Methodologies for the Design and Optimisation of Hydraulic Turbines

Flow Analysis and Design Methodology for Action Turbines

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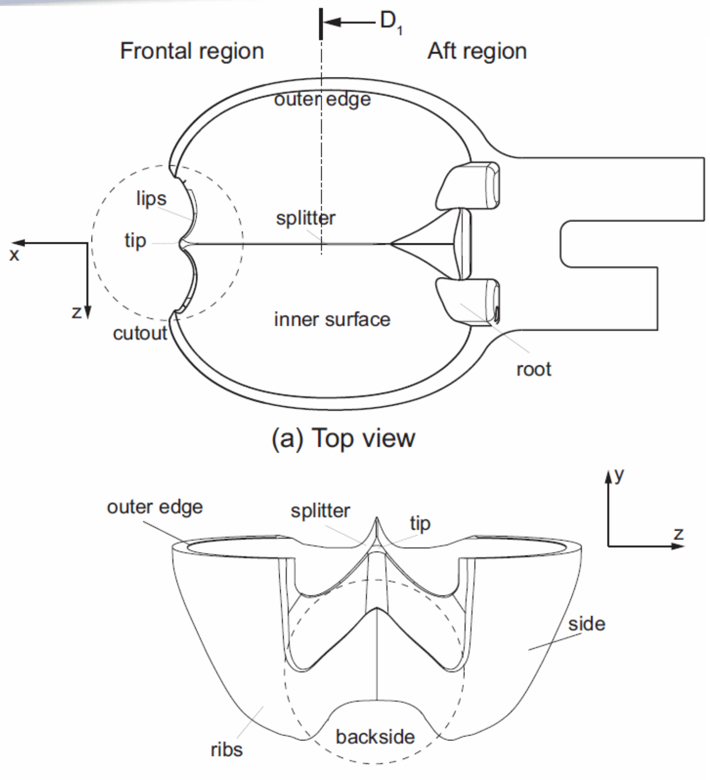
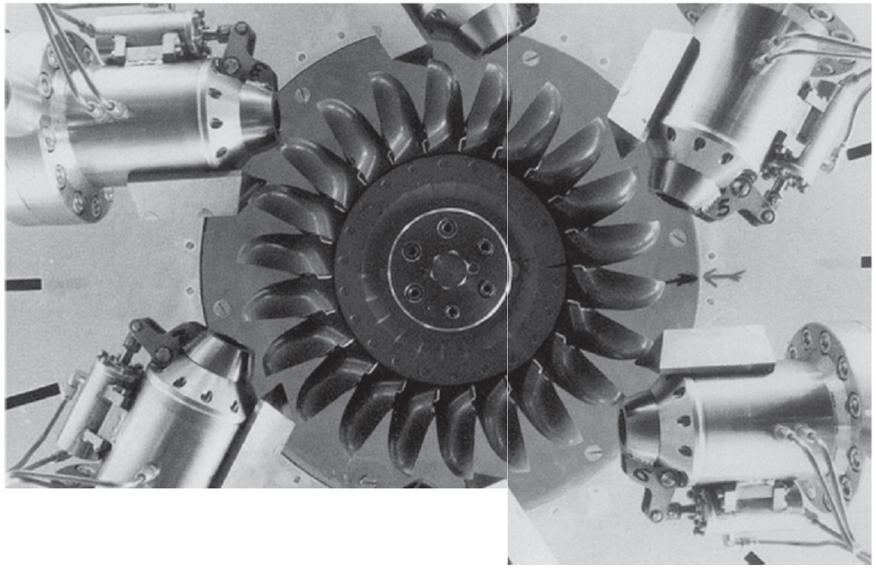
Hydroaction Seminar, Athens, 14 June 2011

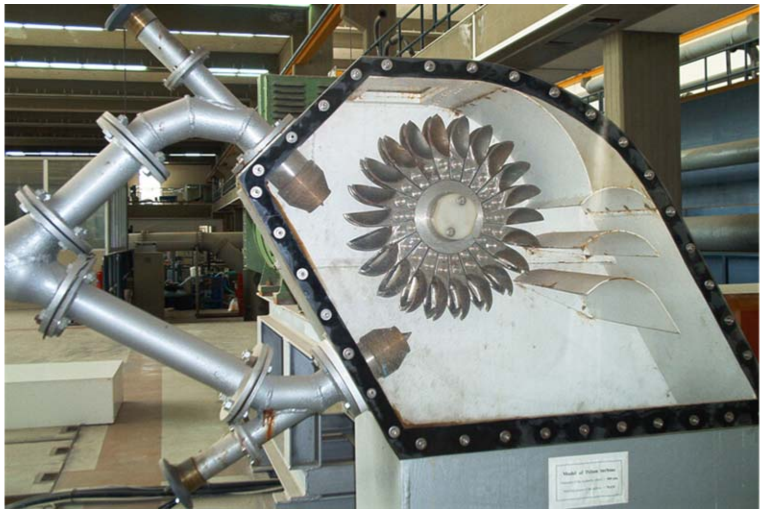
Pelton turbine design



(a) Top view

(b) Front view

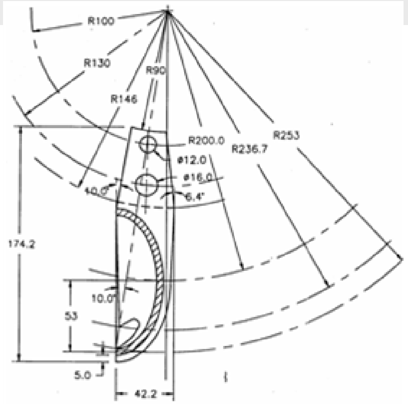


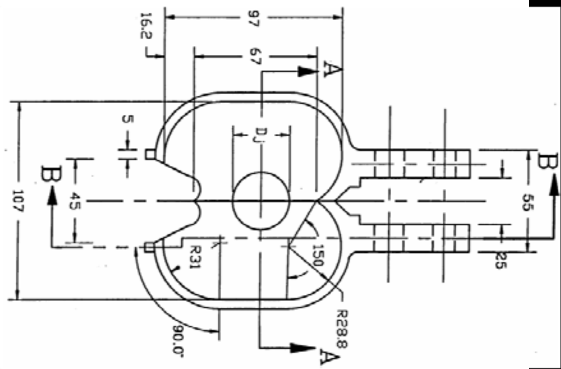


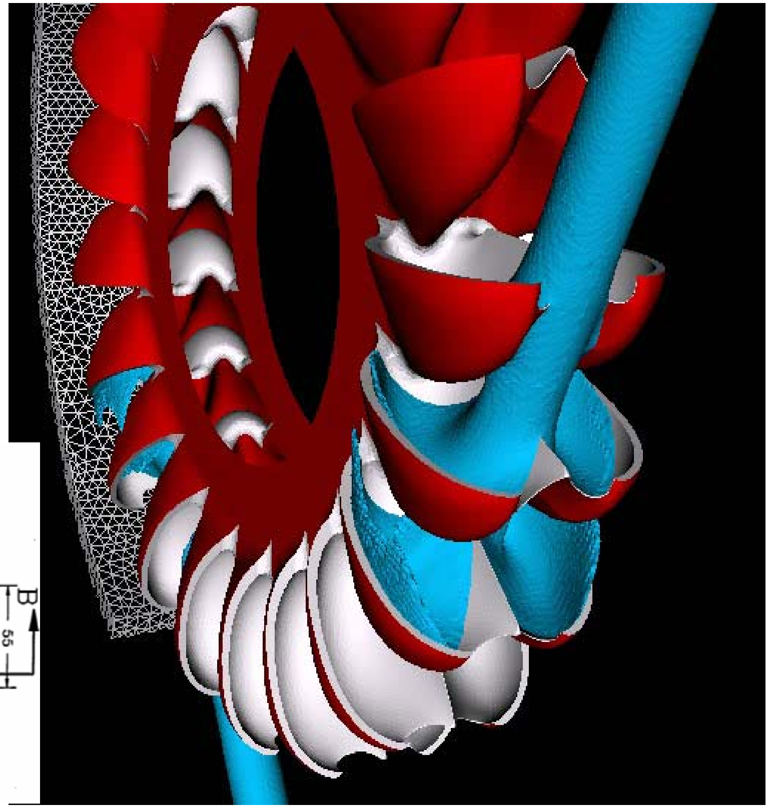
- ❑ Pelton impulse turbines are commonly used in hydroelectric power plants with medium to high water head, as well as in various energy recovery applications (e.g. desalination units, etc.).
- ❑ One - six spear valve injectors. Water jets towards the inner surface of the rotating buckets mounted on the hub.

Pelton turbine design

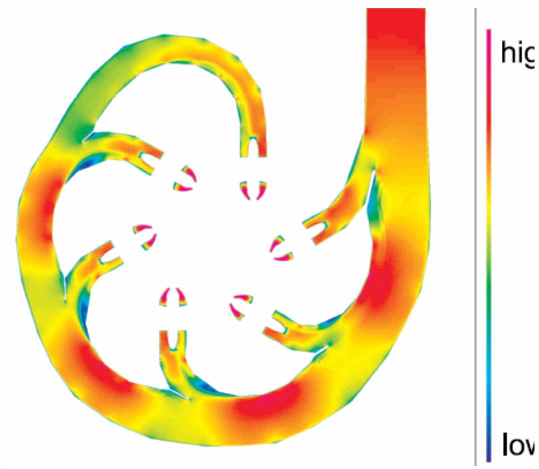
- Since its invention by Lester Pelton and first configurations in the late 19th century, the bucket shape and the performance and efficiency of the runner have substantially improved, mainly based on the accumulated practical experience of manufacturers.
- Design data available in the literature – Publications, books and articles.
- Several advanced experimental and numerical studies – Better understanding of jet-bucke interaction.



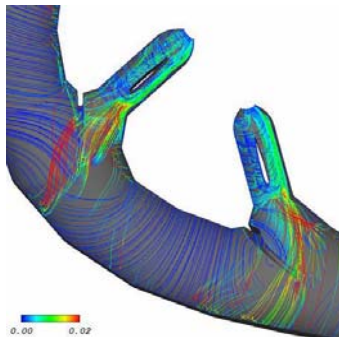


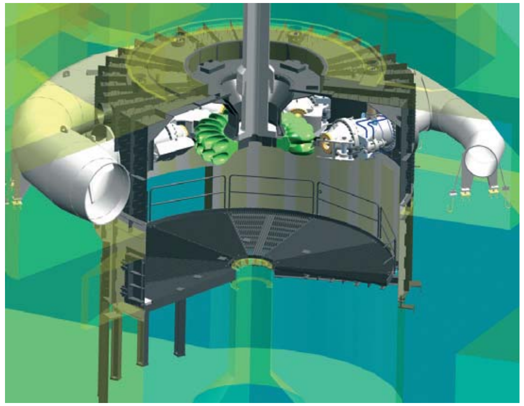


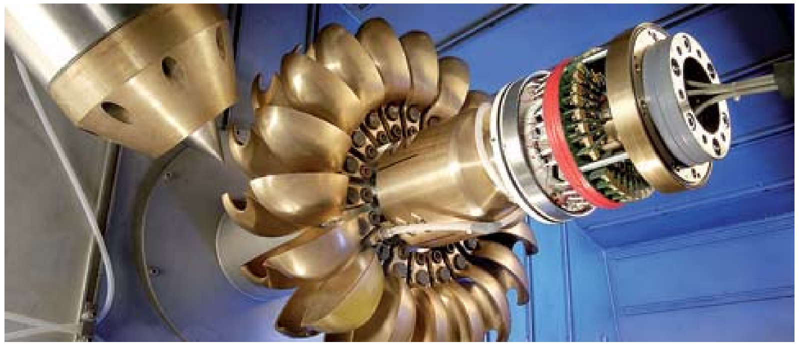
Pelton turbine design

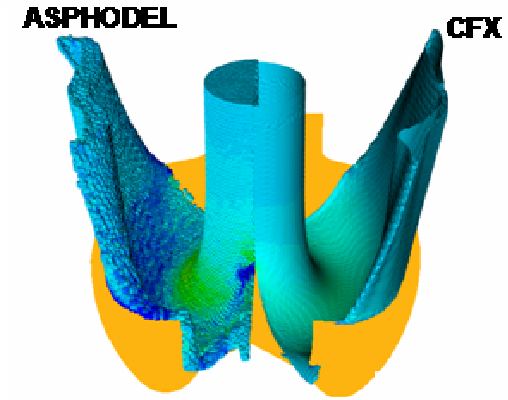


Distribution system







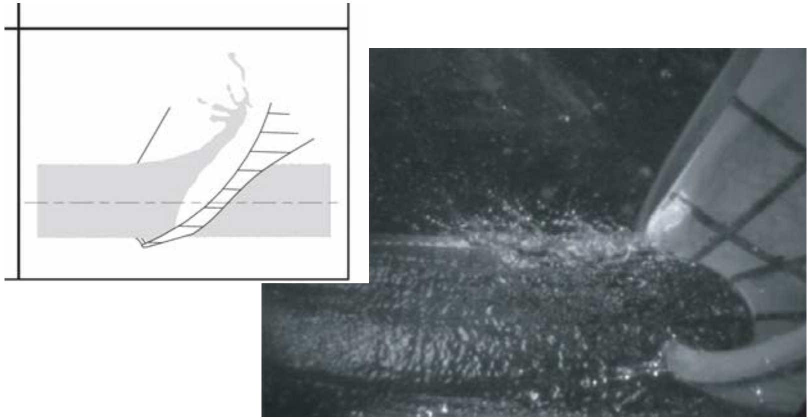


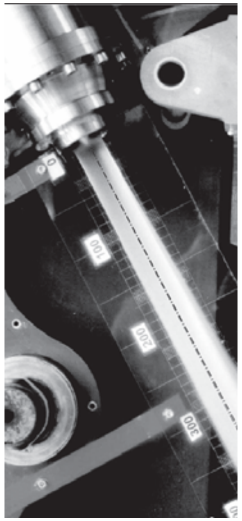
Numerical Tools

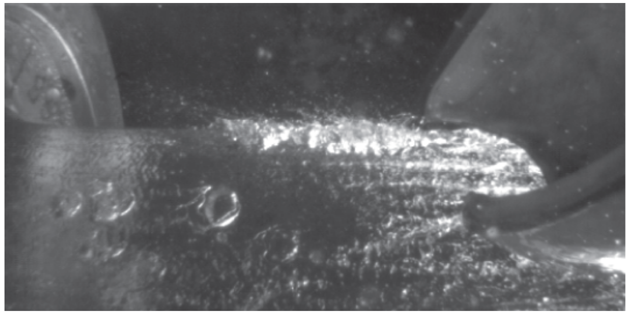
The Hooped
Pelton Turbine

Flow in Pelton runners

- Very complex jet-runner interaction flow: Unsteady, two-phase, free surface flow.
- Flow simulation using modern Eulerian tools possible but very computer demanding.
- Various complex flow mechanisms not well understood and impossible to be modelled.

