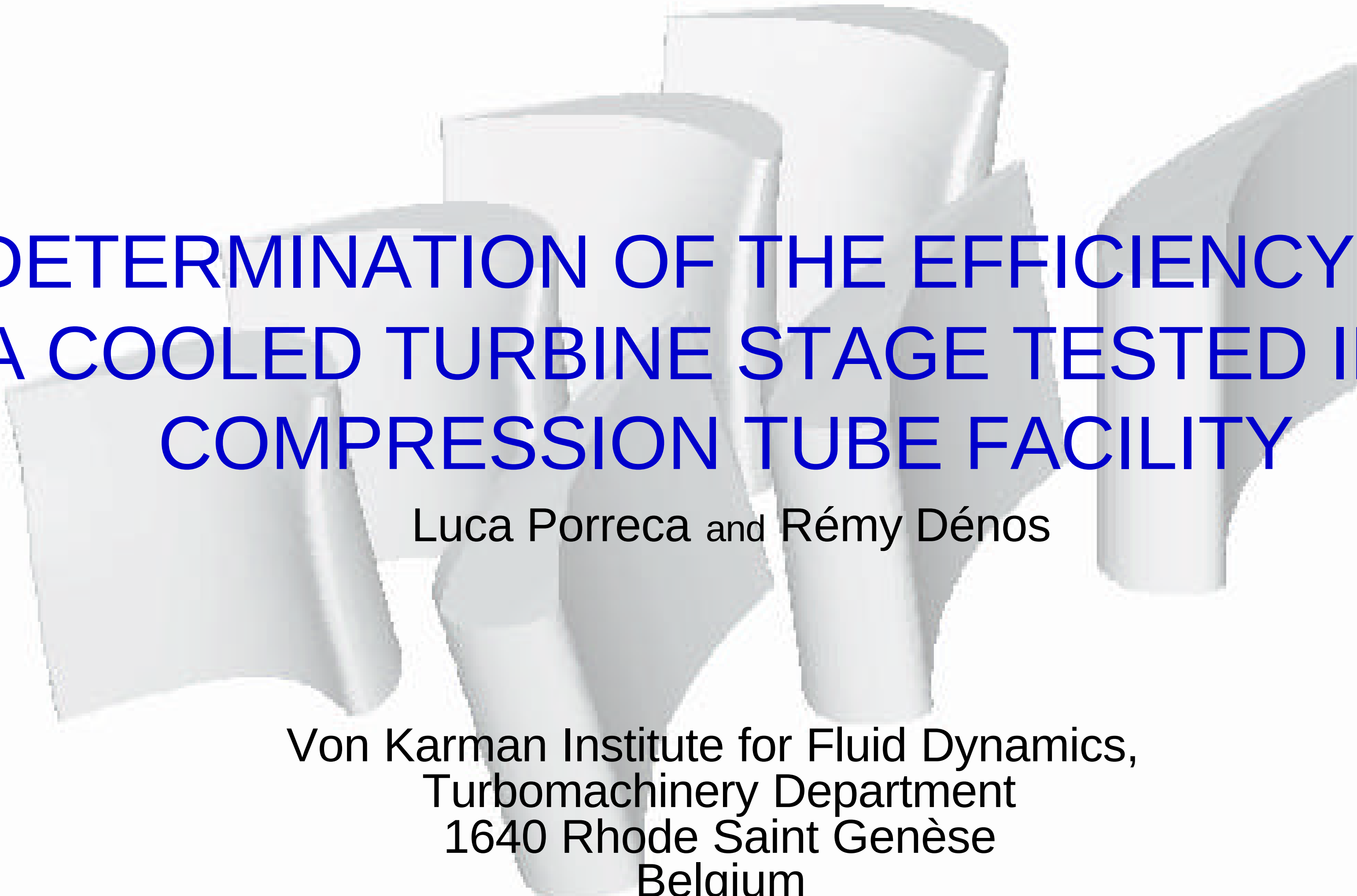

DETERMINATION OF THE EFFICIENCY OF A COOLED TURBINE STAGE TESTED IN A COMPRESSION TUBE FACILITY

Luca Porreca and Rémy Dénos

Von Karman Institute for Fluid Dynamics,
Turbomachinery Department
1640 Rhode Saint Genèse
Belgium
Contact: denos@vki.ac.be

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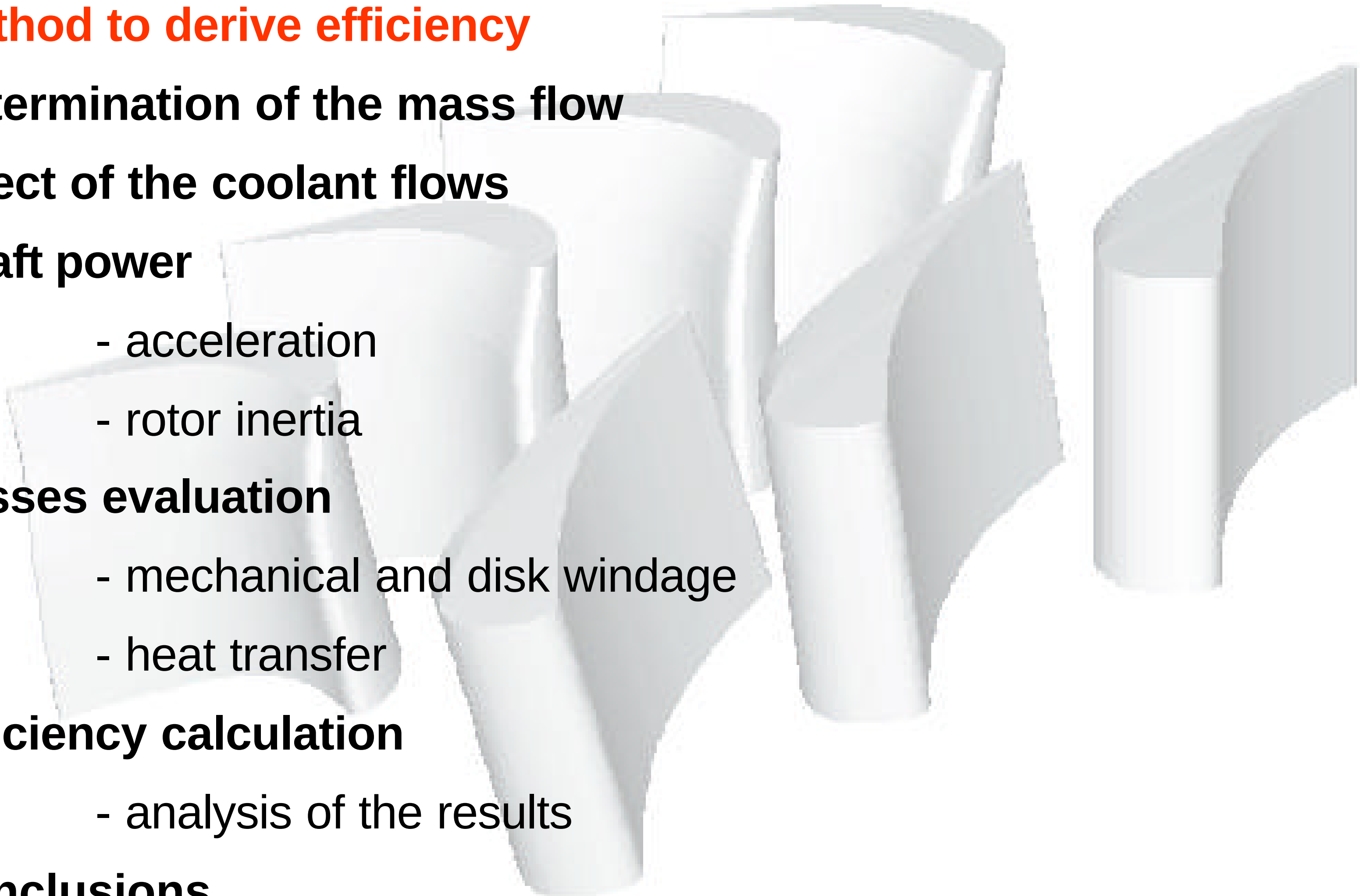
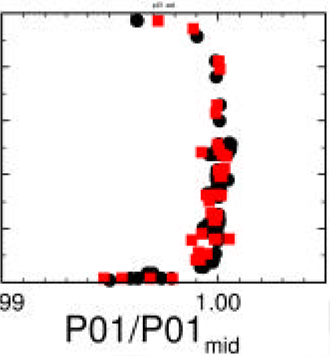
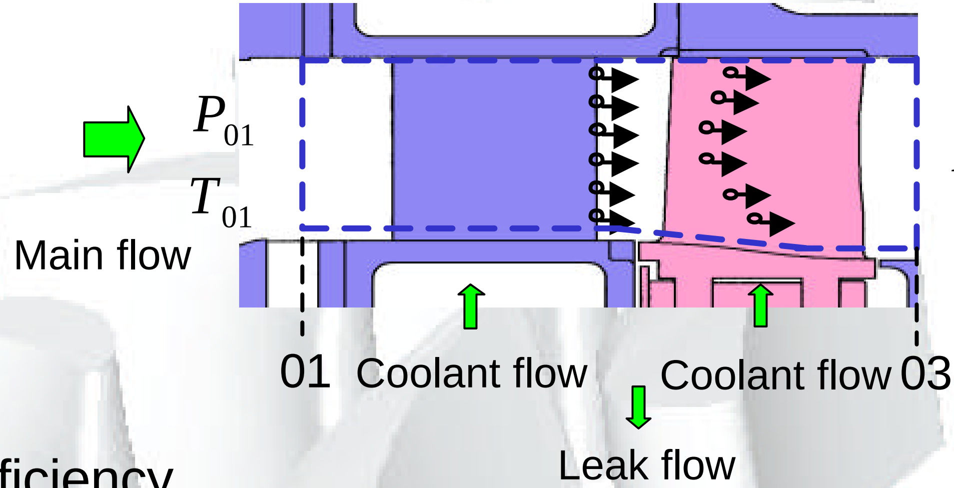
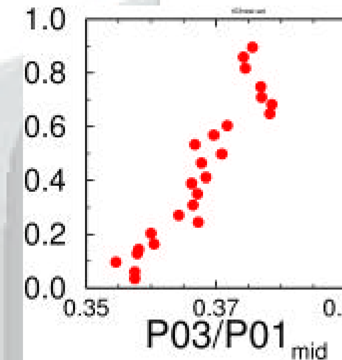


