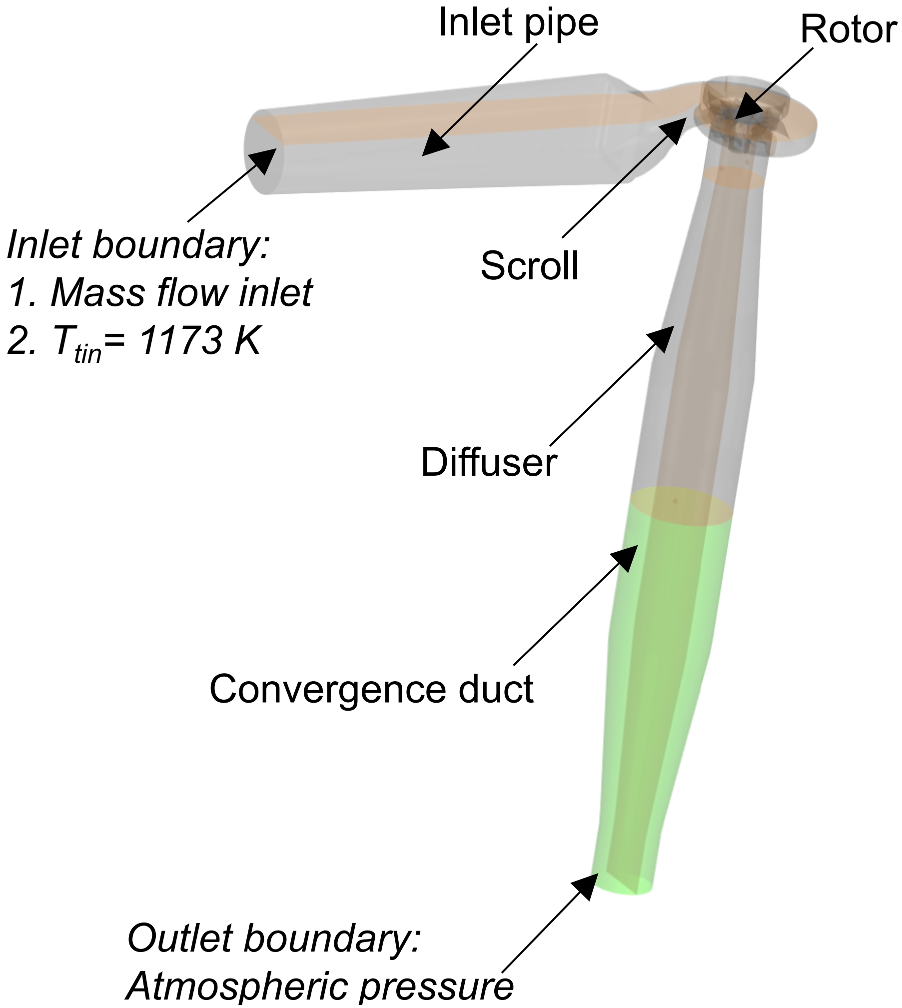
[3]Shaaban, S. and Seume, J. (2012). Impact of turbocharger non-adiabatic operation on engine volumetric efficiency and turbo lag. International Journal of Rotating Machinery, 2012.

[4]Serrano, J., Guardiola, C., Dolz, V., Tiseira, A., and Cervello, C. (2007). Experimental study of the turbine inlet gas temperature influence on turbocharger performance. Technical report, SAE Technical Paper.

Research questions

- How heat transfer affects turbine performance (sensitivity)?
- What are the heat transfer related losses?
- How can we quantify the losses & the effectiveness of resources utilization?
- What is the effects of upstream exhaust manifold (e.g. secondary flow) on heat transfer and turbine performance?