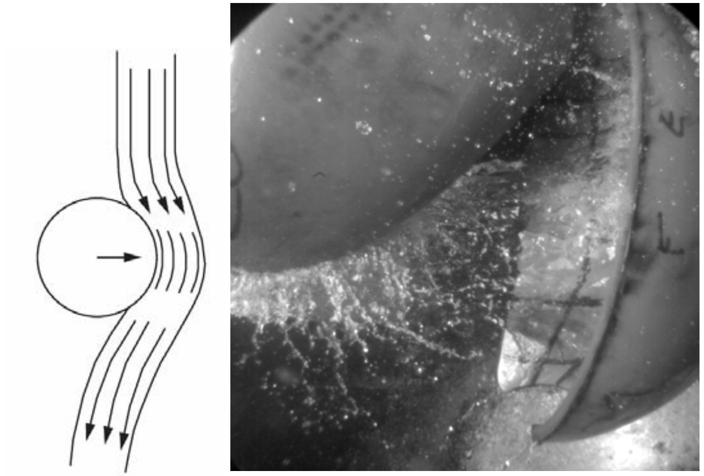


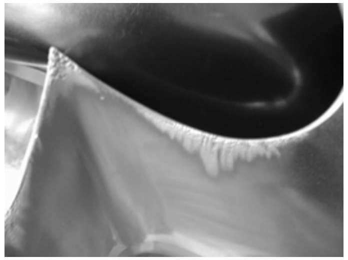


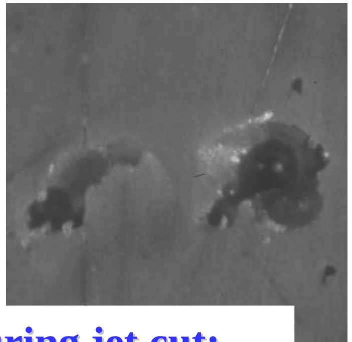


Jet diffusion and surface perturbations

Coanda effect



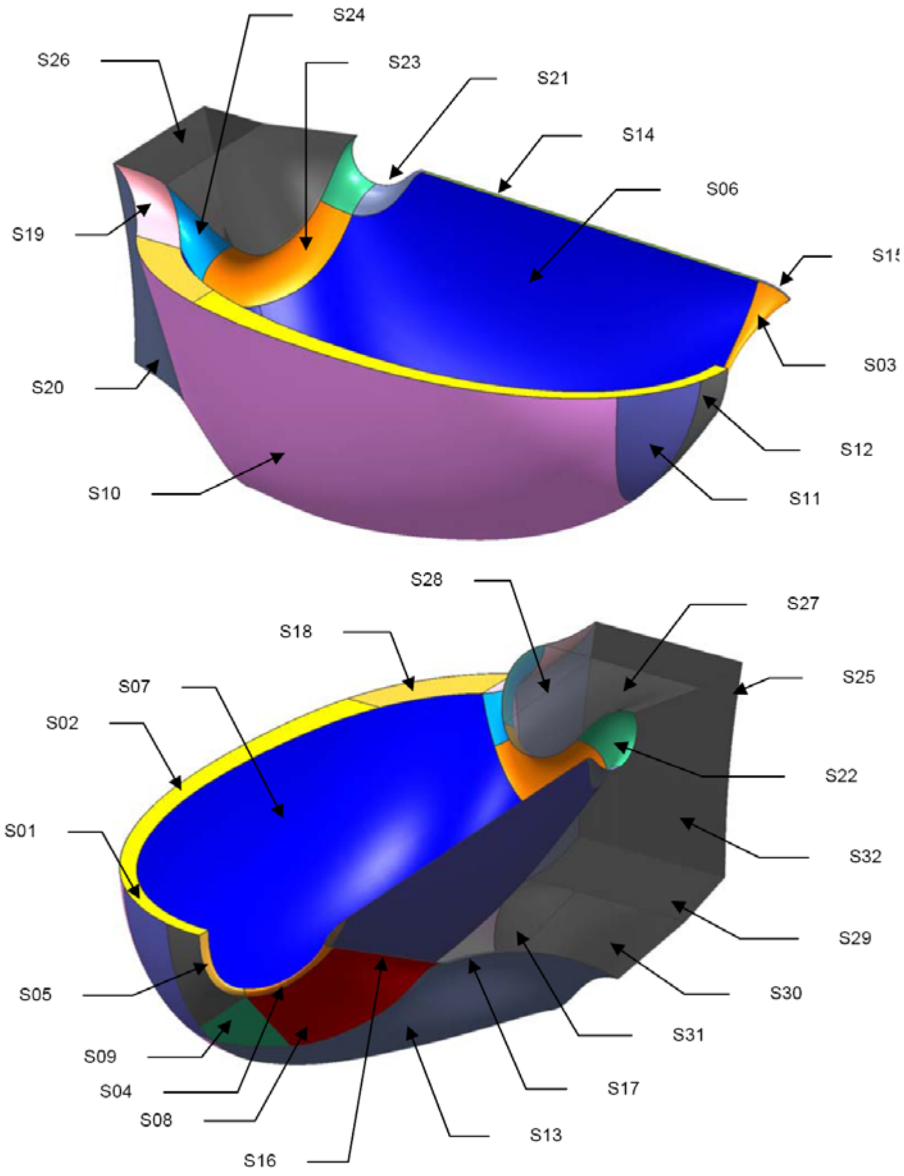




Spillway effect during jet cut: Erosion, Water Hammer(?)

Outflow-casing interactions: Flow re-entering, ventilation losses, jet disturbances

Flow analysis and design optimization



- Pelton bucket shape is complex and requires many design parameters to describe
- Multiparametric design optimization requires numerous flow field evaluations
- A fast and reliable flow analysis tool is needed
- Effects of the various complex flow mechanisms should be accounted.

The Fast Lagrangian Solver (FLS) software

Basic features

- ✓ Lagrangian approach – Representative fluid particle trajectories.
- ✓ Integration of particle motion equations in the rotating system.
- ✓ Hydraulic losses are taken into account by adjustable coefficients.
- ✓ No pressure or other external forces (gravity)
- ✓ Proper time step and number of trajectories for adequate accuracy.

Advantages

- ➢ Very fast simulation (just a few CPU seconds in a P4 PC)
- ➢ Detailed information about the hydraulic behavior and the energy transfer
- ➢ Suitable for parametric, sensitivity and design optimization studies

Drawbacks

- ➢ Less accurate compared to a full CFD (RANS) solution
- ➢ Need for regulation with the aid of experimental or numerical data

The FLS model

Particle motion equations

$$\frac{d^2x}{dt^2} = f_x(x,y)$$

$$\frac{d^2y}{dt^2} = f_y(x,y) + \omega^2 y + 2\omega\frac{dz}{dt}$$

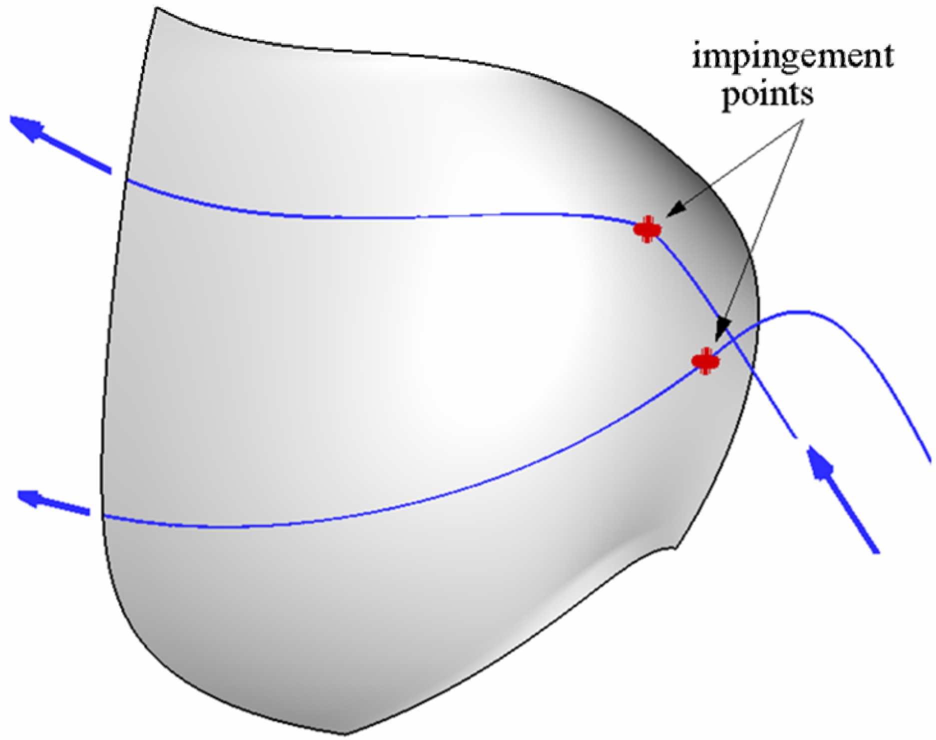
$$\frac{d^2z}{dt^2} = f_z(x,y) + \omega^2 z - 2\omega\frac{dy}{dt}$$

Mechanical torque

$$M_{num} = \rho Q_u\left(\overline{r_{in}\,w_{in}} - \overline{r_{out}\,w_{out}}\right)$$