Definition of the efficiency: Mechanical Method







Areodynamic efficiency

$$h_{areo} = \frac{P_{shaft} + P_{mech} + P_{wind} + P_{Heat}}{\left[\iint_{Surface01} \dot{m}_{01} C_p T_{01} ds + \dot{m}_{Coolants} C_p T_{Coolants}\right] - \left[\iint_{Surface03} \dot{m}_{03} C_p T_{03,is} ds + \dot{m}_{leaks} C_p T_{leaks}\right]}$$

with $T_{03,is} = T_{01} \left(\frac{P_{03}}{P_{01}}\right)^{\frac{g-1}{g}}$

Determination of the mass flow

The stage mass flow is calculated using a model of the facility

Results for 3 operating conditions:

1 and ½ stage	Ct3 Model
0% rotor cooling [kg/s]	15.27
2% rotor cooling [kg/s]	15.35
3% rotor cooling [kg/s]	15.36
Uncertainty	+/- 1.6 %
Dispersion	+/- 0.21 %

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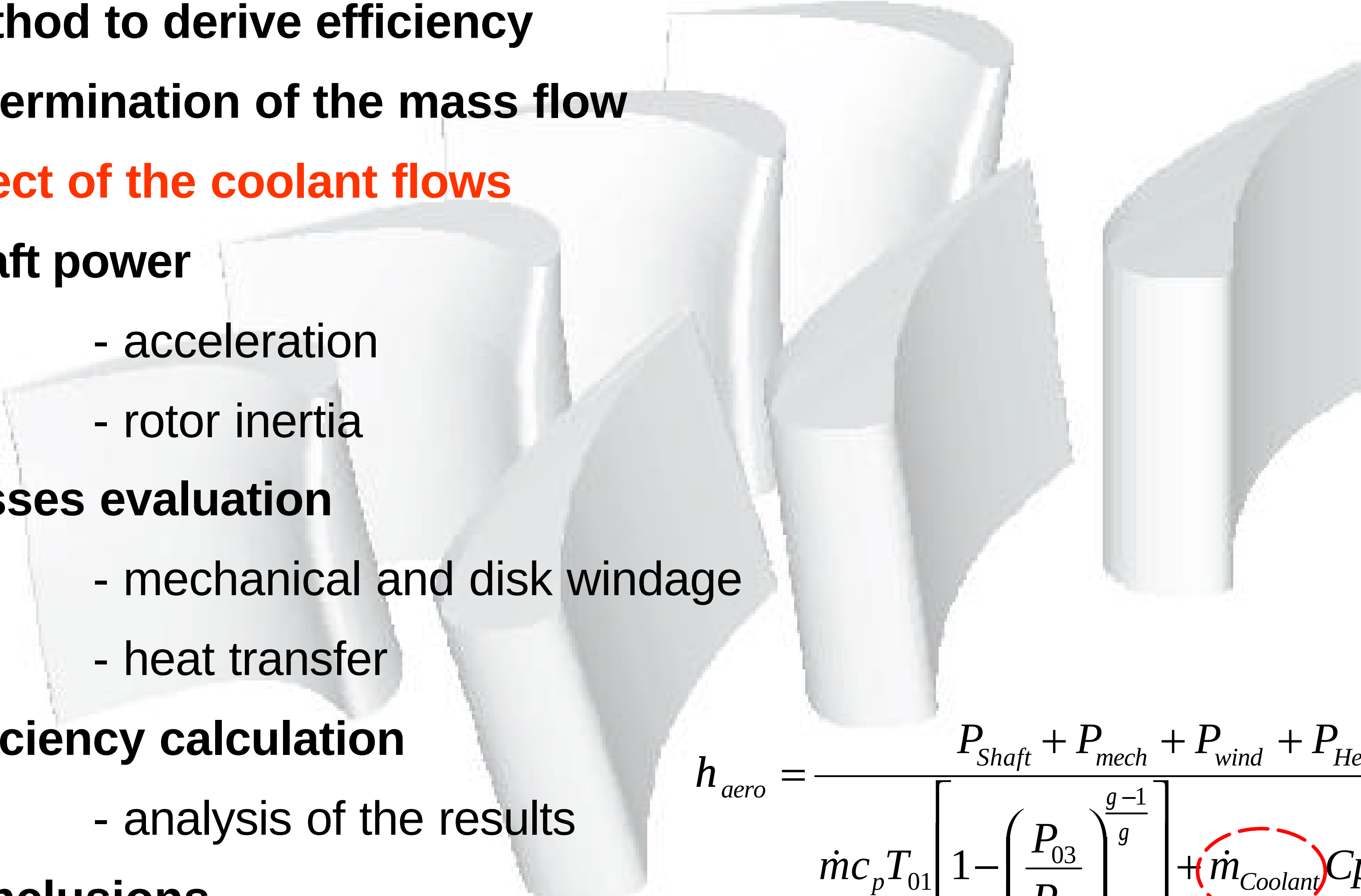
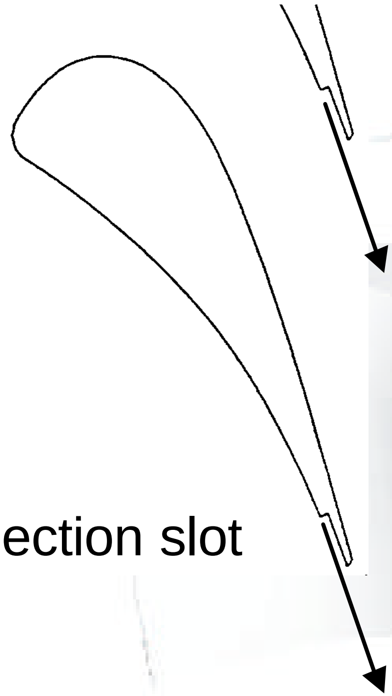


$$h_{aero} = \frac{P_{Shaft} + P_{mech} + P_{wind} + P_{Heat}}{\dot{m} c_p T_{01}\left[1 - \left(\frac{P_{03}}{P_{01}}\right)^{\frac{g-1}{g}}\right] + \dot{m}_{Coolant} Cp \Delta T_{0Coolant}}$$