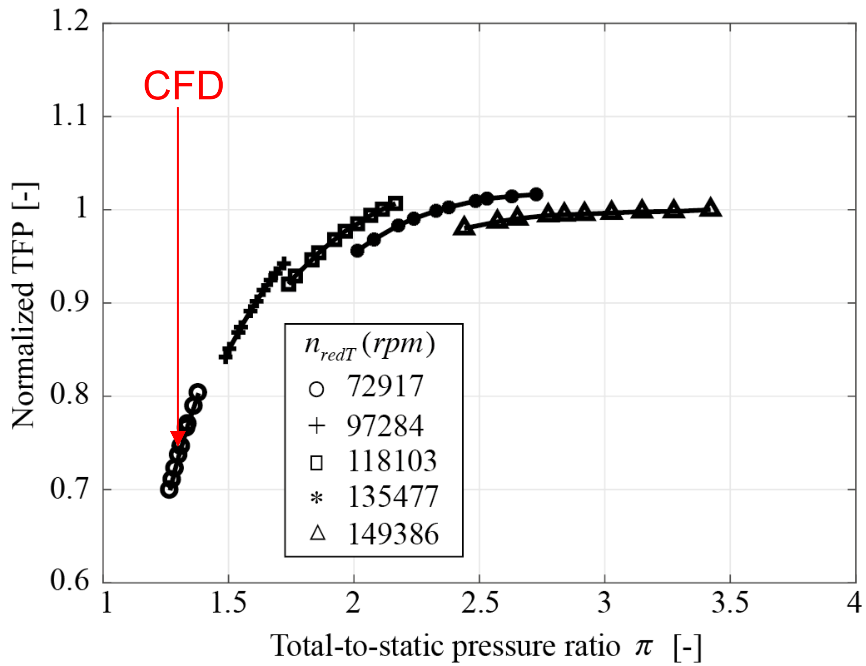
Computational setup

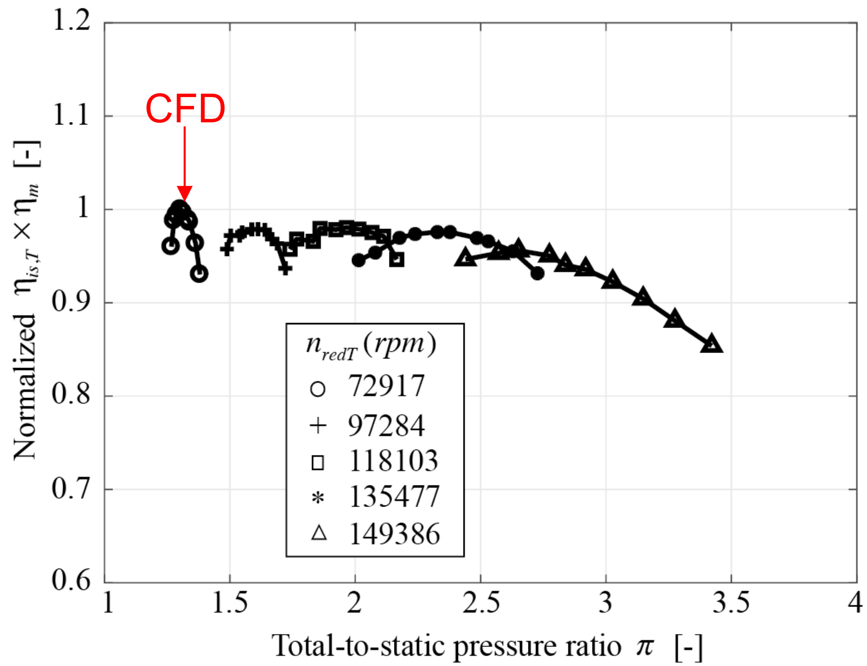


- Wall thermal conditions
  1) Adiabatic
  2) Constant wall temperature [K]
     1002[1], 830, 487
     Increasing heat loss →
- ~ 9 millions polyhedral cells
- Detached Eddy Simulations (DES)
- Sliding mesh
- ~ 7 hours/case with 320 CPUs

[1]Romagnoli, A. and Martinez-Botas, R. (2012). Heat transfer analysis in a turbocharger turbine: An experimental and computational evaluation. Applied Thermal Engineering, 38:58 – 77.