$$\overline{r_{in}\,w_{in}} \cong R_{run} V_{jet} \cdot \cos\varphi_{jet}$$

$$\overline{r_{out}\,w_{out}} \cong \frac{1}{N}\sum_i y_{out,i} w_{out,i}$$

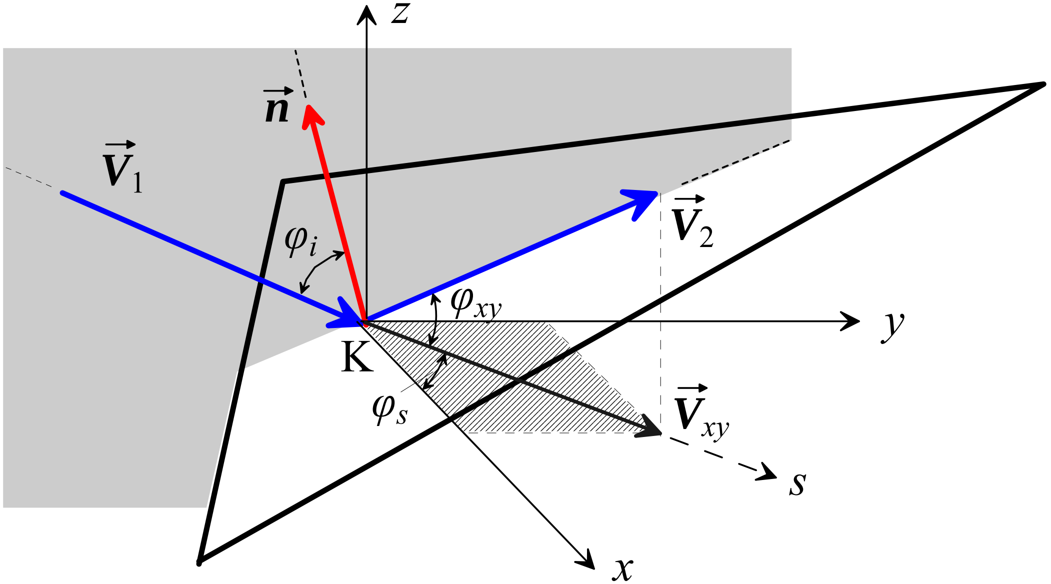


Hydraulic efficiency

$$\eta_h = \frac{M_{num}\,\omega}{\rho\, g\, Q\, H}$$

The FLS model - Tracking

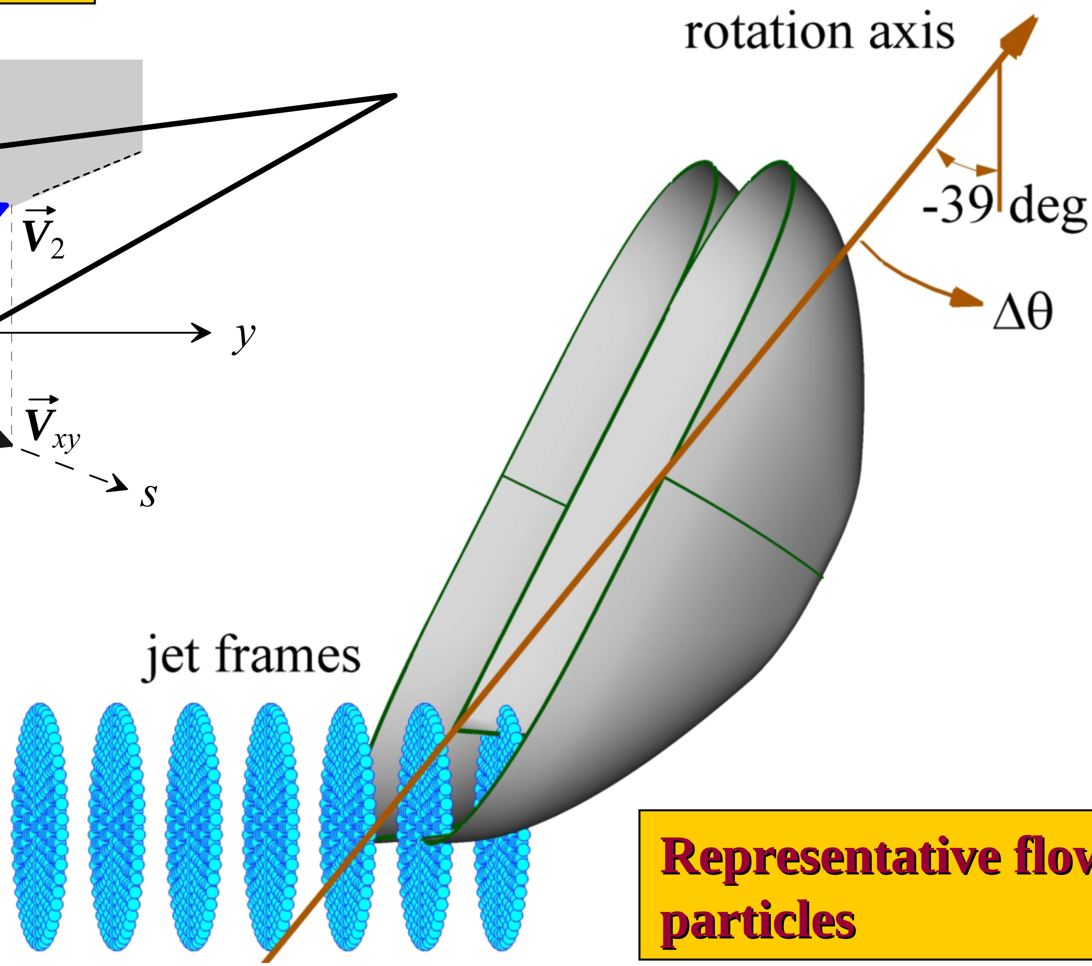
Particle's path calculation



$$u_2 = V_{xy} \cdot \cos(\varphi_s)$$

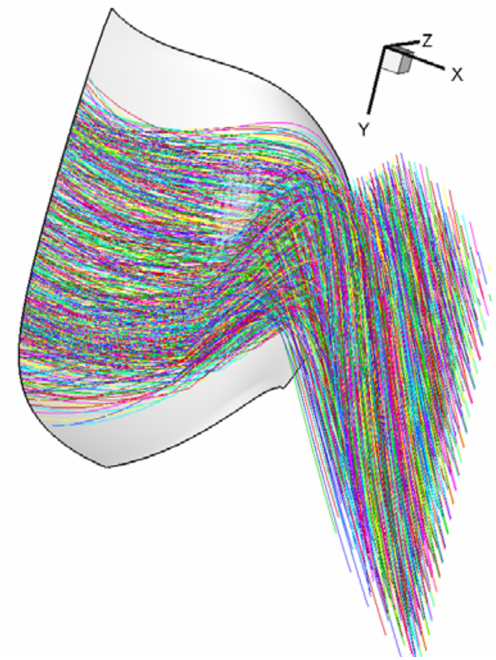
$$v_2 = V_{xy} \cdot \sin(\varphi_s)$$

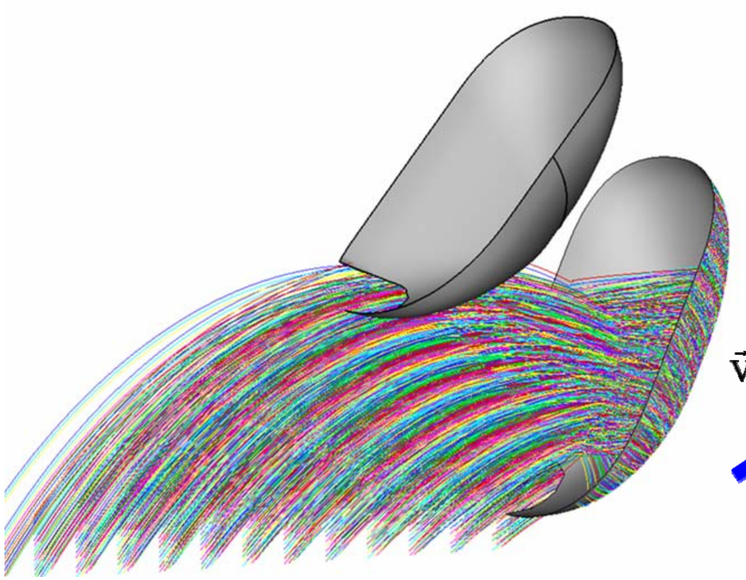
$$w_2 = V_2 \cdot \sin(\varphi_{xy})$$

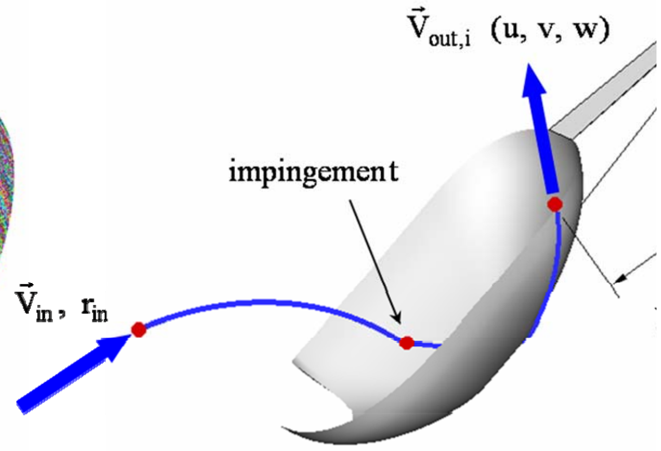


Representative flow particles

The FLS model - Tracking







- **Jet flow is represented by successive cylindrical packets or fluid frames**
- **Uniform distribution of injection points**
- **A trajectory terminates when the fluid particle:**
  - **→ Exits from the blade (after previous impact and sliding)**
  - **→ Passes by the blade without impinging on its internal surface**
  - **→ Impinges on the next coming blade**
- **The jet flow is completed when the next coming blade cuts the jet**

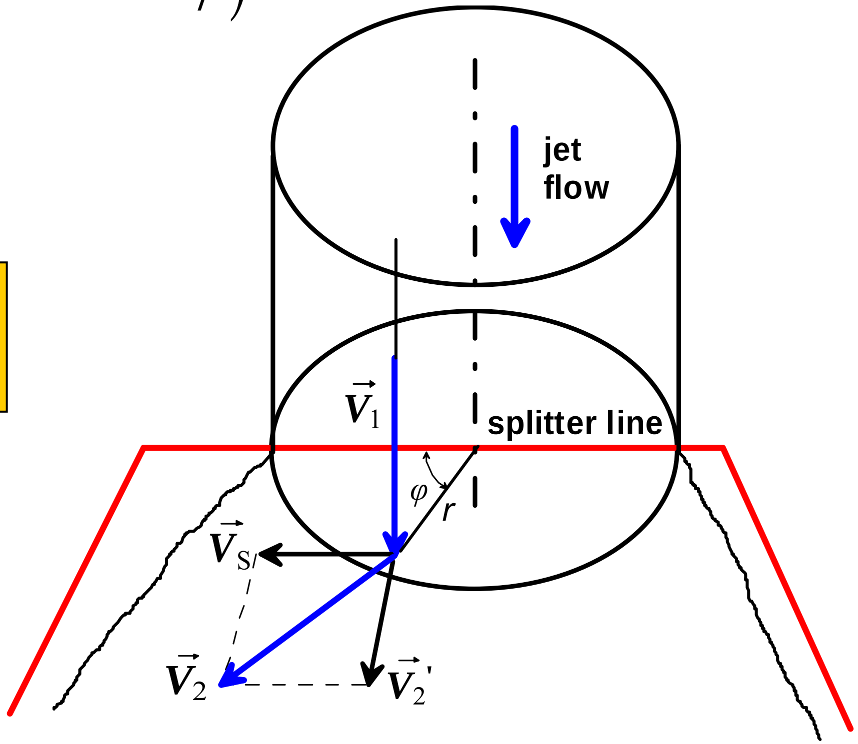
FLS model – The adjustable terms

Friction losses: $$V_p' \approx V_p \cdot \left(1 - C_f \cdot V_p \cdot \Delta t\right)$$

Impact losses: $$V_2' \approx V_2 \cdot \left(1 - C_i \cdot \cos^2 \varphi_i\right)$$

Changing path direction: $$V_2' \approx V_2 \cdot \left(1 - C_p \cdot \cos^2 \Delta\varphi\right)$$

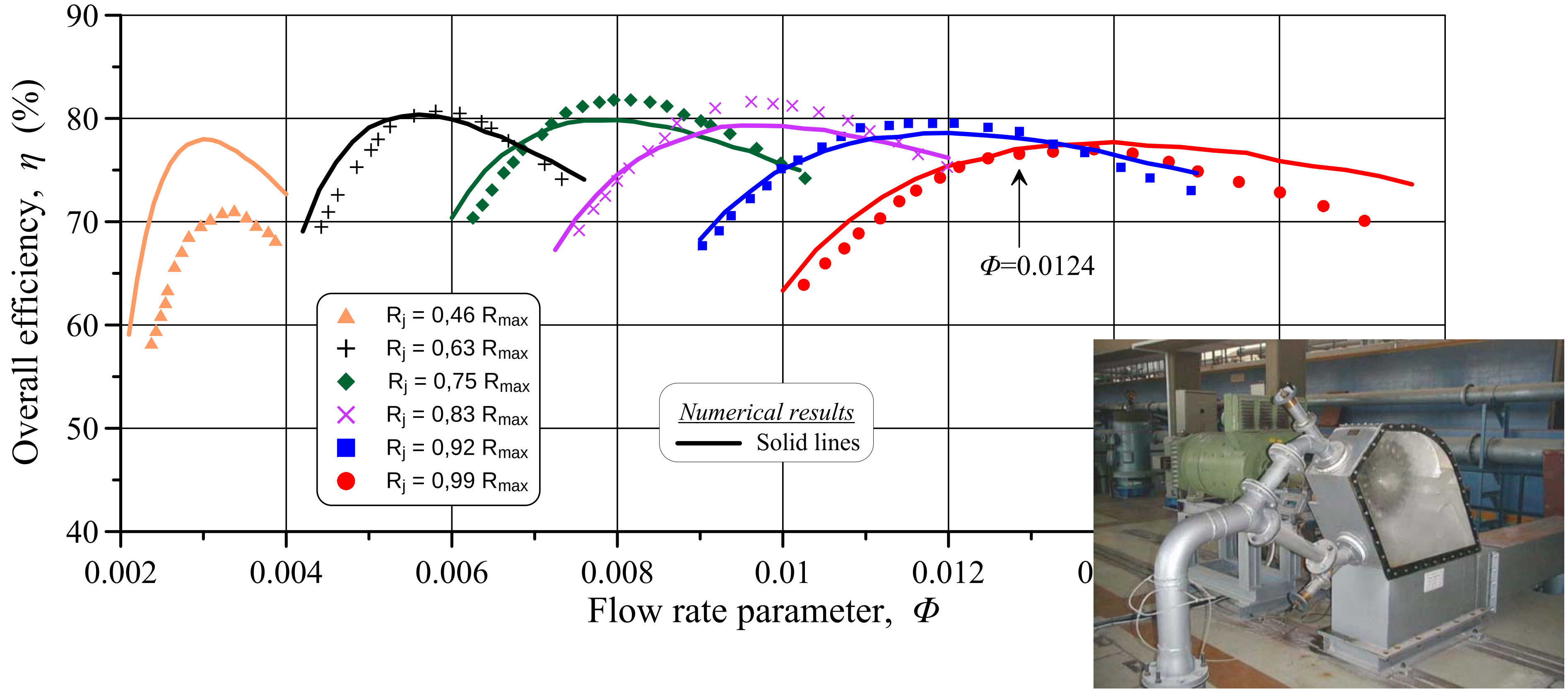
Flow spreading:



4 adjustable coefficients

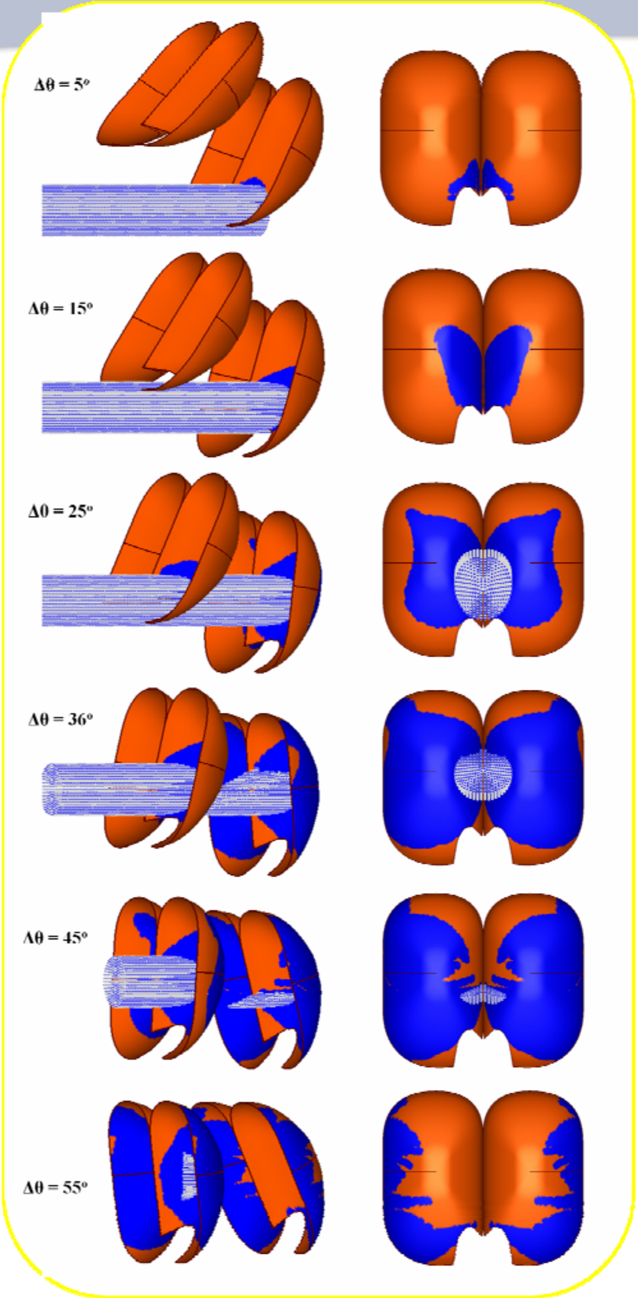
FLS Model Regulation

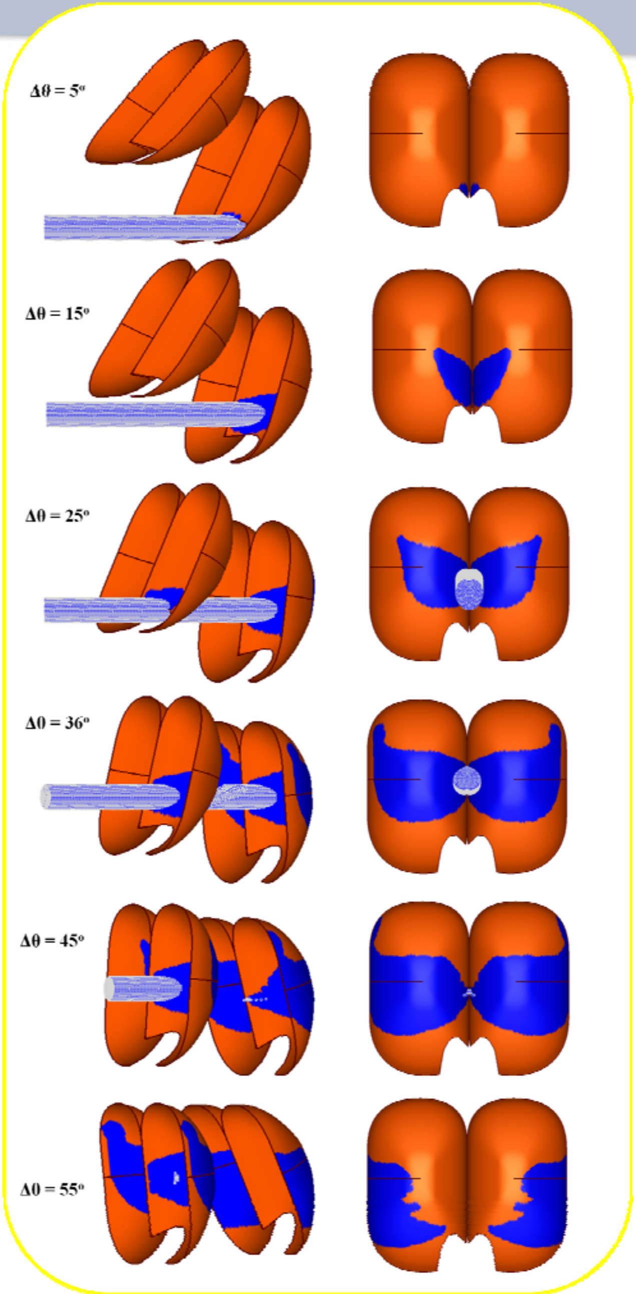
Regulation of model coefficients to much the measurements, using the EASY optimizer