Stator Coolant

he NGV internal coolant flow is taken into account:



jection slot

- Isentropic power:

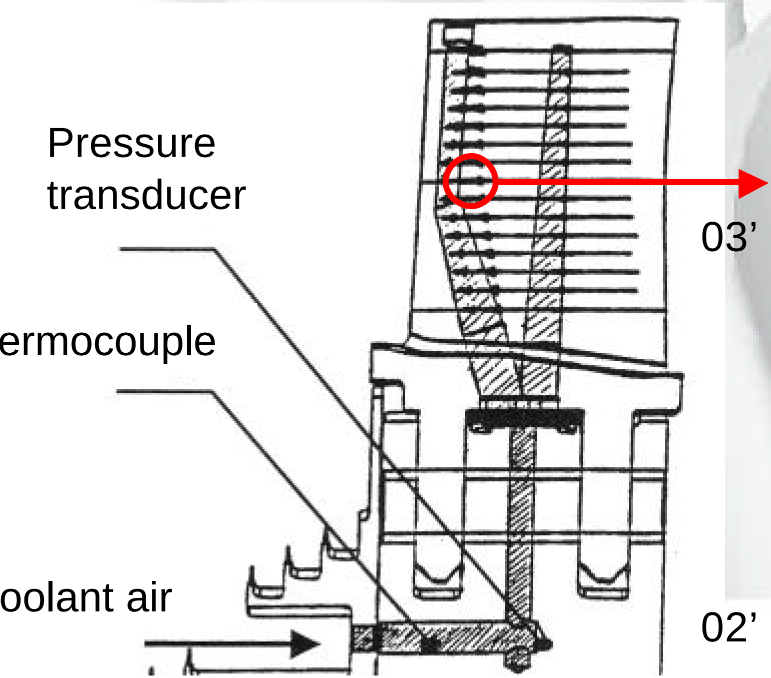
$$P_{is} = \dot{m}_{Stator} Cp(T_{01} - T_{03,is}) + \dot{m}_{StatCool} Cp(T_{0C} - T_{03,is})$$

	With cooling	*Without cooling*
Inlet mass flow [kg/s]	10.27	10.6
Coolant mass flow[kg/s]	0.33 (3%)	0
Real power [kW]	1023.3	1023.3
Isentropic power [kW]	1094.5	1103.3
Efficiency at midspan	0.935	0.927
Difference %	~ 0.9 %	

Rotor Coolant

he rotor film coolant flow is taken into account:

- The coolant flow must be mixed with the main flow
- The rotor is performing as a radial compressor
  - the pumping work is taken into account



Test #006 3% condition

Stage mass flow [kg/s]	15.36
Coolant mass flow [kg/s]	0.111 (0.72%)
P real [kW]	1506.3
P isentropic [kW]	1675.27
P pumping [kW]	1.73
T_{02abs} *with cooling*	466.52
T_{02abs} *without cooling*	467.05
h with cooling	0.8991
h without cooling	0.8974

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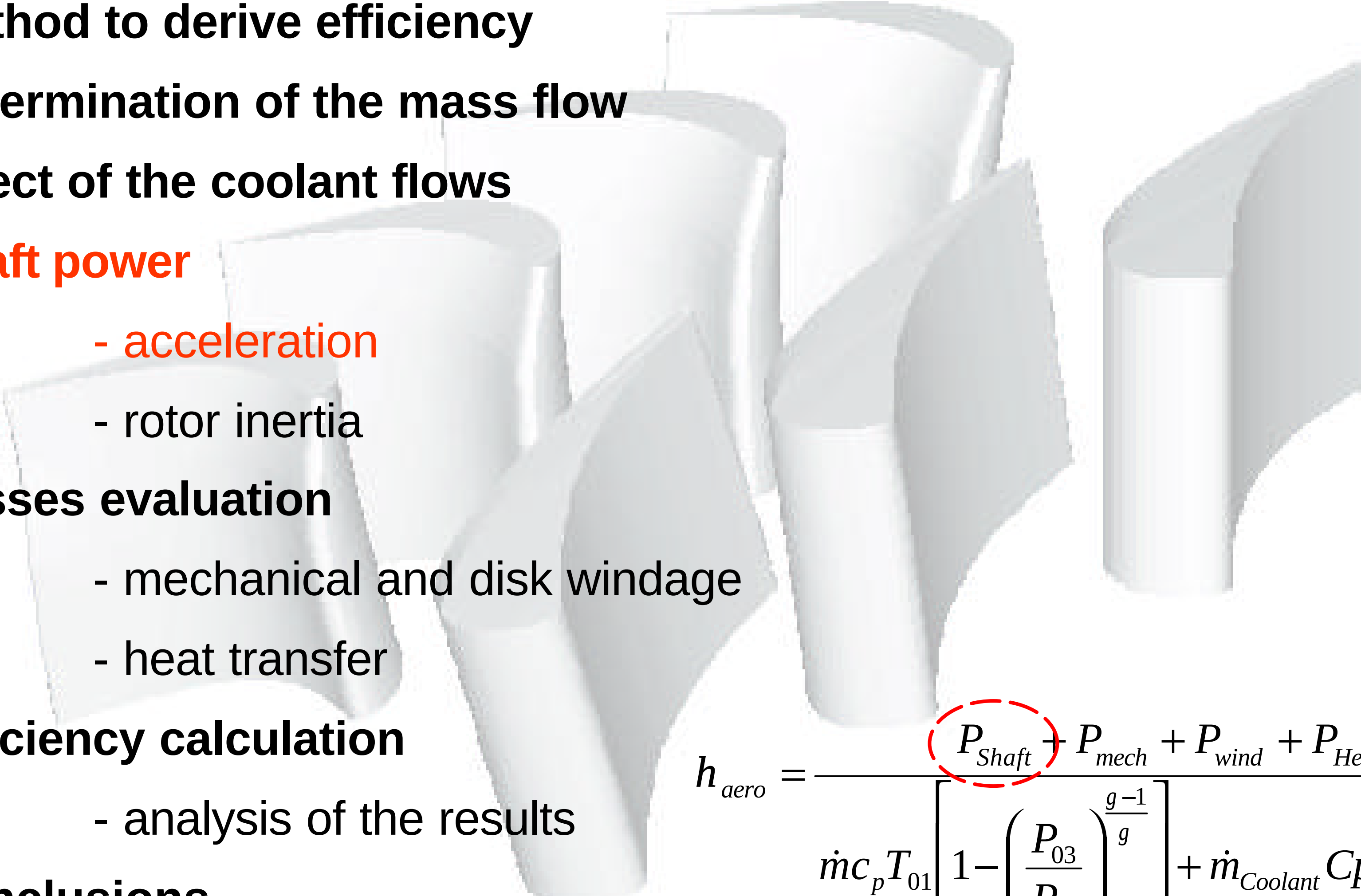