Investigated operating point



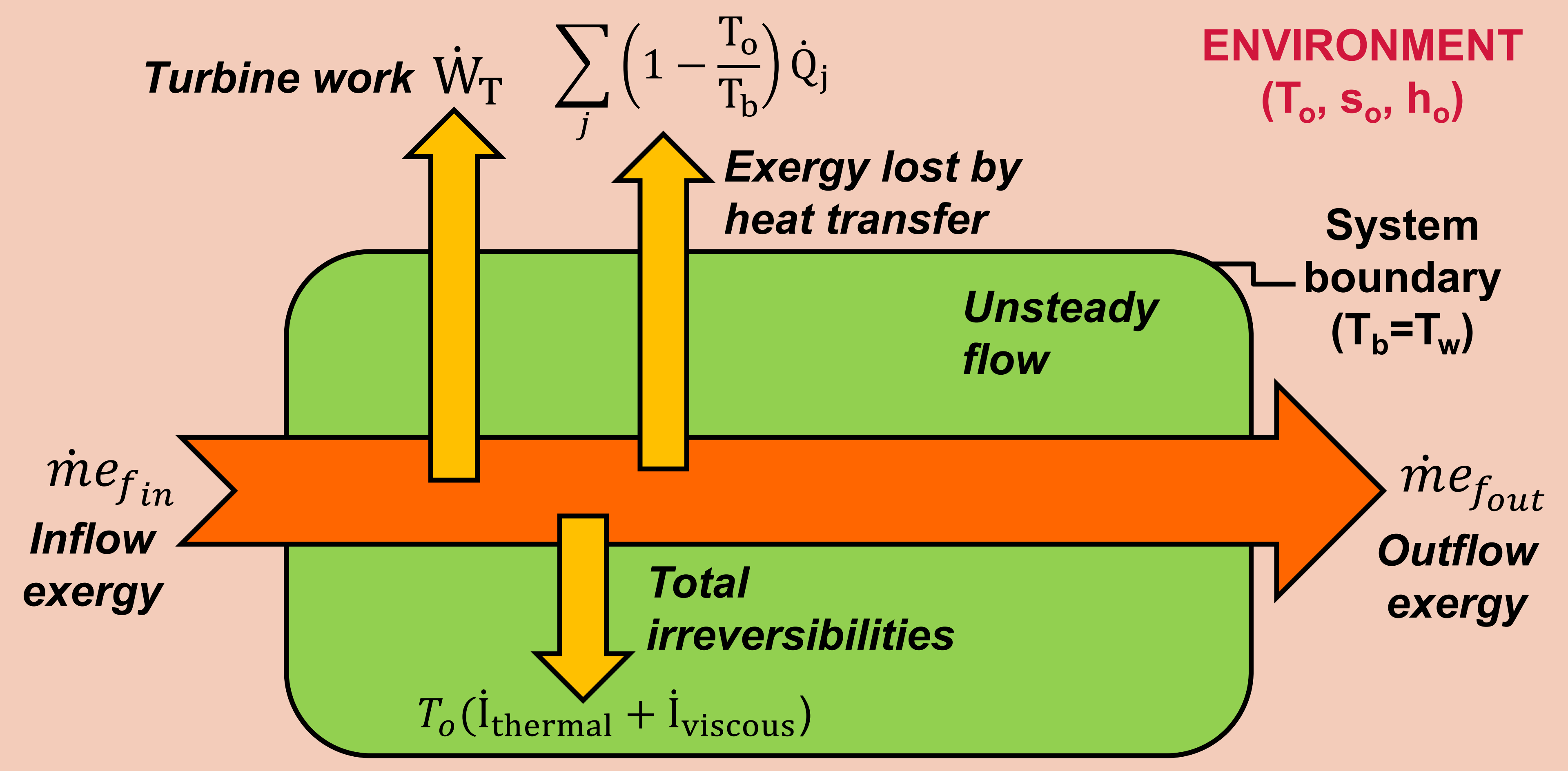


CFD performed on an operating point on

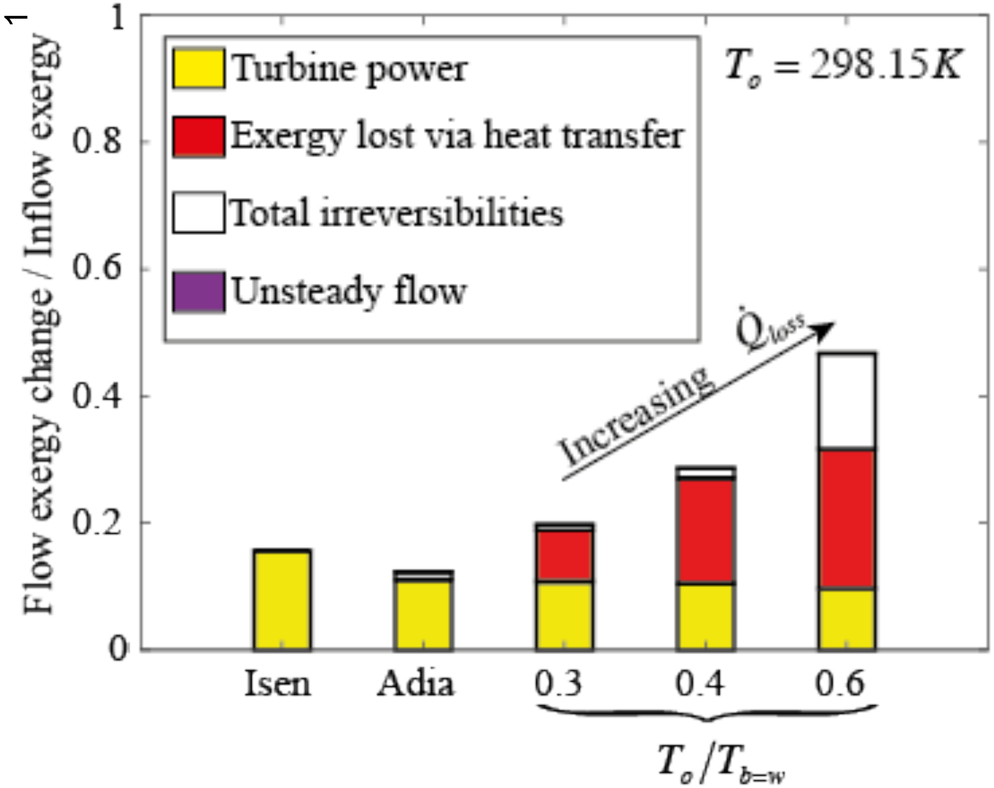
- Lowest speed line, and
- Maximum efficiency point.

* Turbine performance maps are normalized by the maximum value, respectively.