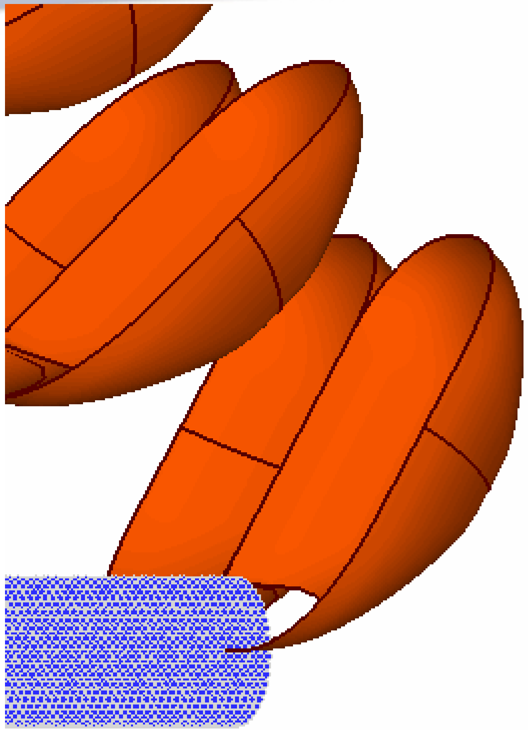
- Model of a real Pelton turbine (Aoos river, scale 1:6), 80 KW.
- Designed using standard guidelines from the literature and constructed in the Lab.
- Measurements for various operation conditions (flow rate, head, speed).

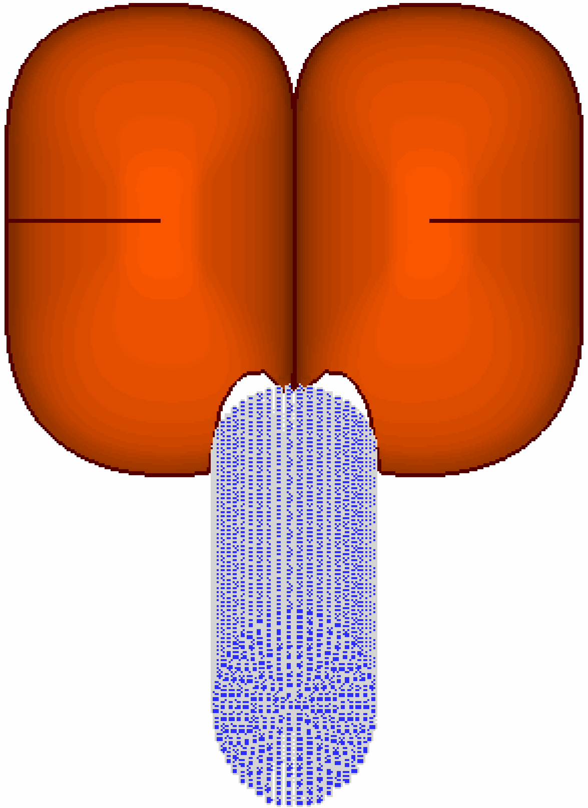
FLS model results



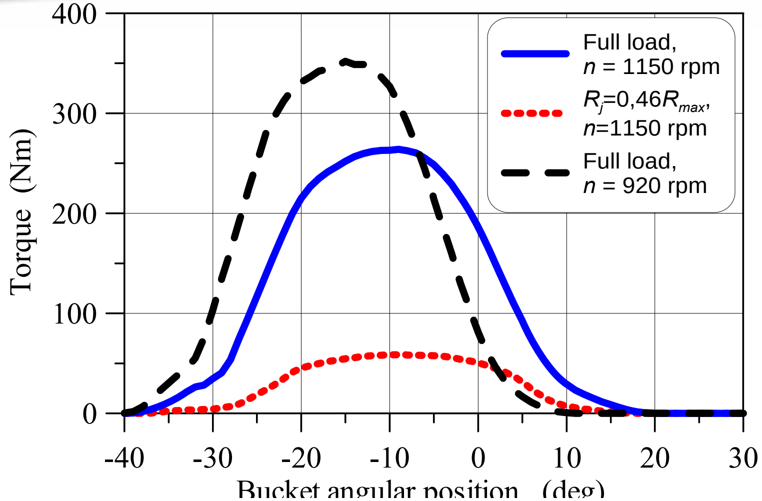


FLS model results - Animation

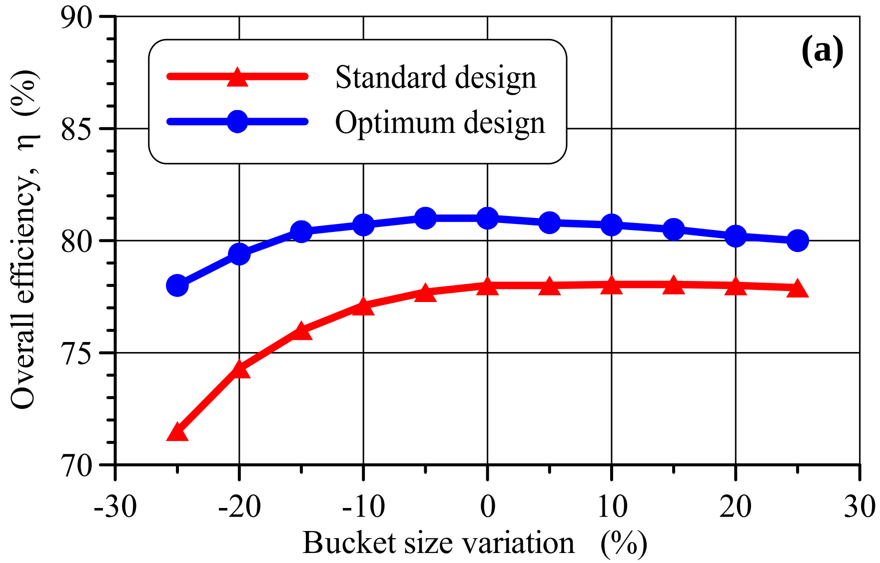




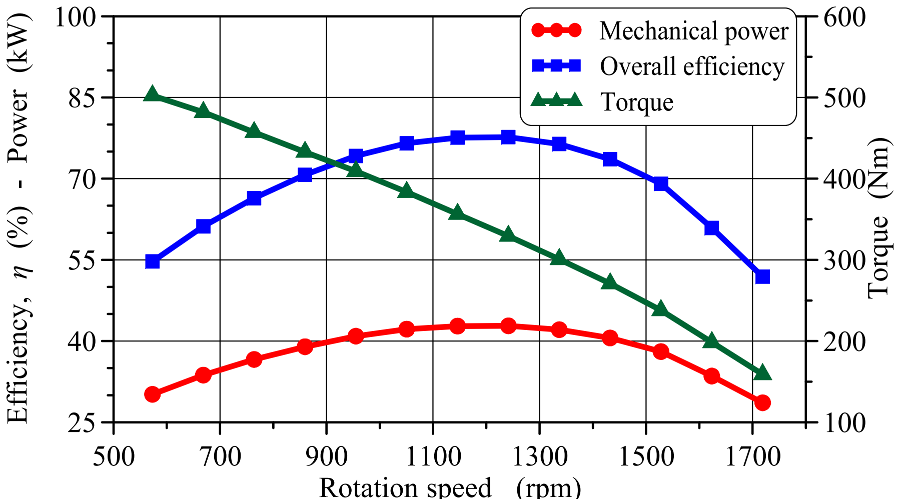
FLS model results



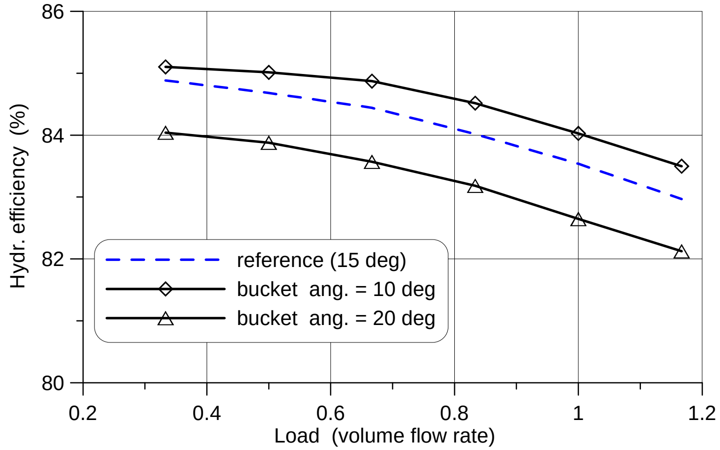
Bucket torque history curve



Effect of the bucket size



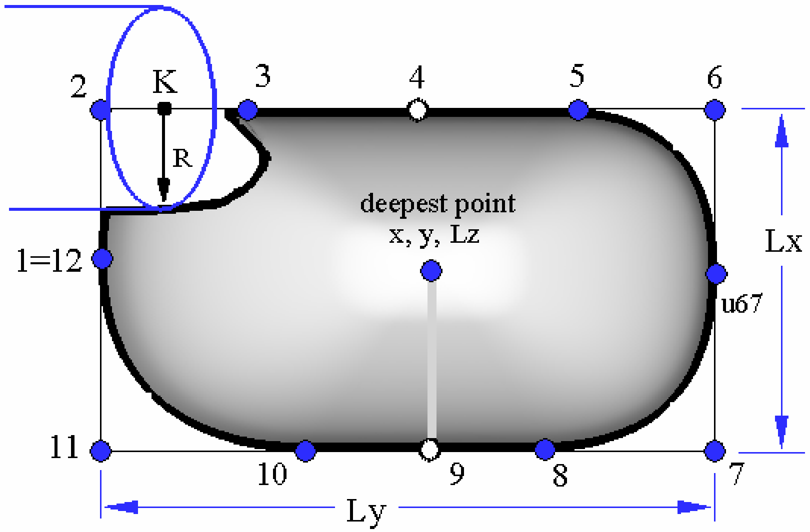
Effect of the rotation speed



Effect of the bucket fastening angle

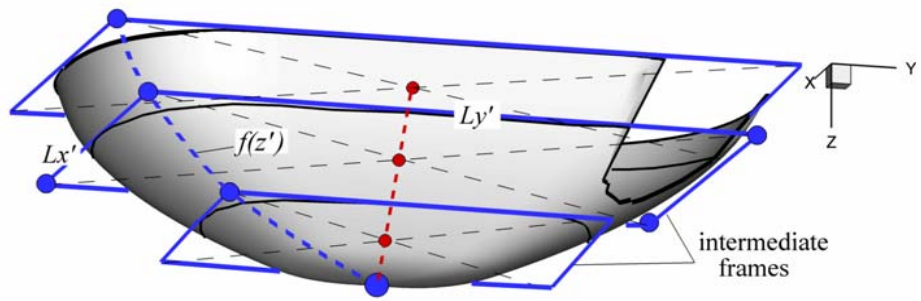
Pelton runner design optimization

I. Bucket surface parametric design



Nurbs regression polynomials

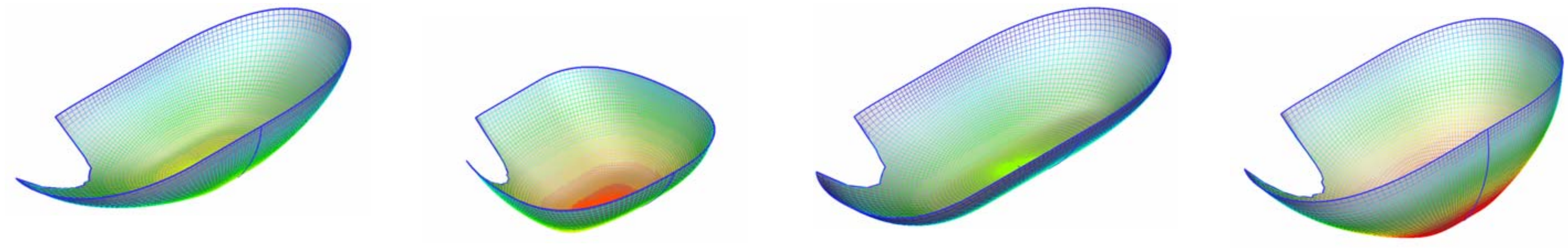
18 design variables in total

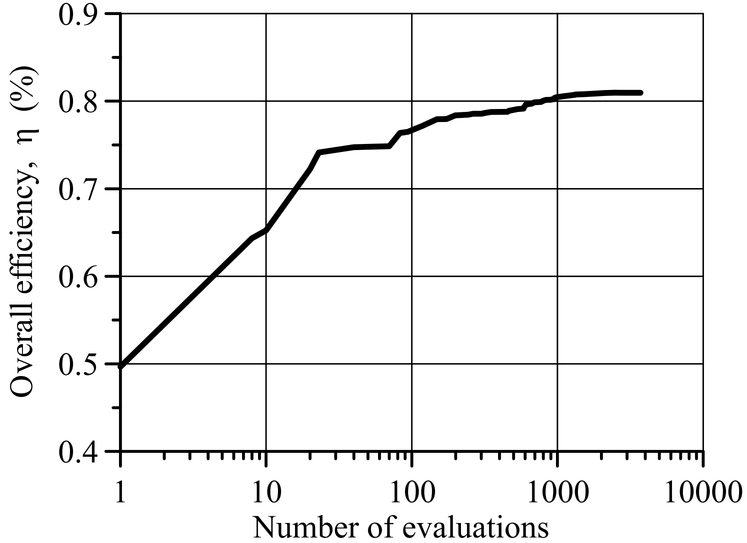


Free design variables

- ✓ Main bucket dimensions (length, width, depth) + rotor diameter = 4 variables
- ✓ 6 control points for the rim shape + 2 for the cutout lips = 8 variables
- ✓ Lateral surface formed by successive parallel slices up to the tip - 4 variables for two slices
- ✓ 2 points for the tip relative location