Method to derive efficiency

Determination of the mass flow

Effect of the coolant flows

Shaft power

- acceleration
- rotor inertia

Losses evaluation

- mechanical and disk windage
- heat transfer

Efficiency calculation

- analysis of the results

Conclusions

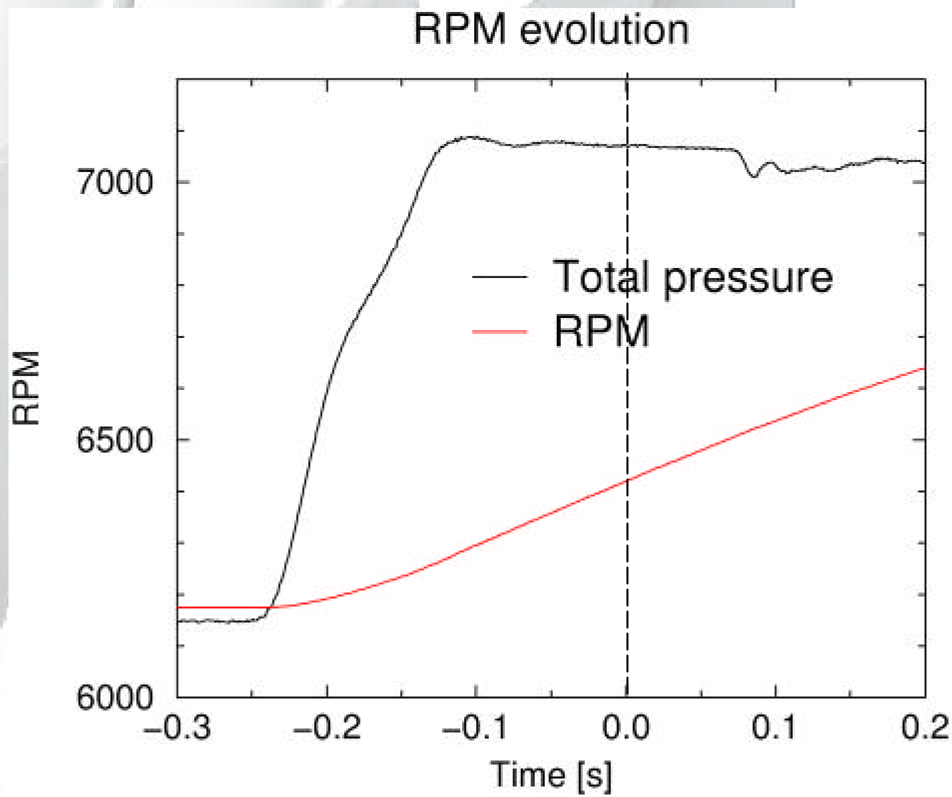
$$h_{aero} = \frac{P_{Shaft} + P_{mech} + P_{wind} + P_{Heat}}{\dot{m} c_p T_{01}\left[1 - \left(\frac{P_{03}}{P_{01}}\right)^{\frac{g-1}{g}}\right] + \dot{m}_{Coolant} Cp \Delta T_{0Coolant}}$$

Rotor acceleration

No power absorption system

Rotor is accelerated during the test time

Shaft power ➡ $P_{Shaft} = I \dfrac{\partial w}{\partial t} w$



Acceleration is derived by a linear fitting

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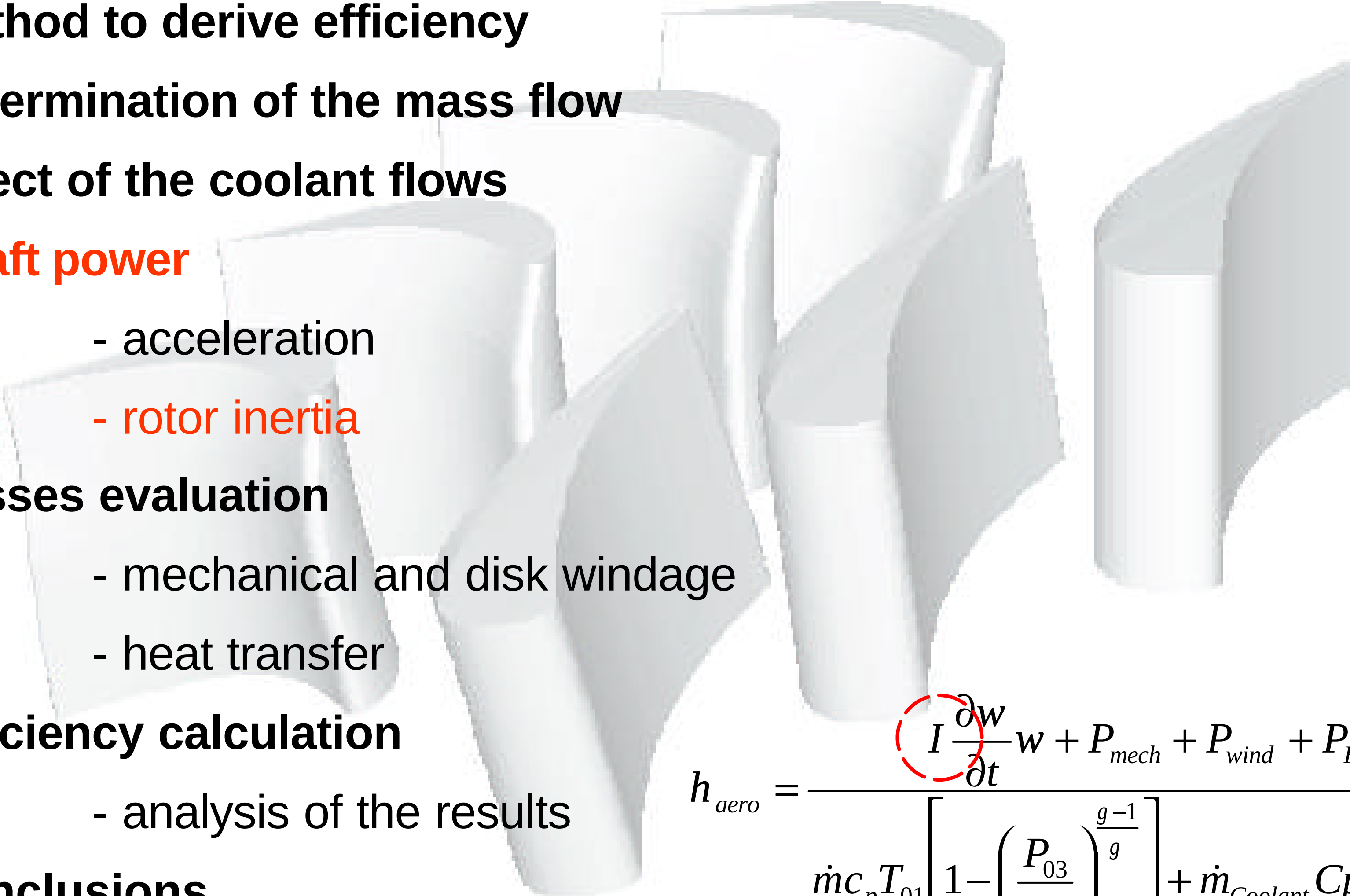
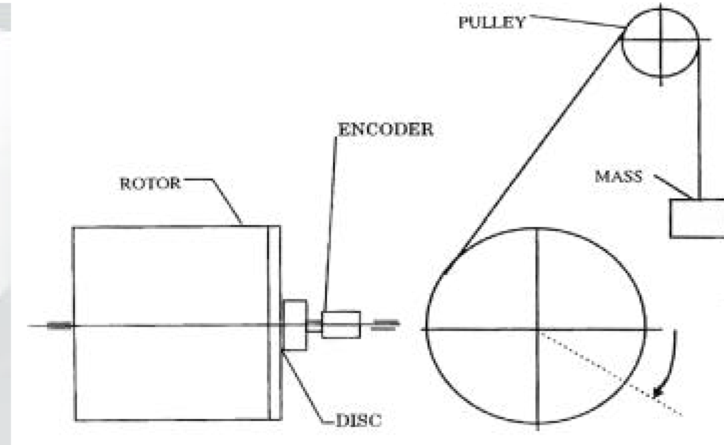


$$h_{aero} = \frac{I\frac{\partial w}{\partial t}w + P_{mech} + P_{wind} + P_{Heat}}{\dot{m}c_p T_{01}\left[1 - \left(\frac{P_{03}}{P_{01}}\right)^{\frac{g-1}{g}}\right] + \dot{m}_{Coolant} Cp\Delta T_{0Coolant}}$$