Flow exergy $e_f = [h_t(T_t, P_t) - h_o] - T_o[s(T_t, P_t) - s_o]$



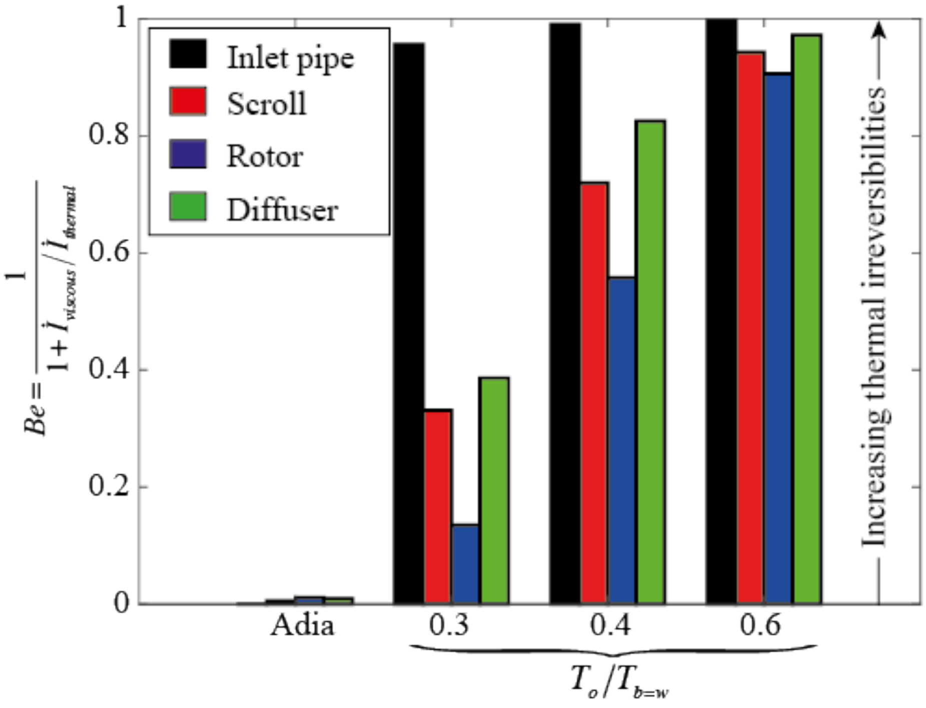
Exergy budget



- Turbine power reduction << flow exergy lost via heat transfer and irreversibilities.
- Most of the flow exergy is discharged without usage.
- Exergetic utilization: $\eta_{ex} = \frac{\dot{W}_T}{\dot{m}e_{f\,in}}$
- Limit: $\eta_{ex,max} \sim 16\%$

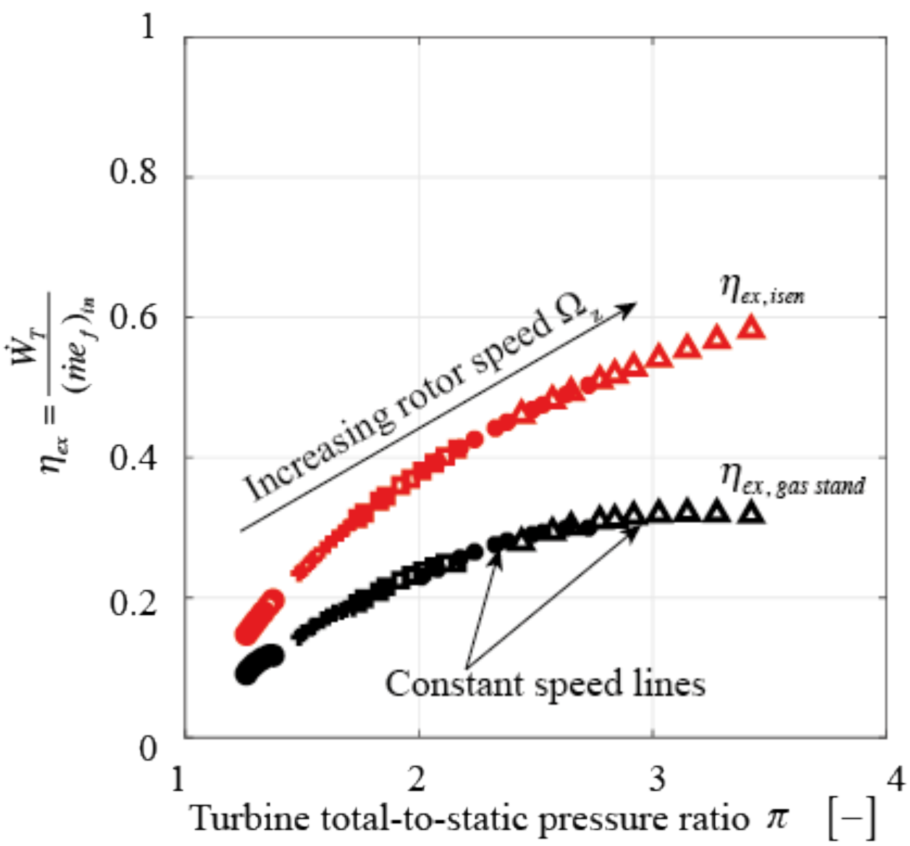
[1]A value of one means fully use of available energy, i.e. flow exergy.

Bejan number



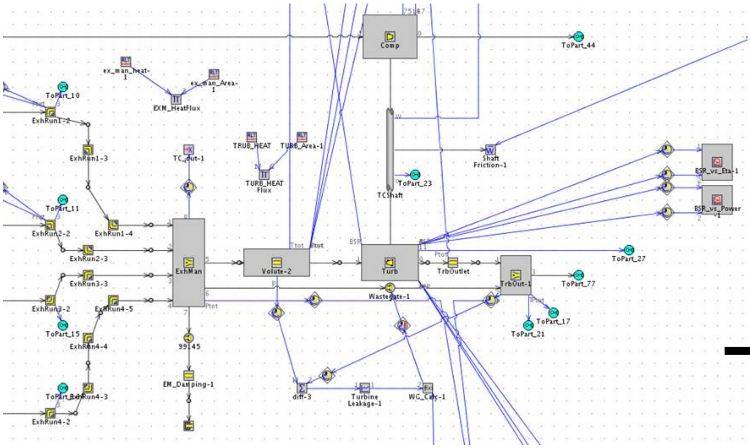
- Quantify relative importance of thermal and viscous irreversibilities.
- Upstream component is more sensitive to thermal loss.
- Insulate upstream component to reduce heat transfer effects.