II. Use of the EASY optimization software



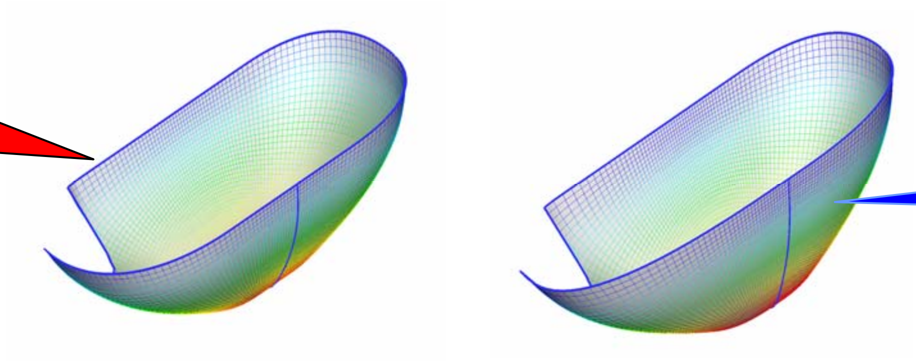


- **Many different shapes are examined during the automated process.**
- **Optimal design is obtained after several hundred evaluations due to the large number and the wide variation range of the free design variables.**
- **Various geometrical constraints are considered (minimum possible surface slope at the splitter line and the outflow region etc.)**

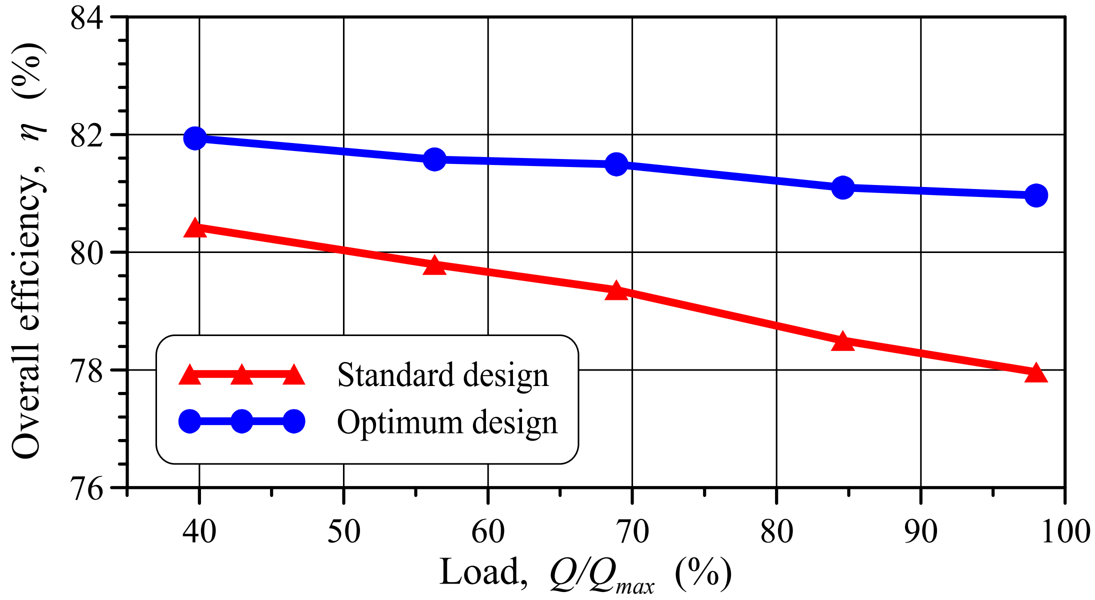
Pelton runner design optimization

III. Results

Standard surface

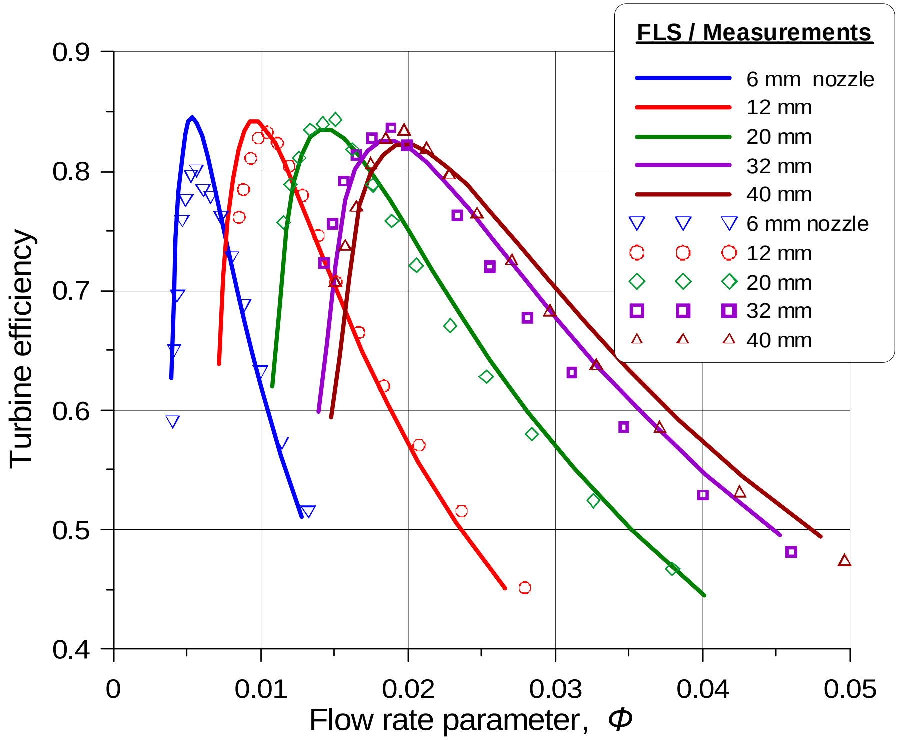


Optimum surface



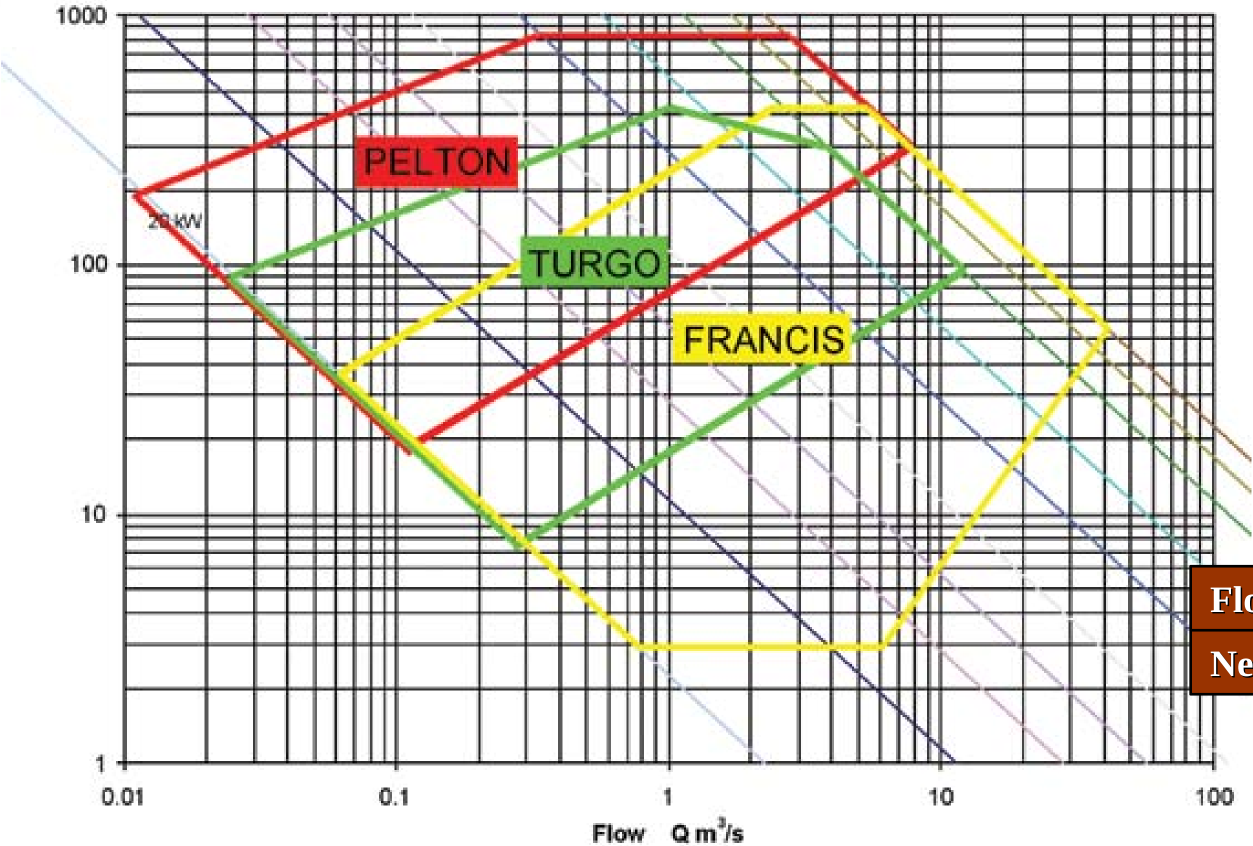
Small differences between the two shapes, but remarkable efficiency improvement.

IV. Application



Design and construction of a new small Pelton turbine (150 KW)

Turgo turbine invention



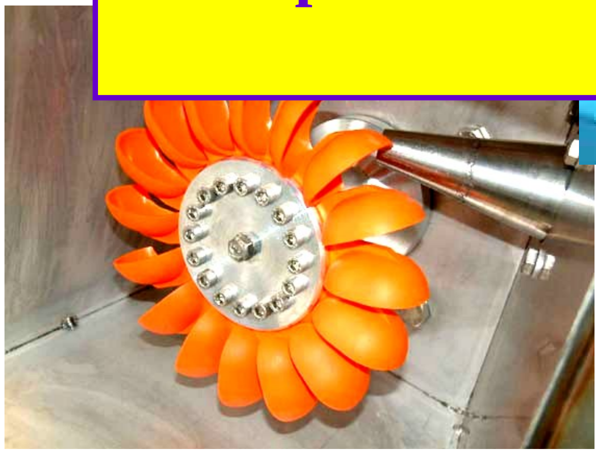
Turgo Turbine range

Flow rate	0,05 - 5 m^3/sec
Net Head	10 - 300 m

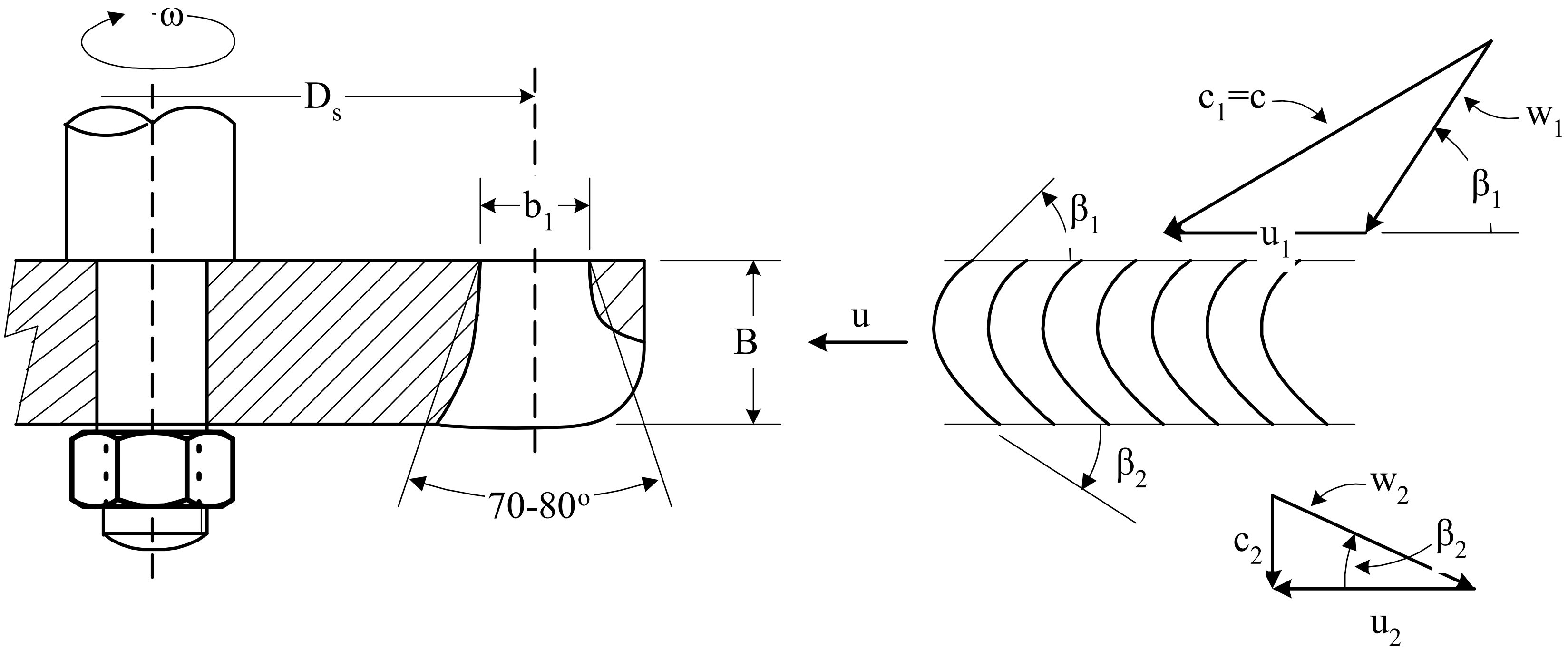
- Gilkes patented design – First machine in Scotland 1919.
- Developed to provide a simple Impulse machine with higher specific speed than a Pelton.
- Larger water jet – more compact & cheaper generator – no runner/outflow interaction
- Turgo covers the boundary between Pelton and Francis machines and can deals extremely well with “dirty” water without any detriment to performance.
- There is no danger of cavitation damage to the runner or the casing.