Rotor inertia evaluation

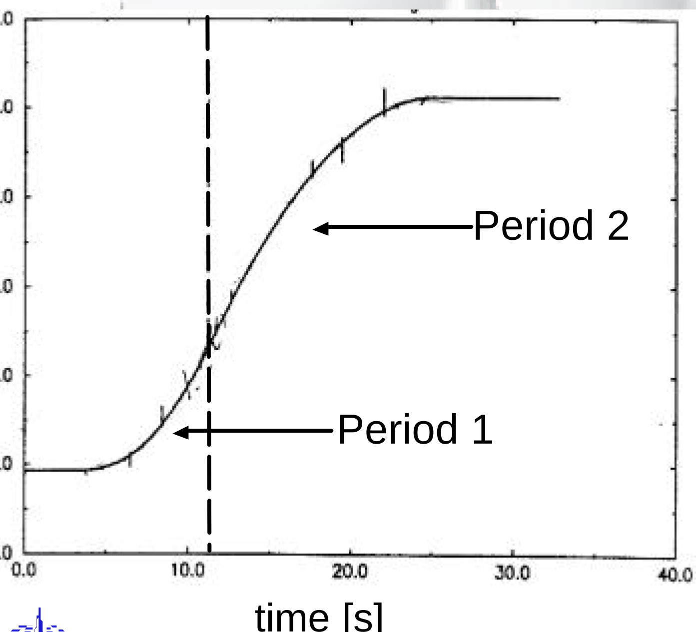
he inertia of the cooled rotor is evaluated:

Experimental set-up:



Period 1: The mass is falling down, the rotor is accelerated.

Period 2: The mass is laying in the floor, the rotor is decelerated by the mechanical friction.



➡ Quadratic regression coefficiencts from th periods 1 and 2 *(Paniagua 1997)*

- *Results:*

- Rotor inertia = 17,715 kg*m^2 disp = +/- 0.4

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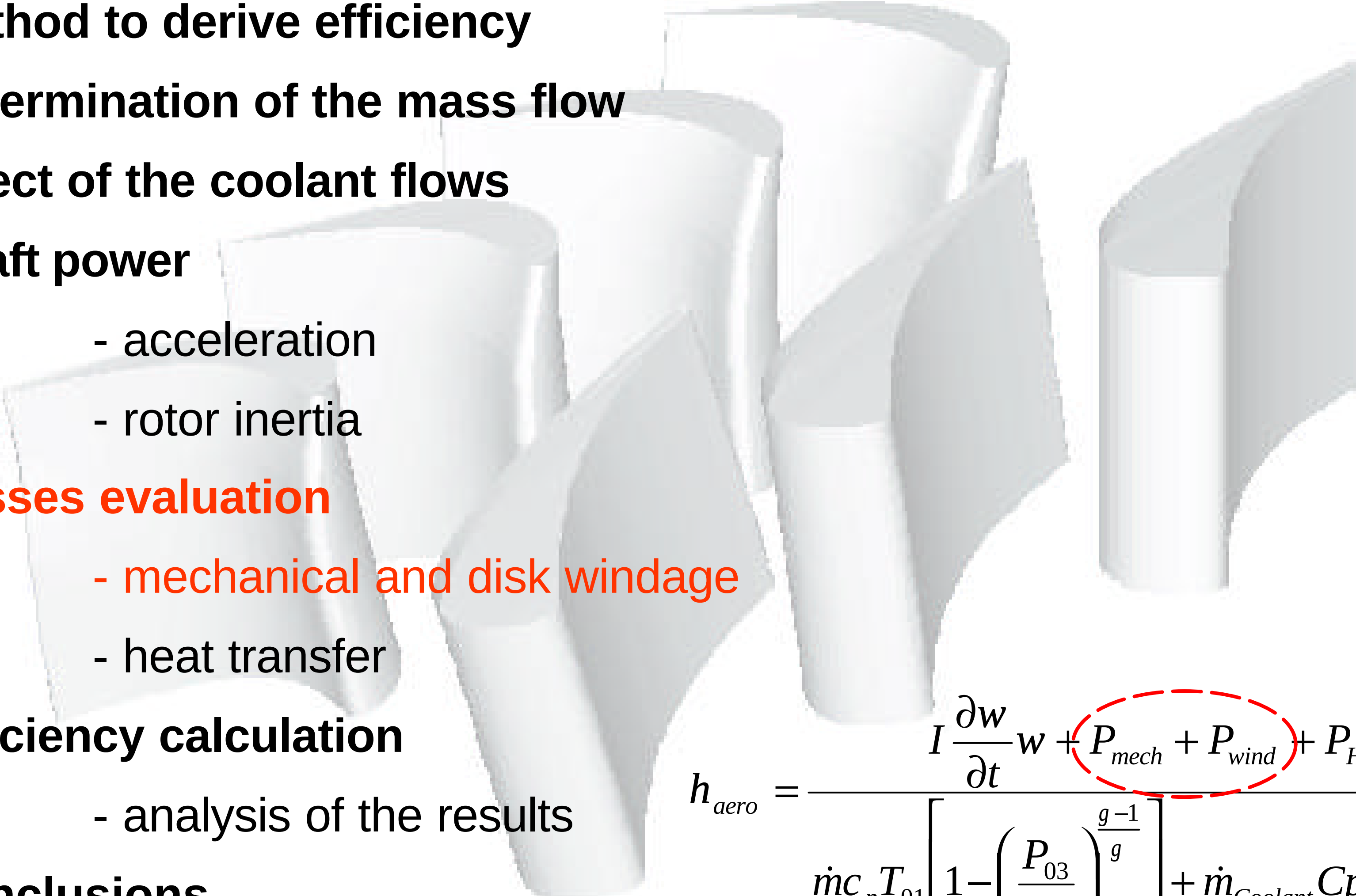
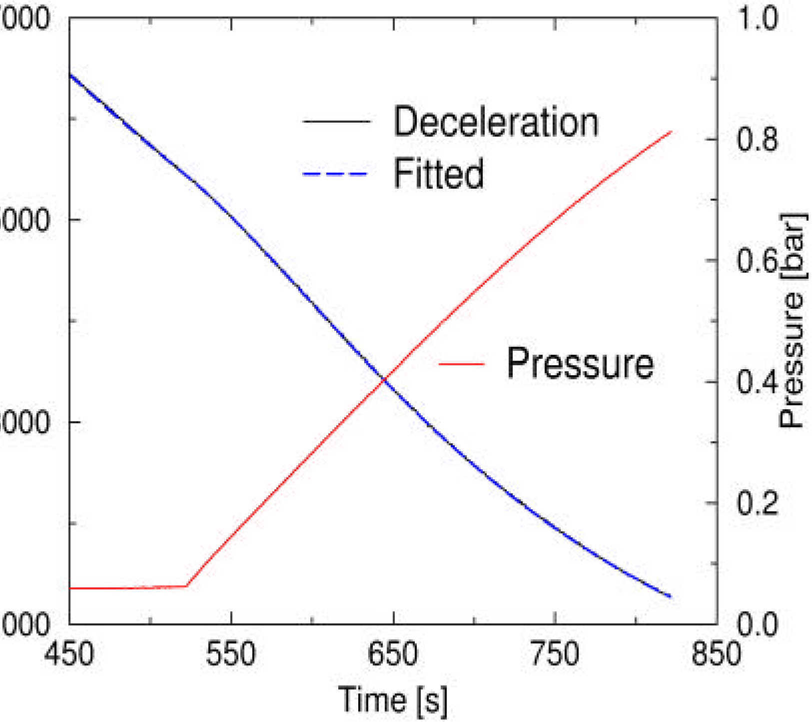


$$\eta_{aero} = \frac{I\dfrac{\partial w}{\partial t}w + P_{mech} + P_{wind} + P_{Heat}}{\dot{m}c_pT_{01}\left[1-\left(\dfrac{P_{03}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}}\right] + \dot{m}_{Coolant}Cp\Delta T_{0Coolant}}$$