Exergetic utilization map

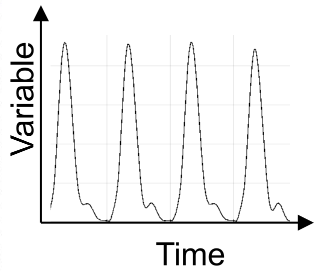


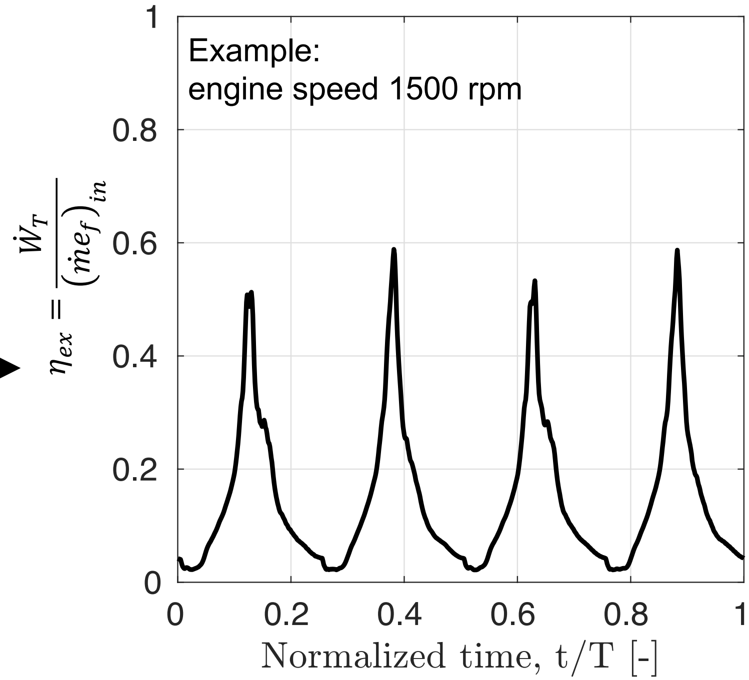
- Constructed from turbine performance maps data.
- Incorporate into 1D engine model.
- Quick assessment of available energy usage for different
  1. Turbochargers
  2. Configurations (e.g. multi-stage)
  3. Exhaust valve strategies

Exergetic utilization under pulsating flow



Courtesy of Volvo cars





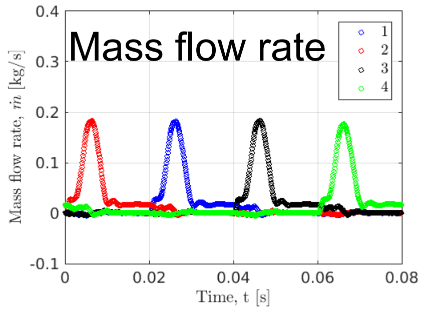
- Constructed from GT-Power time-varying output data.

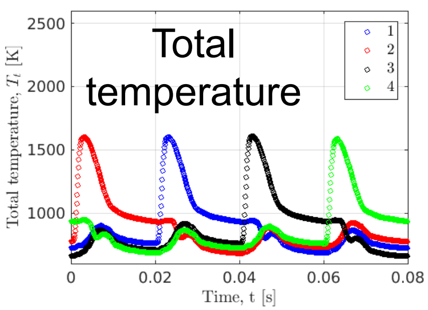
Highlights & future plan

Research questions	Highlights
1. How heat transfer affects turbine performance? 2. What are the heat transfer losses? 3. How can we quantify the losses & the effectiveness of resources utilization?	❑ Exergy-based approach. ❑ CFD: detail quantification of losses. ❑ Turbine power reduction << flow exergy lost via heat transfer and irreversibilities. ❑ Upstream component is more sensitive to thermal loss. ❑ 1-D: quick assessment of exhaust energy utilization effectiveness. ❑ Need more effective way to harvest the available exhaust energy (than a single stage turbine).
	Future plan
4. What is the effects of upstream exhaust manifold (e.g. secondary flow) on heat transfer and turbine performance?	❑ Comparison of exergy budget for engine-like pulsatile flow scenario (adiabatic vs. heat transfer) ❑ Flow field analysis to understand the associated physics. ❑ Effects of different exhaust valve strategies.