Turgo turbine design

- Complex design, difficult manufacturing
- No design guidelines in the literature
- No scientific articles, books or other publications
- No performance results



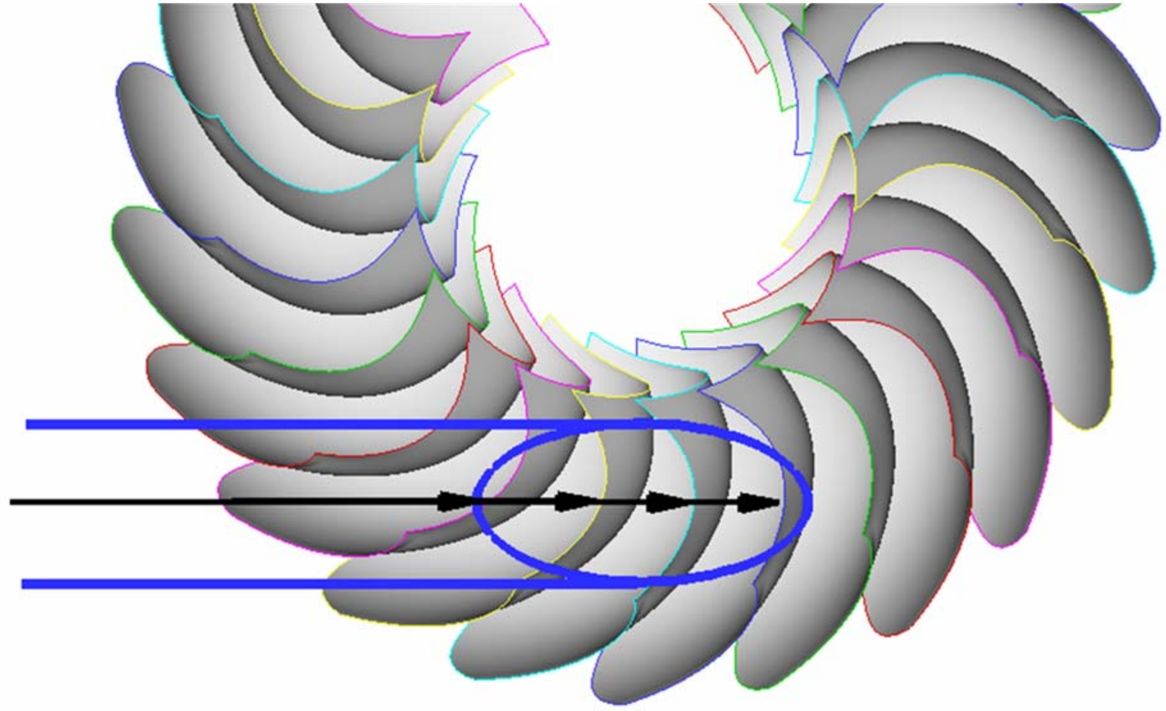
1st Step: Hydrodynamic design of the runner



Simple hydrodynamic design

- ✓ Total flow impulse approach – The fluid is assumed to fill the runner section
- ✓ Calculation of blade inlet and outlet angles from the corresponding velocity triangles
- ✓ Linear variation of the blade angle along a meridian stream line.

Turgo turbine design

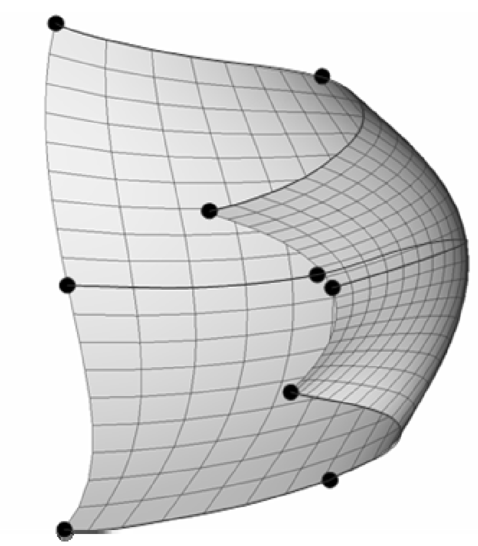


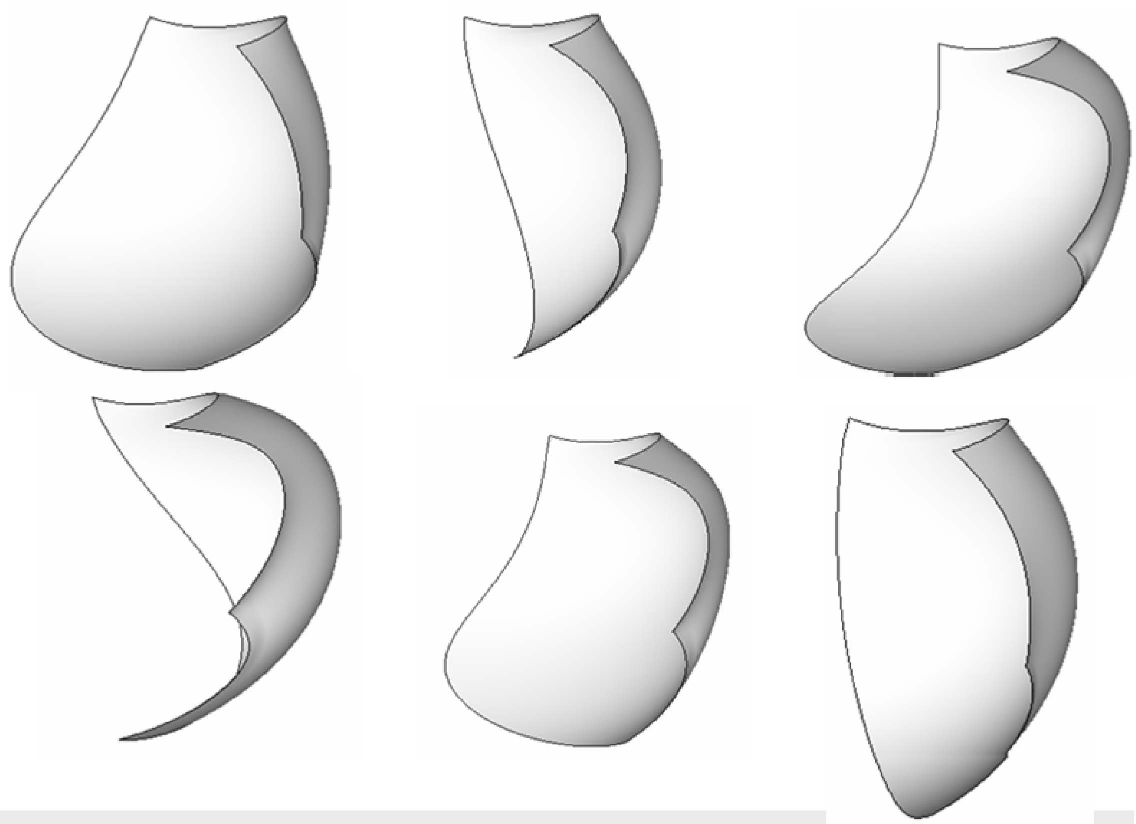
Actual jet–runner interaction conditions

- The jet interacts with more than one blade at the same time – Elliptic inlet section
- Fluid particles on the same trajectory impinge at different locations and with different relative impact angles on these blades.
- Also, their path lines and exit points and conditions are completely different.
- The best efficiency design cannot be obtained theoretically or empirically.

Turgo turbine design

2nd Step: Parameterization using Bezier polynomials



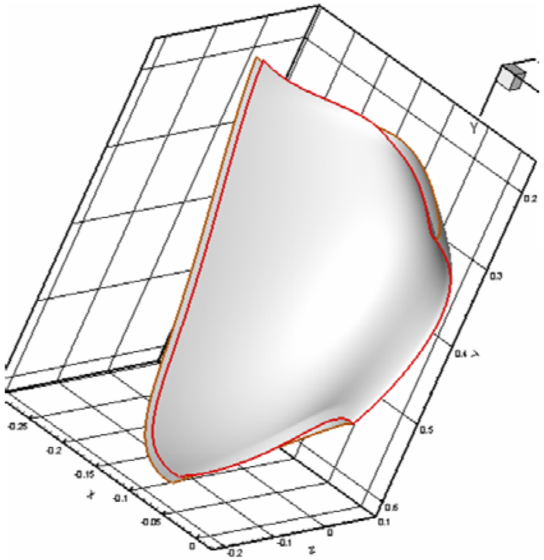


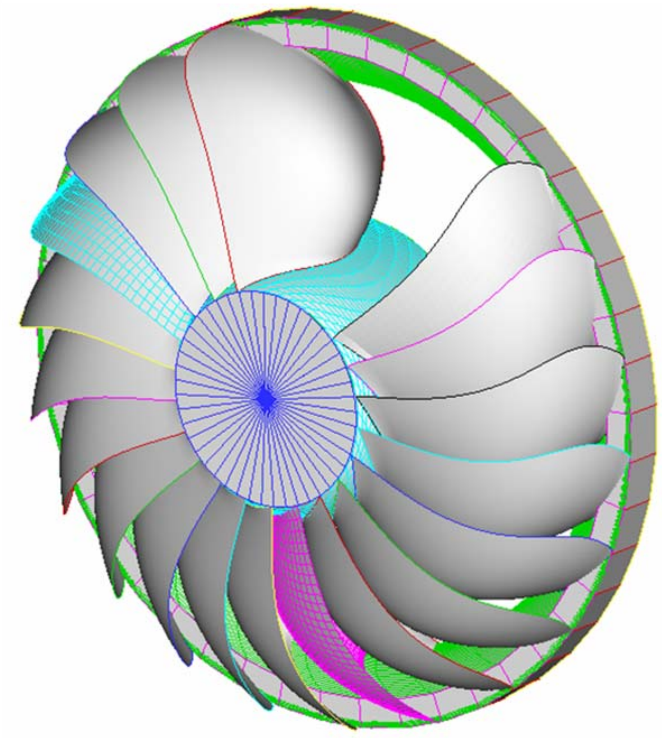
Parametric design

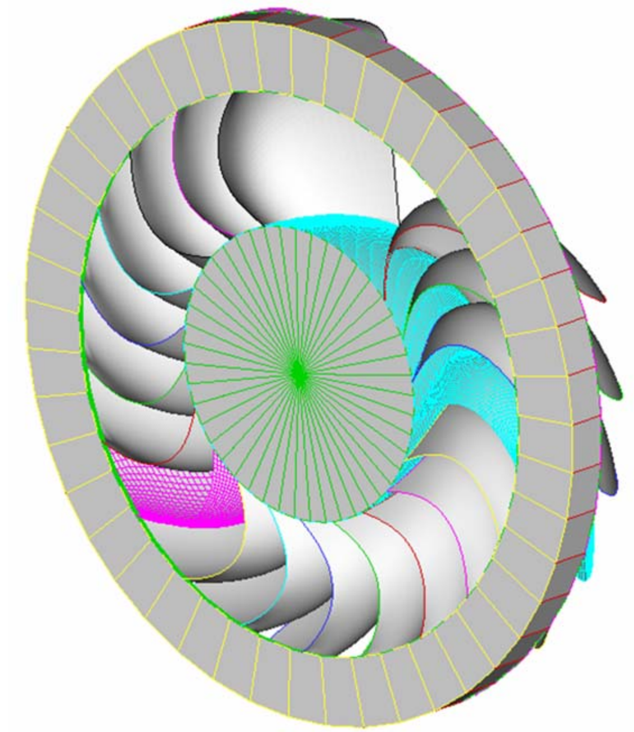
- Quadratic variation of the blade angle along meridian stream lines
- Use of Bezier polynomials and interpolation techniques.
- Introduction of 12 free variables for wide shape modifications

Turgo turbine design

3nd Step: Addition of axissymetric hub and shroud, and blade width

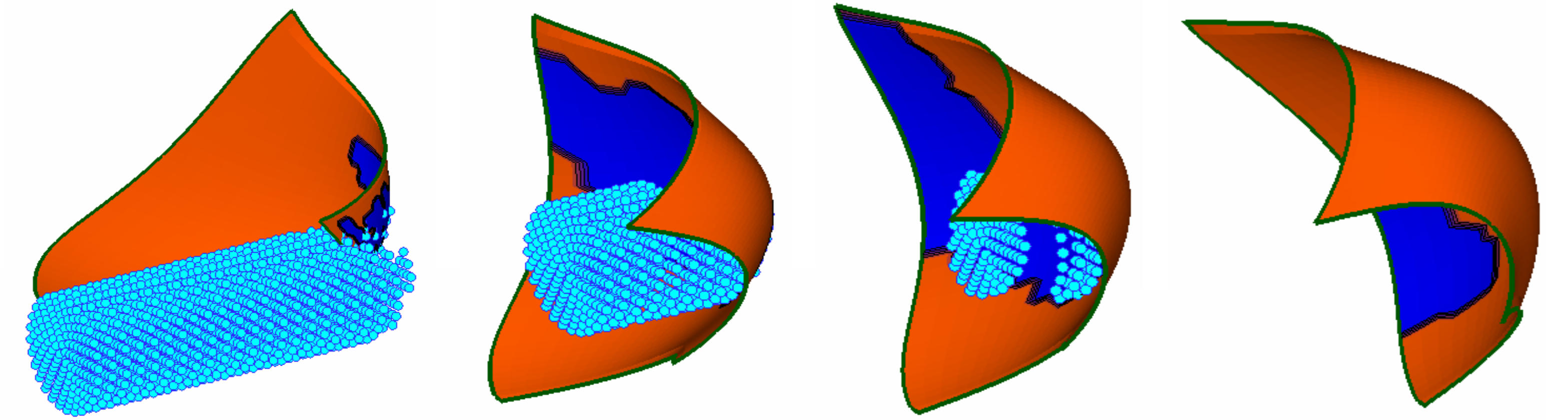


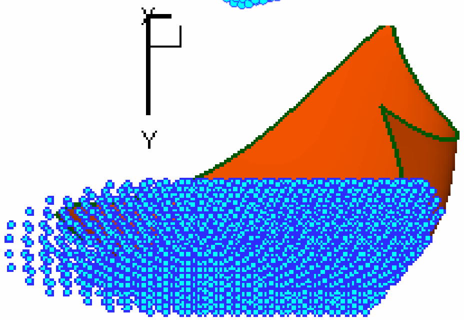


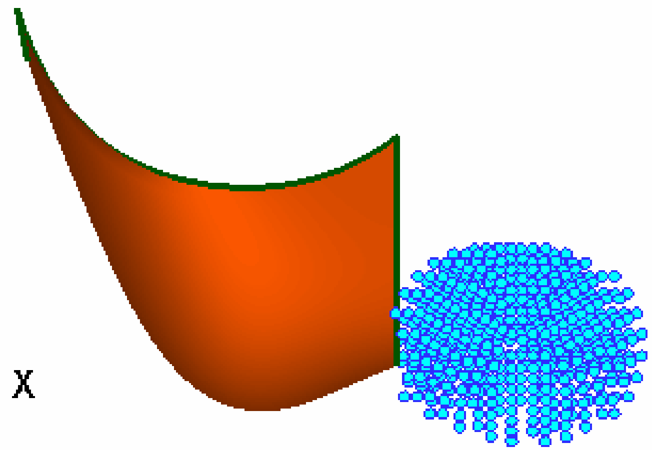


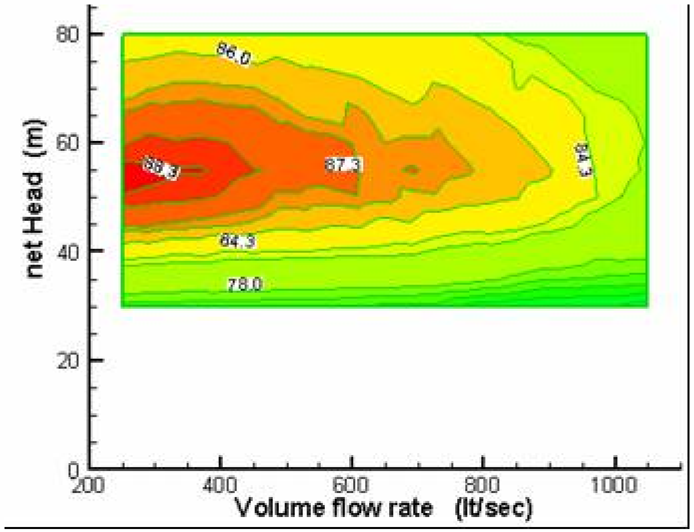
Turgo turbine design

4[th] Step: Application of the FLS software









Turgo design validation

1st Step: Visit in field!