Mechanical losses



- Free deceleration of the rotor due to th losses:

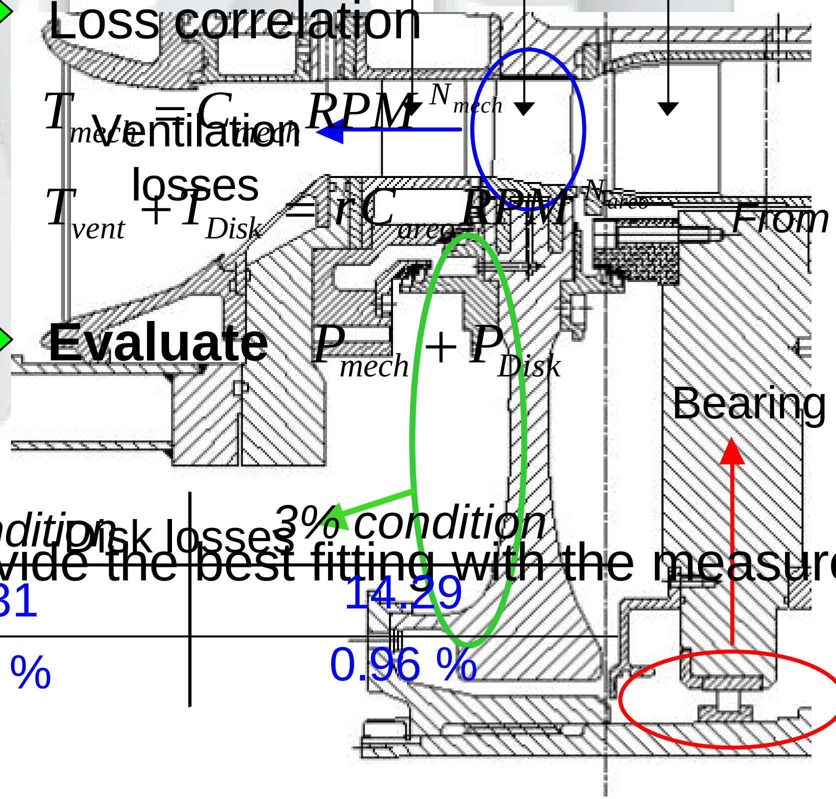
$$P_{Loss} = P_{mech} + P_{Disk} + P_{ventilation}$$

- Loss correlation

$$T_{mech} = C_{mech} RPM^{N_{mech}}$$

$$T_{vent} + T_{Disk} = r C_{area} RPM^{N_{area}}$$

- **Evaluate** $P_{mech} + P_{Disk}$



Numerical optimisation procedure:

- Find the loss coefficients which provide the best fitting with the measured f deceleration

	0% condition	3% condition
Tot Power [kW]	14.31	14.29
% of tot power	0.93 %	0.96 %

- Axial loading is taken into account

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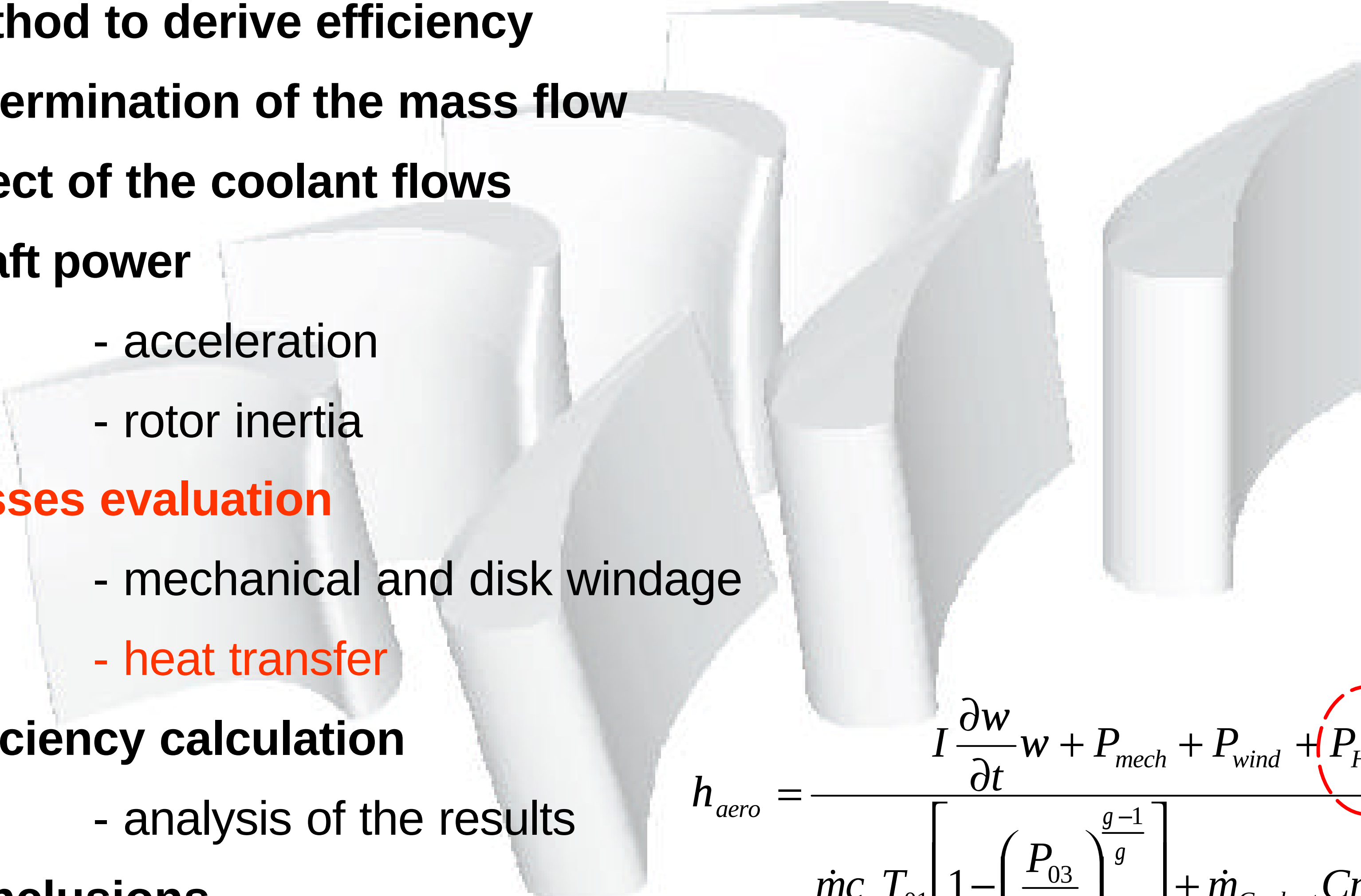