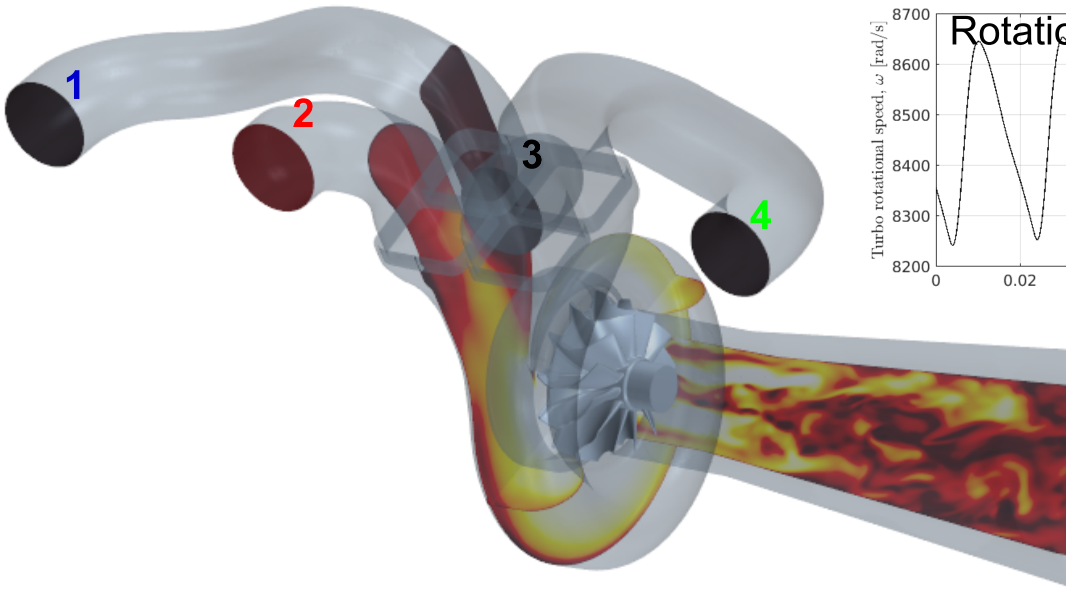
Pulsatile flow computational setup

Inlet boundaries

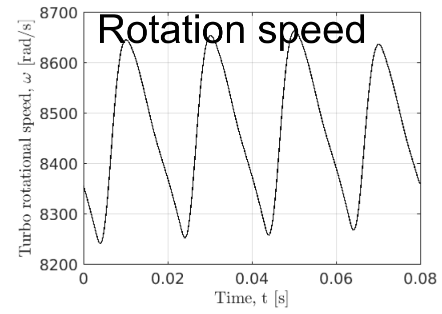




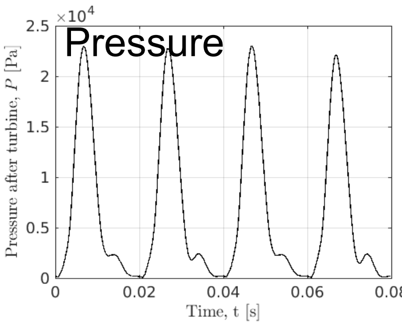
n_{engine}=1500 rpm