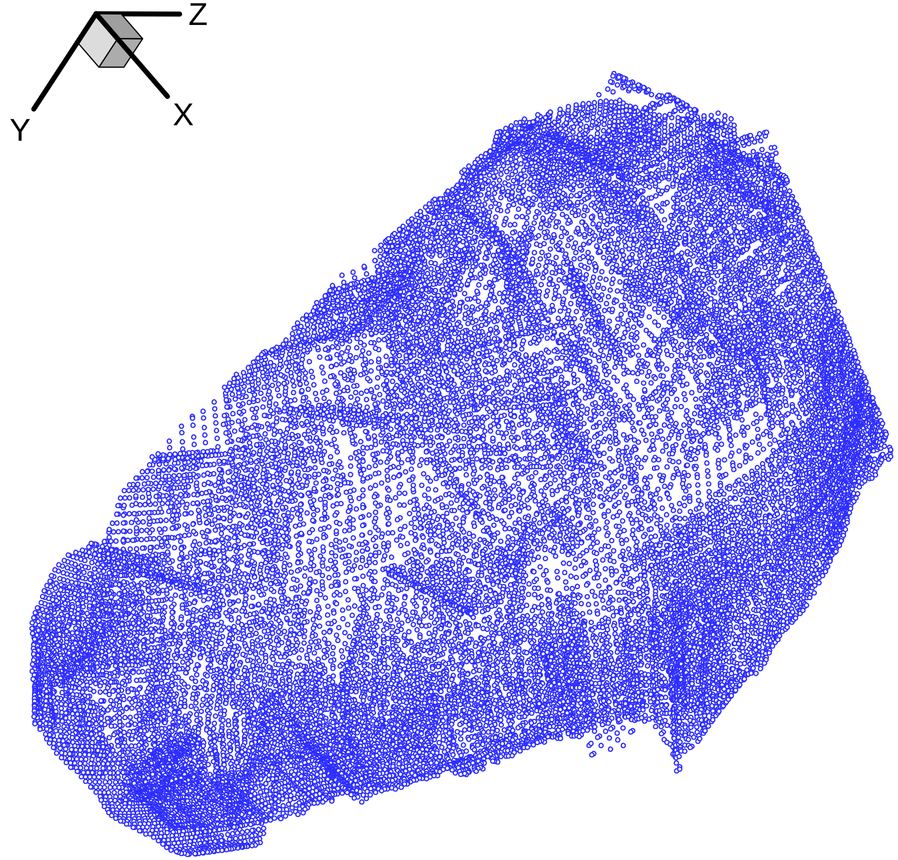
SHP Kastaniotiko
550 KW / two injectors Turgo turbine

Turgo design validation

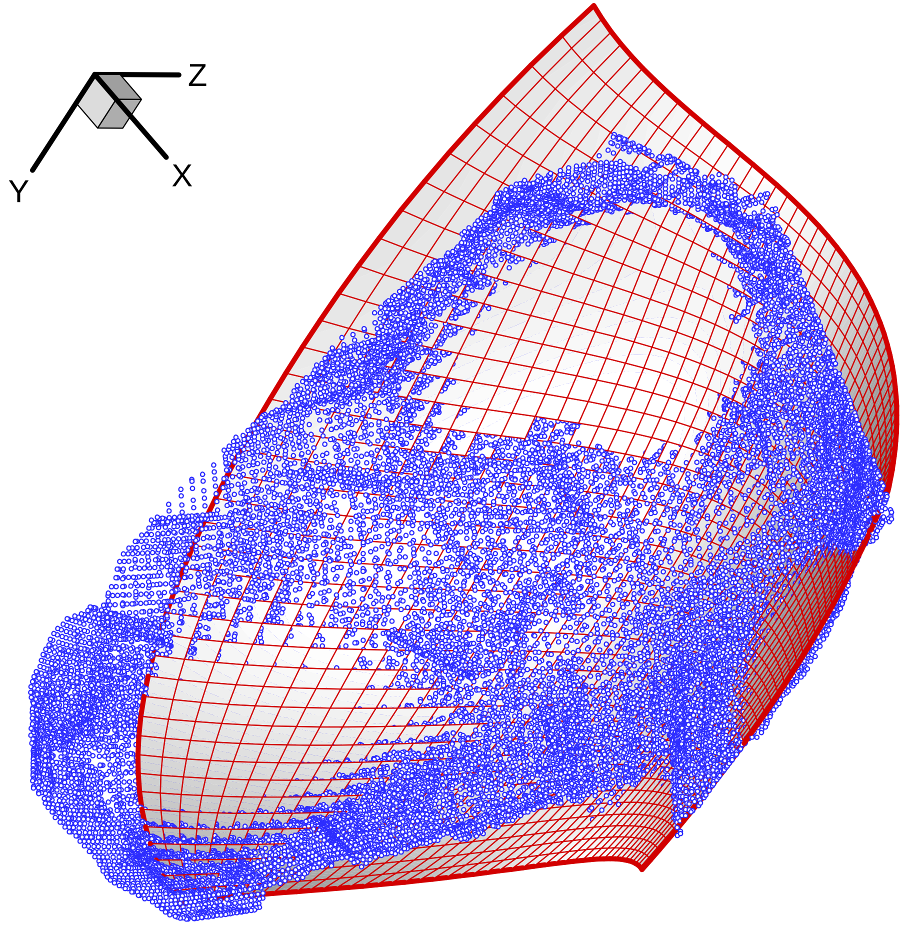
2nd Step: Blades geometry identification

Turgo design validation

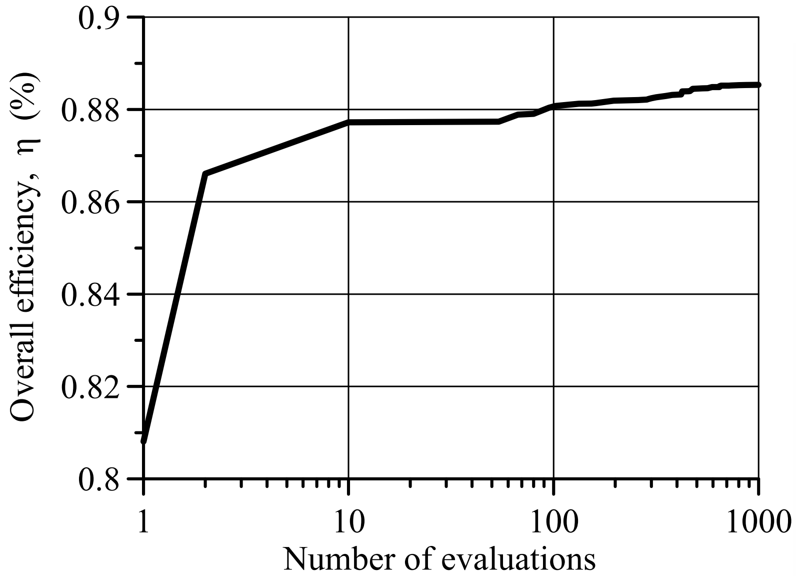
3rd Step: Mapping with 3D scanning



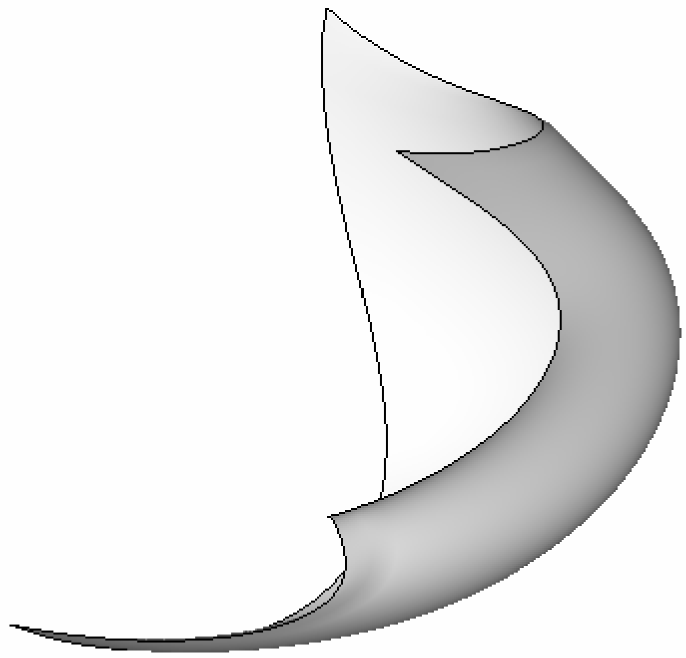
4th Step: Inverse design using the EASY software



Turgo design optimization



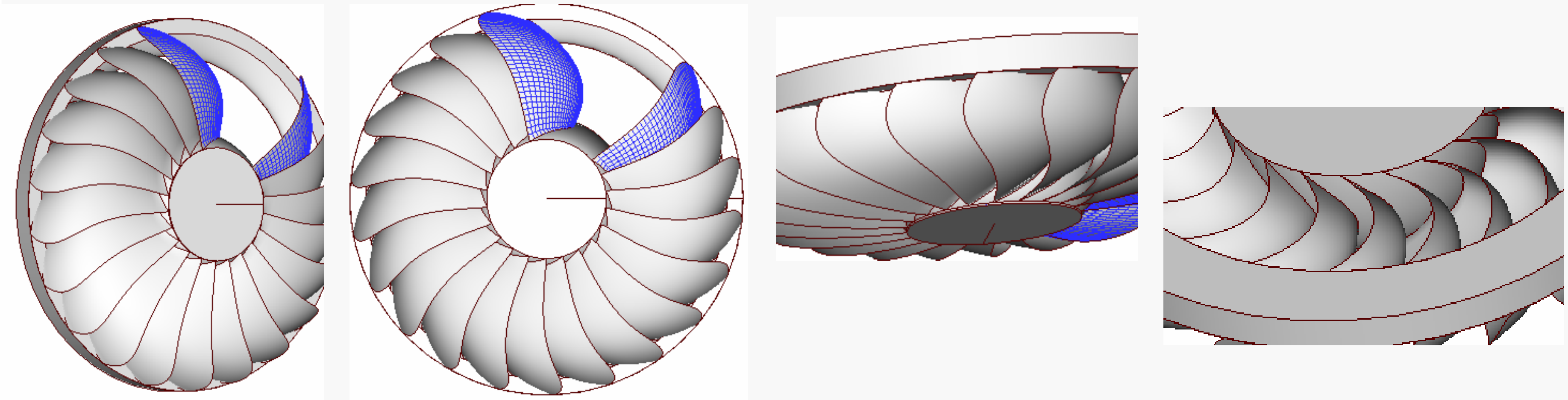
5th Step: Desing optimization with the EASY software



- ➢ **Many different shapes are examined during the automated process.**
- ➢ **Optimal design is obtained after several hundred evaluations due to the large number and the wide variation range of the free design variables.**