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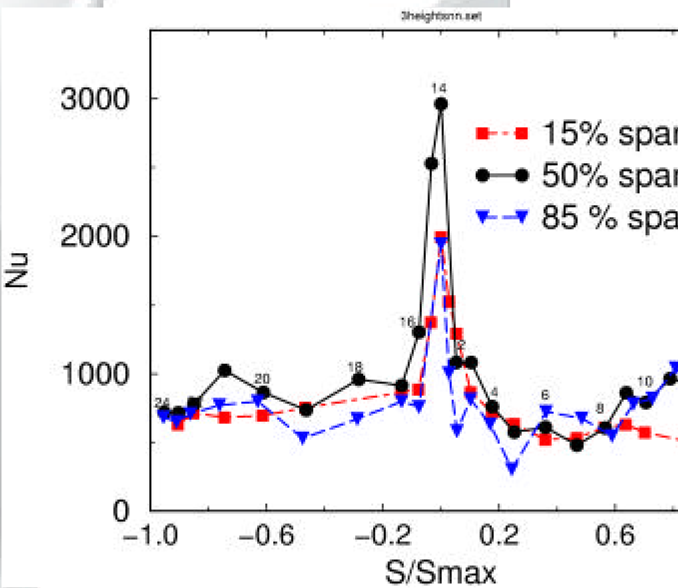
Heat transfer

Evaluate the heat transfer in the control domain (no work is provided)

- Rotor :
  - Measured Tgas and Twall history
  - Heat flux
  - Nusselt distribution *(Didier 2000, Chana 2000)*

➡ heat transfered to the rotor blades
heat transfered to the rotor endwalls



- Stator :

From LS89 measurements *(Arts 1990)*

➡ heat transfered to the stator blades
heat transfered to the stator endwalls

	Re High P/p Nom
Total heat [kW]	52.94
% of Power	3.65 %

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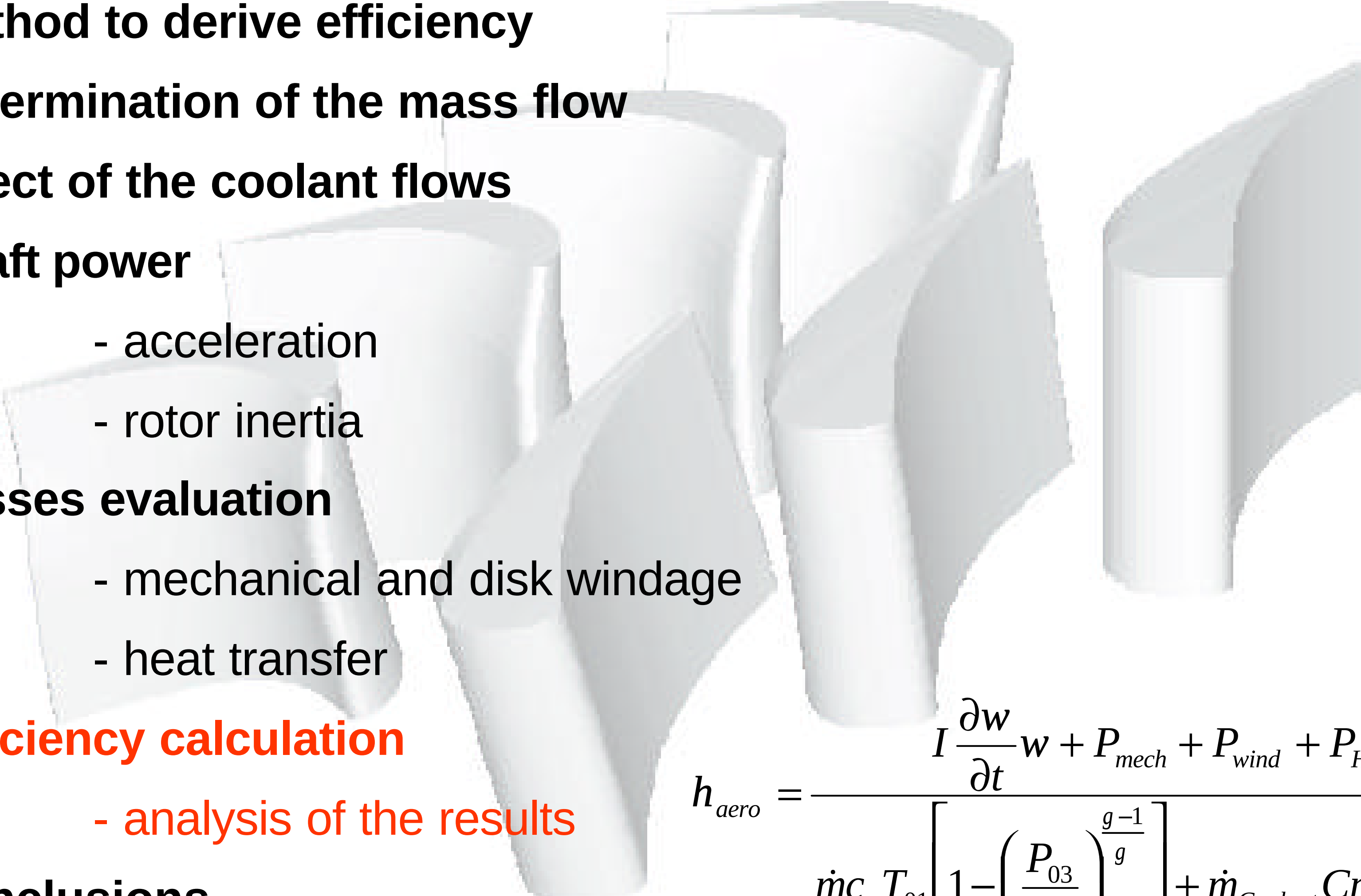
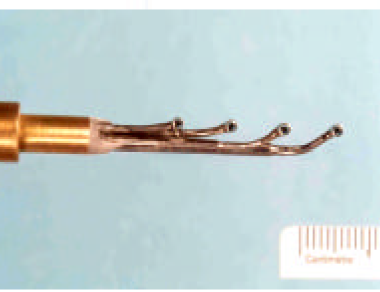


$$h_{aero} = \frac{I\frac{\partial w}{\partial t}w + P_{mech} + P_{wind} + P_{Heat}}{\dot{m}c_pT_{01}\left[1-\left(\frac{P_{03}}{P_{01}}\right)^{\frac{g-1}{g}}\right] + \dot{m}_{Coolant}Cp\Delta T_{0Coolant}}$$

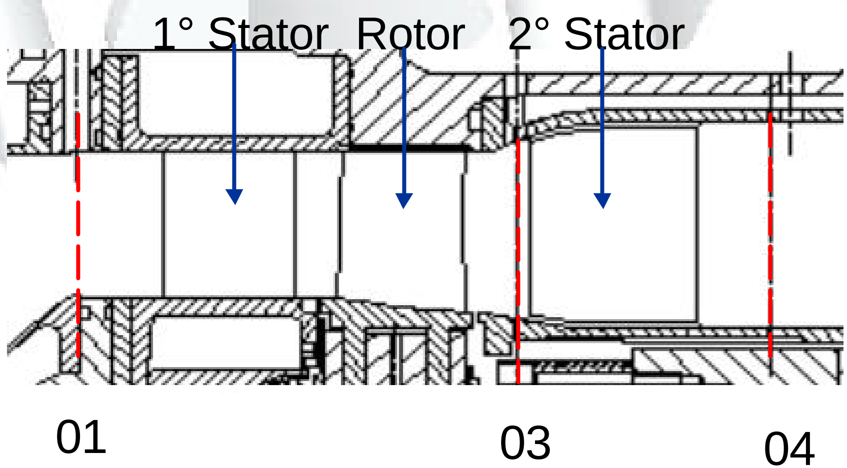
Efficiency results

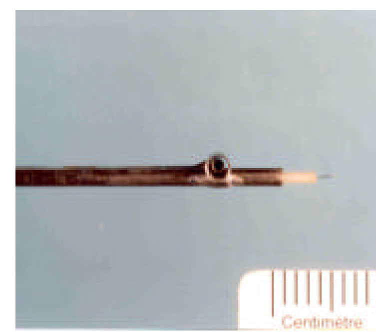
%	T_{01}	P_{01}	Press ratio	Mass flow	P real	P isentr	Acc	Rpm	h
ean	480,74	2,221	2,690	15,265	1526,1	1743,1	1154,5	6513,2	**0,876**
d %	1,11	0,52	2,55	0,19	1,24	2,20	1,26	0,24	**2,30**