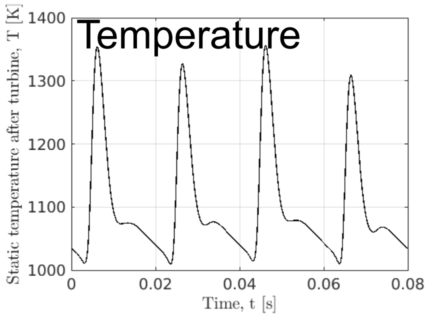


Turbine wheel



Outlet boundary



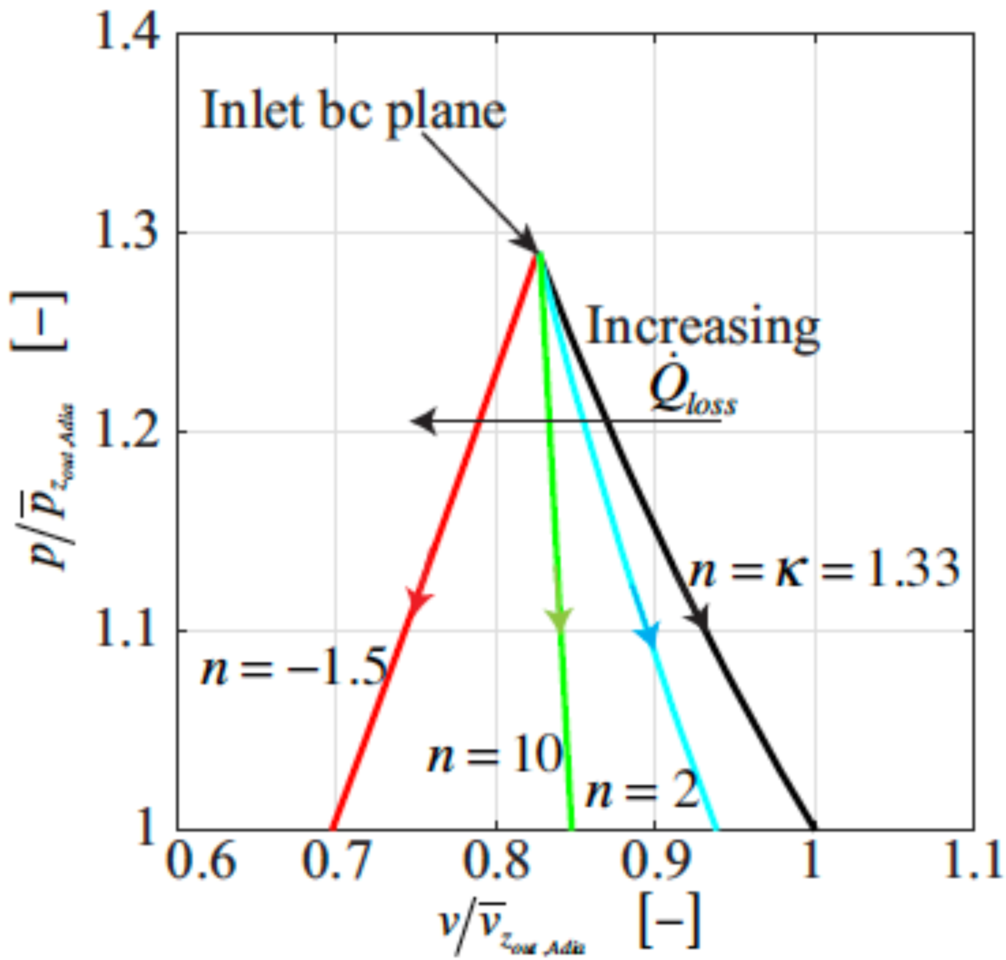


Competence Center for Gas Exchange

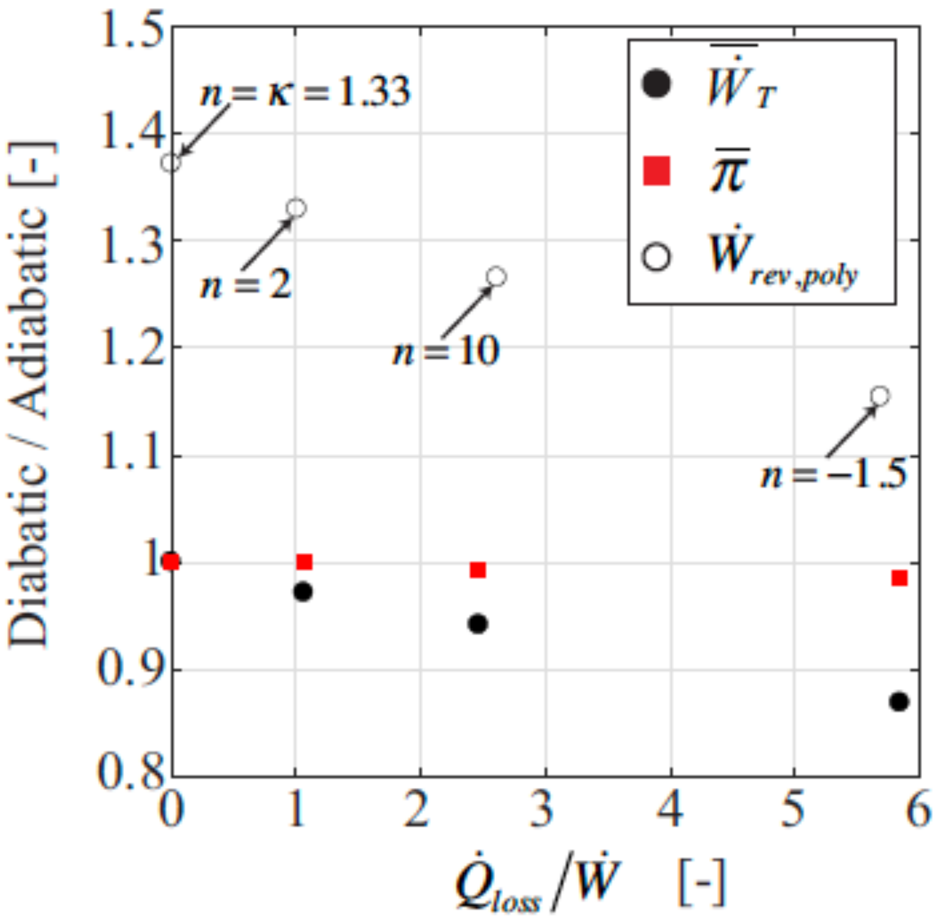
CCGEx

”Charging for the future”