- Accurate inlet pressure measurements
- Large dispersion in *p* is provided by the inaccuracy of P_{03}



probe, stage inlet





Kiel+thermocoupl
stage inlet and out

Efficiency results

- Take into account the exit pressure P_{04}: lower test to test dispersion

- Pressure ratio *p* is evaluated as: $p^* = \dfrac{P_{01}}{P_{04} + \Delta P_0}$

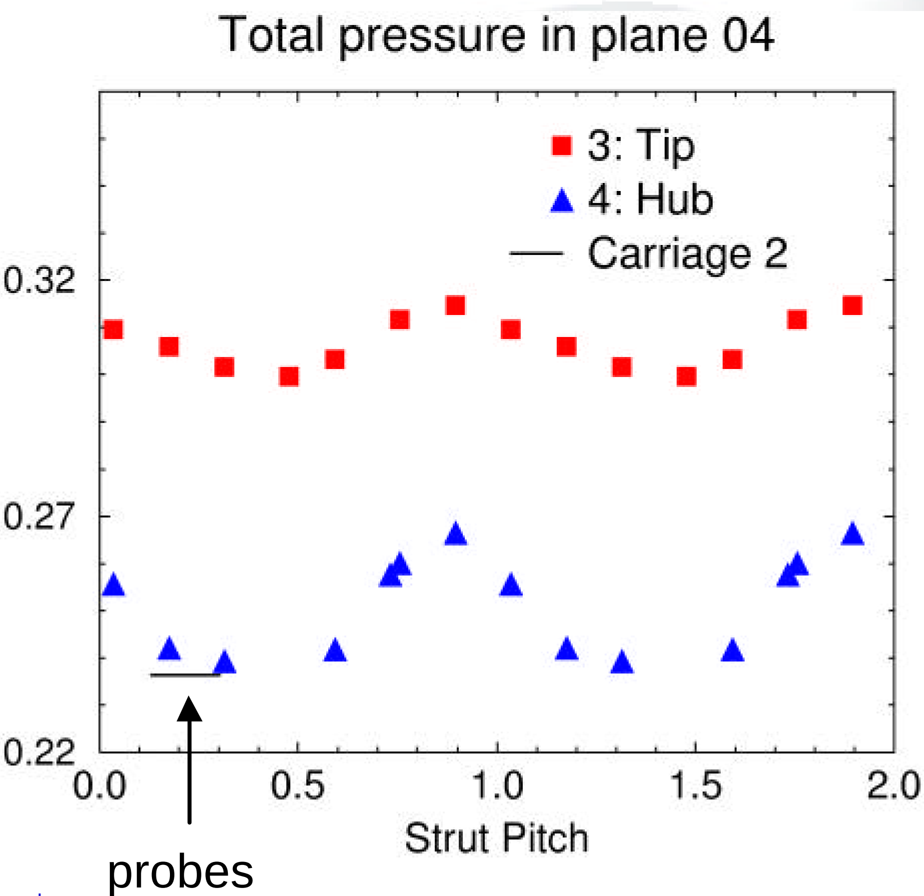
%	T_{01}	P_{01}	Press ratio*	Mass flow	P real	P isentr	Acc	Rpm	*h*
ean	480,74	2,221	2,751	15,26	1526,1	1778,6	1154,5	6513,2	**0,858**
d %	1,11	0,52	0,84	0,19	1,24	1,51	1,26	0,24	**1,35**

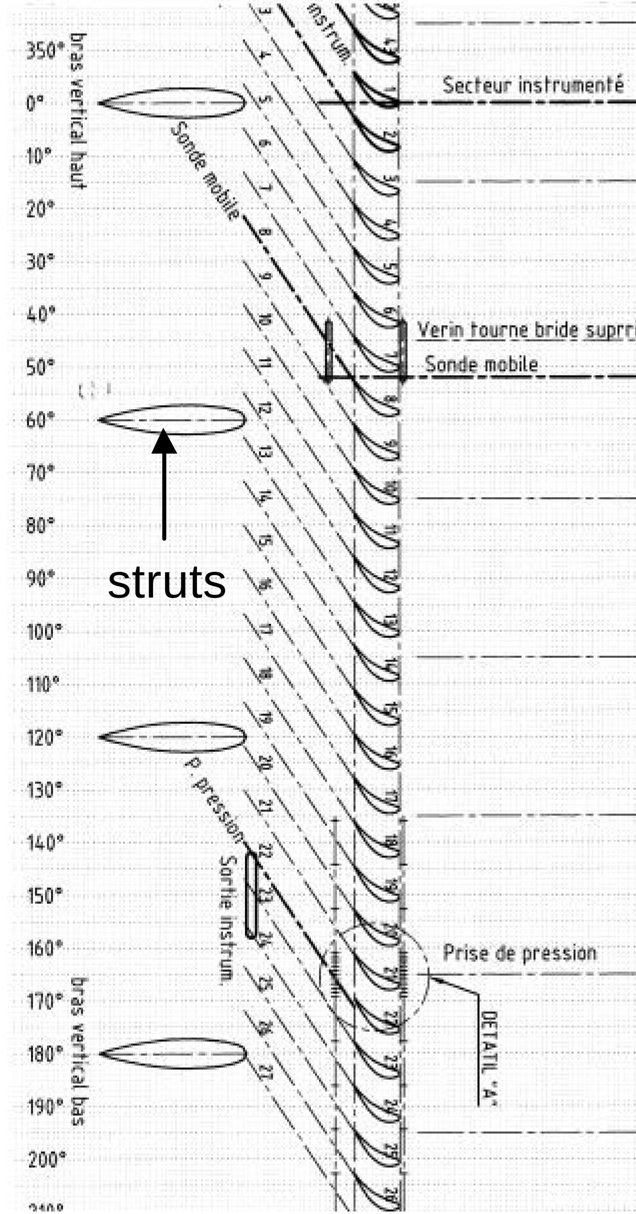
%	T_{01}	P_{01}	Press ratio*	Mass flow	P real	P isentr	Acc	Rpm	*h*
ean	480,66	2,223	2,671	15,36	1488,7	1744,3	1123,6	6520,5	**0,851**
d %	1,06	0,62	0,72	0,23	1,68	1,15	1,95	0,22	**1,34**

Efficiency results

he pressure P_{04} is not uniform

➡ Presence of 6 module struts





Efficiency results

- 1 and ½ stage configuration:

Accurate efficiency evaluation

single test uncertainty +/- 1.44%

Most sensitive parameters:

Pressure ratio - large dispersion detected in P_{03}

- take into account P_{04}

Acceleration - dispersion is affecting sensibly the efficien

Conclusions

complete overall efficiency analysis is presented

- The mass flow is calculated thanks to an accurate modelling of the facility

- The effect of the NGV and rotor coolant flow is analysed:
  - non negligible contribution of the NGV coolant (3% of $\dot{m}_{Stage}$)
  - small influence of the rotor coolant (0.7 % of $\dot{m}_{Stage}$)

- An accurate evaluation of the mechanical losses (~1.4 % of P_{tot}), hea transfer (~3 % of P_{tot}) and rotor inertia is performed

- efficiency is calculated and critical parameters are identified

Future plans

- Improve the accuracy of the exit rotor pressure measuremets
  - investigate the pressure variation at the stage exit
  - install rakes of Kiel probes
- Improve the accuracy of the rotor acceleration
  - investigate the accuray of the actual system
  - design a new RPM detection system if required