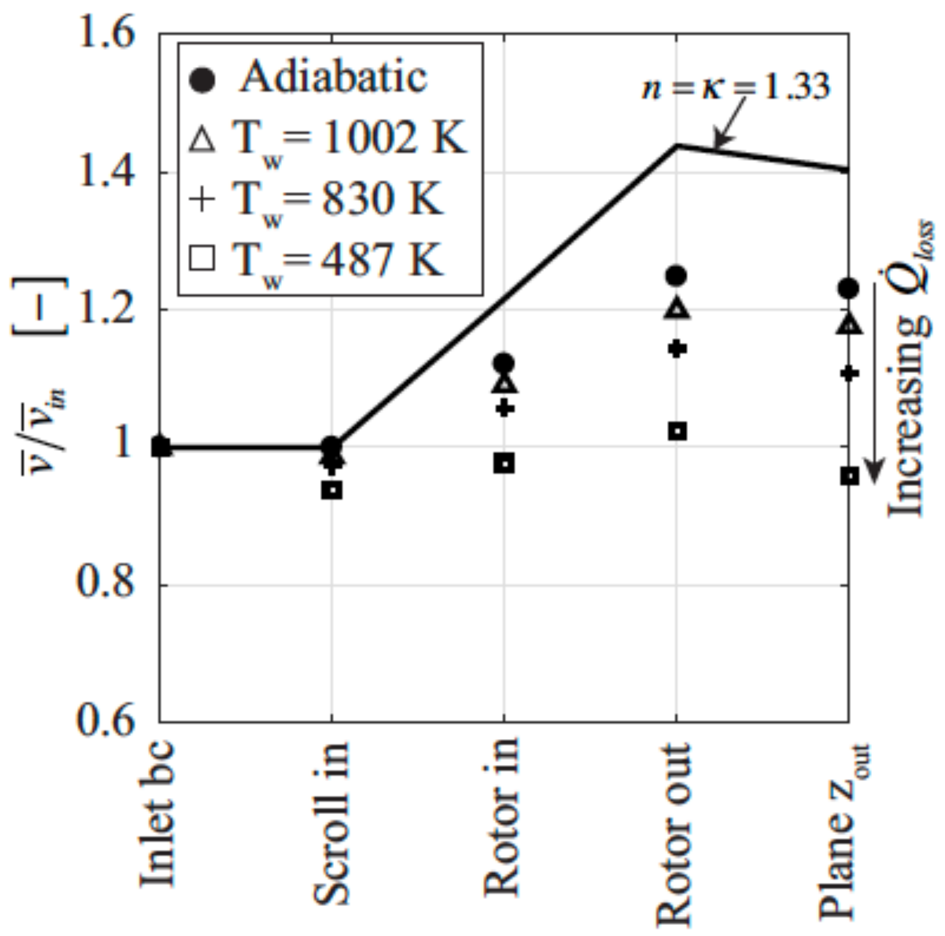
Polytropic gas expansion with heat loss



Performance sensitivity to heat loss



Gas specific volume



Flow exergy equation

$$\overbrace{\underbrace{\frac{d}{dt}\left[\iiint\limits_{V^*(t)} (\rho e_f)\ \mathrm{d}V\right]}_{\text{A}} + \underbrace{\oiint\limits_{S*(t)} \left[\rho e_f \left\{(\vec{u} - \vec{u}_b)\cdot\vec{n}\right\}\right]\ \mathrm{d}S}_{\text{B}}}^{\frac{D}{Dt}\left[\iiint_{V(t)}(\rho e_f)\ \mathrm{d}V\right]} =$$

$$-\underbrace{\oiint\limits_{S^*(t)} \left[\vec{r}\times\left(\vec{f}_{pressue} + \vec{f}_{shear}\right)\cdot\vec{\Omega}\right]\ \mathrm{d}S}_{\text{C}}$$

$$+\underbrace{\oiint\limits_{S^*(t)} \left[\left(1 - \frac{T_o}{T_b}\right)(\vec{q}\cdot\vec{n})\right]\ \mathrm{d}S}_{\text{D}}$$

$$-\underbrace{T_o\dot{S}_{gen}}_{\text{E}} + \underbrace{\frac{d}{dt}\left[\iiint\limits_{V^*(t)} p\ \mathrm{d}V\right]}_{\text{F}}\ ,$$

$$-B = (A - F) + C - D + E$$

Entropy generation computation method

$$\dot{S}_{gen,thermal} = \iiint_{V^*(t)} \left[\frac{(k_{mol} + k_{turb})}{T^2} (\nabla T)^2 \right] \mathrm{d}V$$

$$\dot{S}_{gen,viscous} = \iiint_{V^*(t)} \left[\frac{(\mu_{mol} + \mu_{turb})}{T} \Phi \right] \mathrm{d}V$$

$$\Phi = \tau_{ij} \frac{\partial u_i}{\partial x_j} = 2 S_{ij} S_{ij} - \frac{2}{3} S_{kk} S_{kk}$$

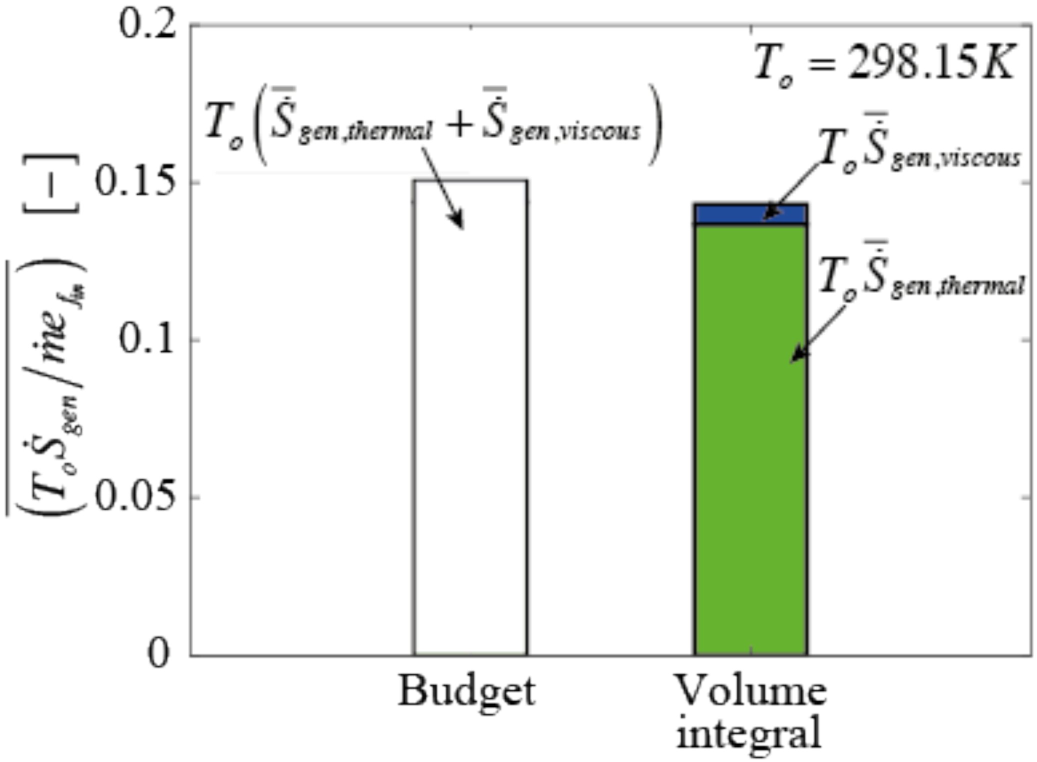
$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial u_j} + \frac{\partial u_j}{\partial u_i} \right)$$

} Volume integral method

$$T_o \dot{S}_{gen} = E = -B - C + D - (A - F)$$

} Budget method

Uncertainty of irreversibilities computation



$$\Sigma = \frac{\dot{S}_{gen,volume\ integral}}{\dot{S}_{gen,budget}}$$

$$\sum \approx 0.7$$