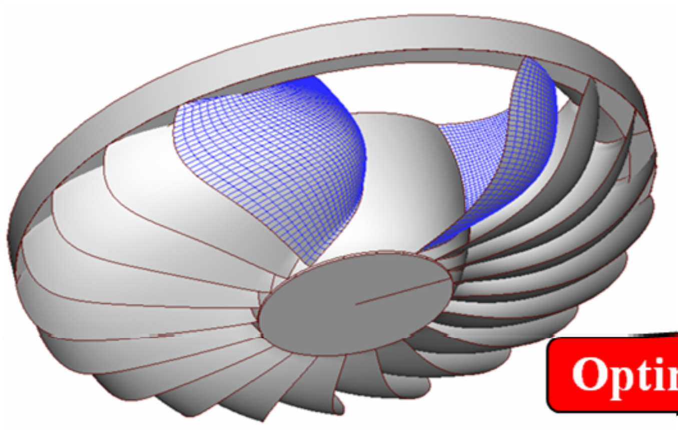
Design optimization method evaluation

Real Turgo turbine operating in a SHP

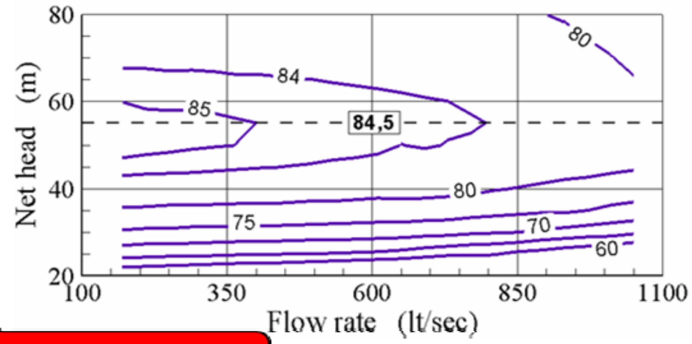


Runner design obtained by numerical optimization

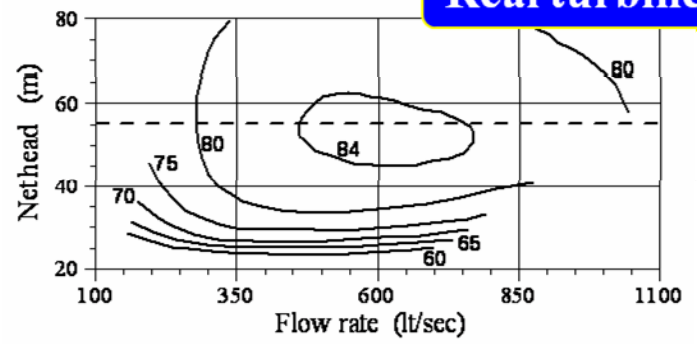
Design optimization method evaluation

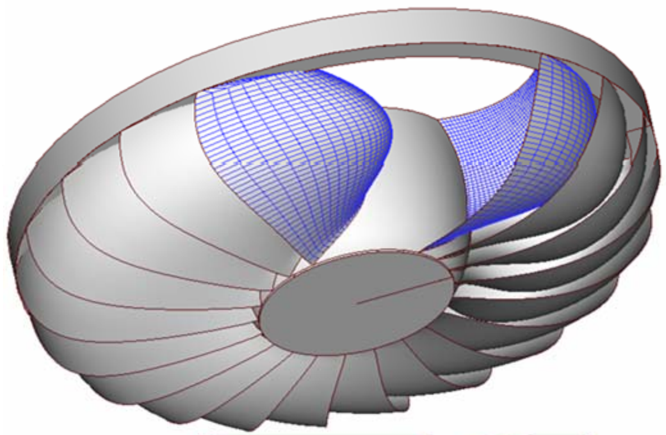


Optimum design



Real turbine





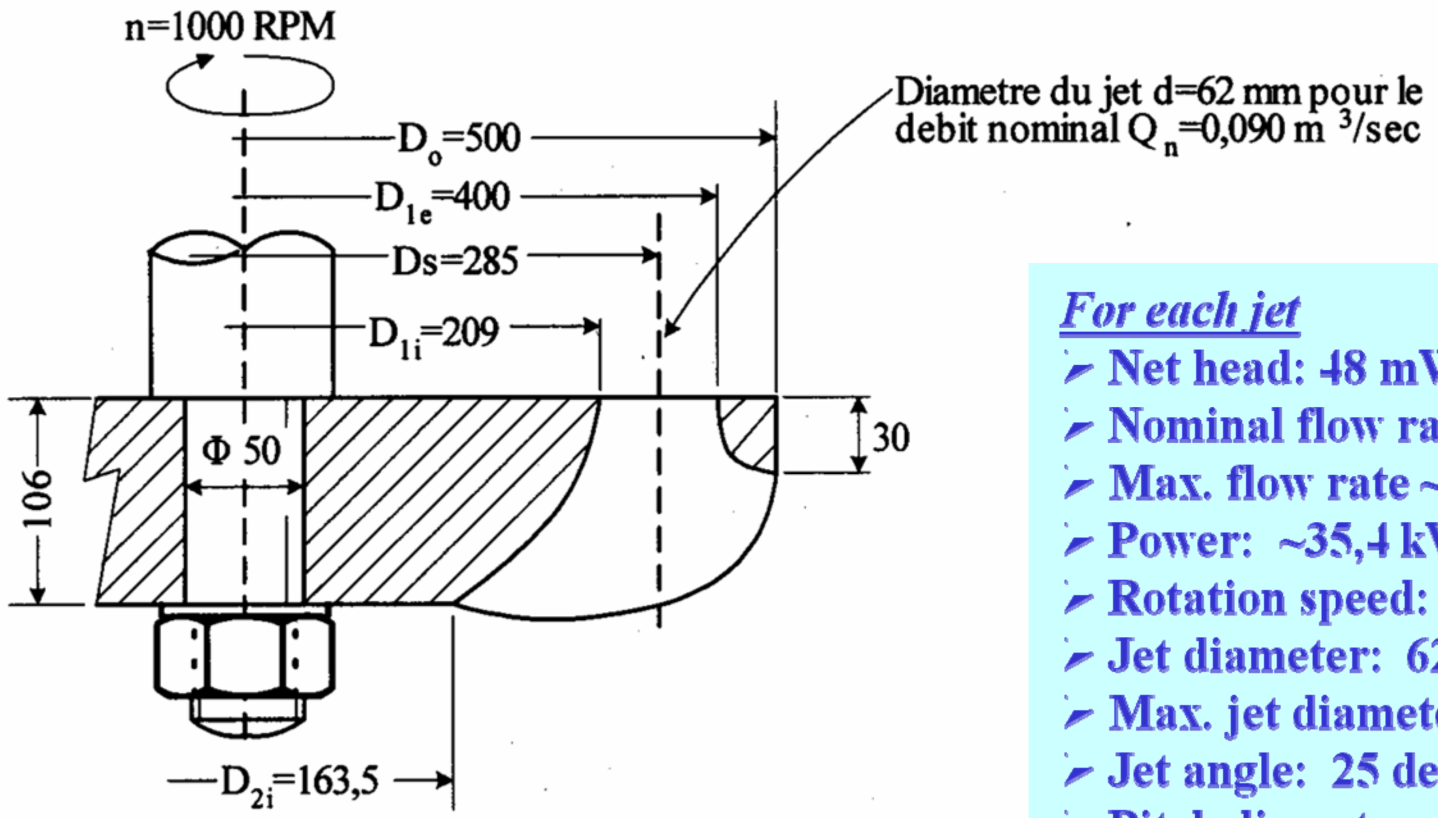
Simple design

The optimum design shape and characteristic curves are similar to the real Turgo machine.

The valve deficiency and the increased jet impact losses at low load conditions are not modeled.

Turgo prototype model

Main design data and dimensions of Turgo model turbine



For each jet

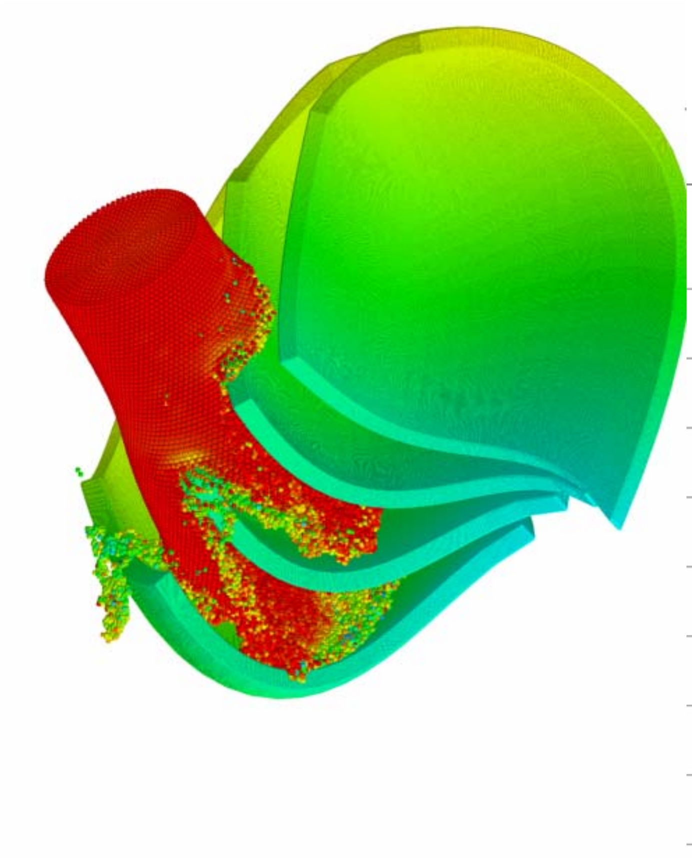
- Net head: 48 mWG
- Nominal flow rate: 0,09 m³/s
- Max. flow rate ~0,138 m³/s
- Power: ~35,4 kW
- Rotation speed: 1000 rpm
- Jet diameter: 62 mm (nominal)
- Max. jet diameter: 76,8 mm
- Jet angle: 25 deg
- Pitch diameter: 284,5 mm

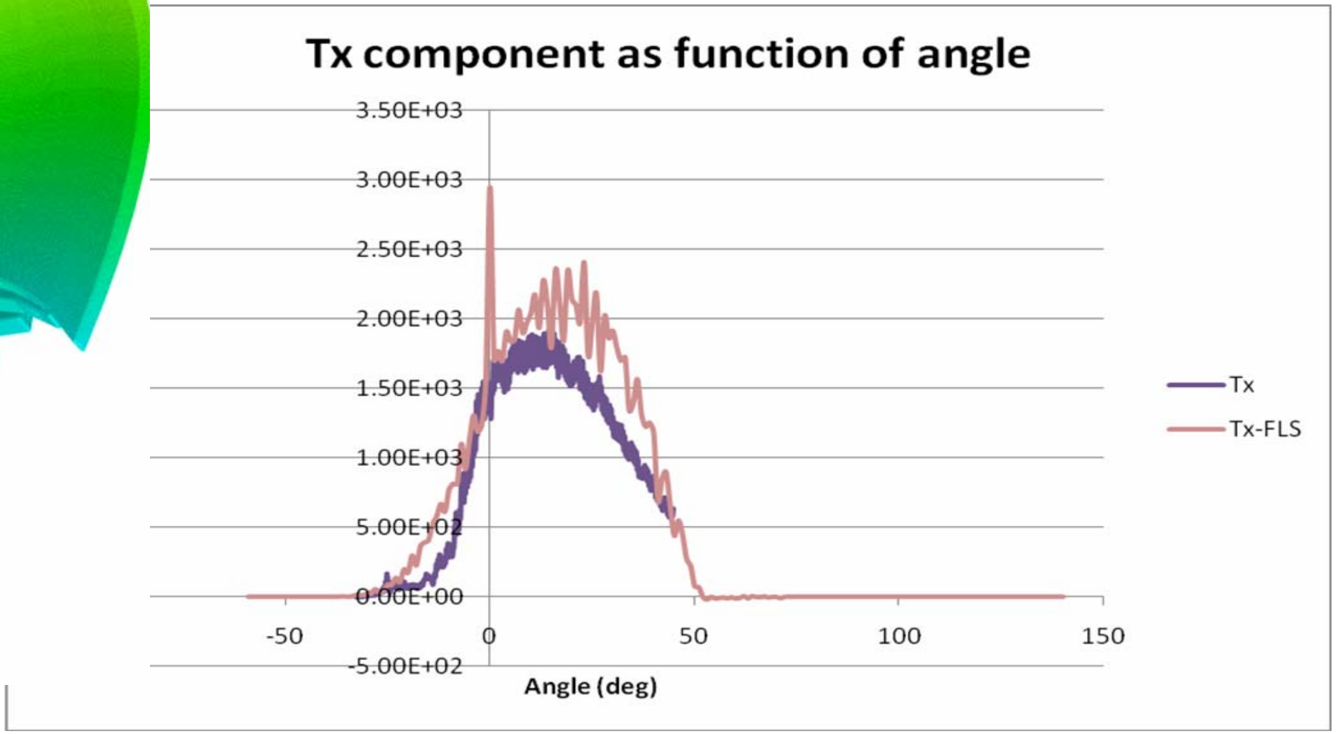
Forces

Peripheral: Fu = 2387 Nt
Radial: Fr = 2424 Nt
Axial thrust: Fa = 1133 Nt

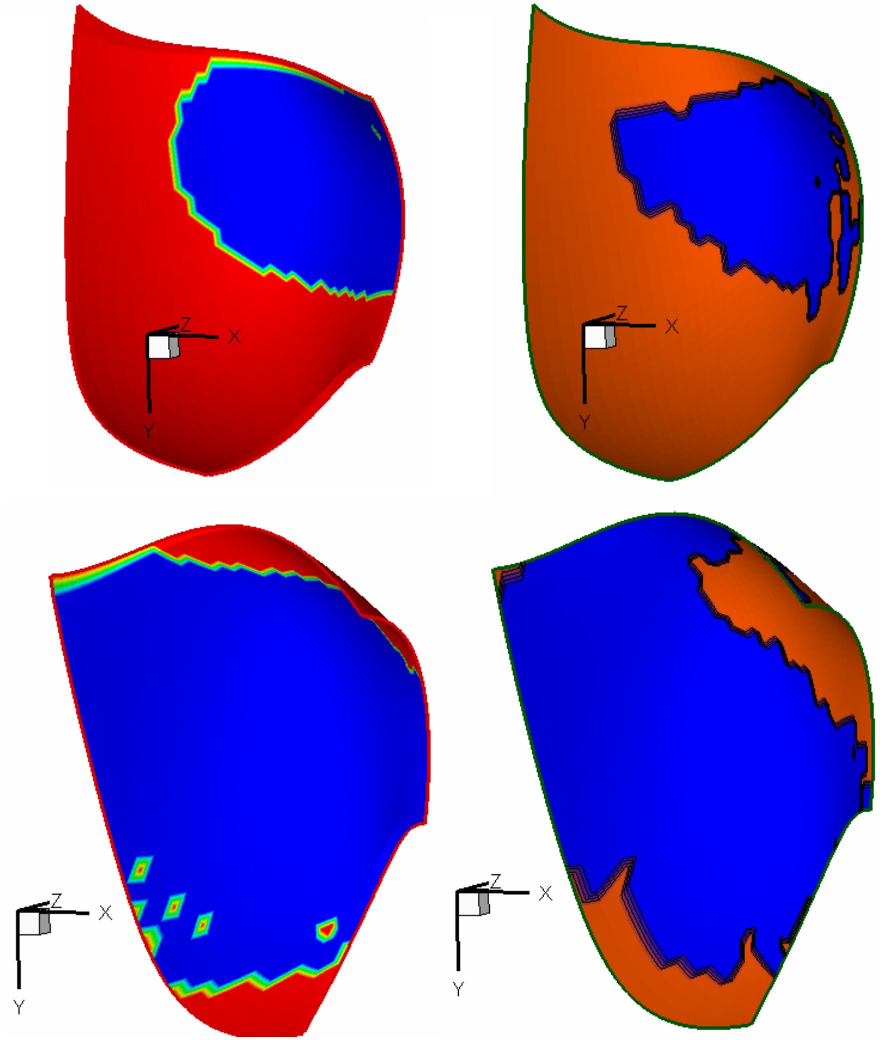
Turgo prototype model

Re-adjustment of FLS model coefficients using results from the SPH simulation



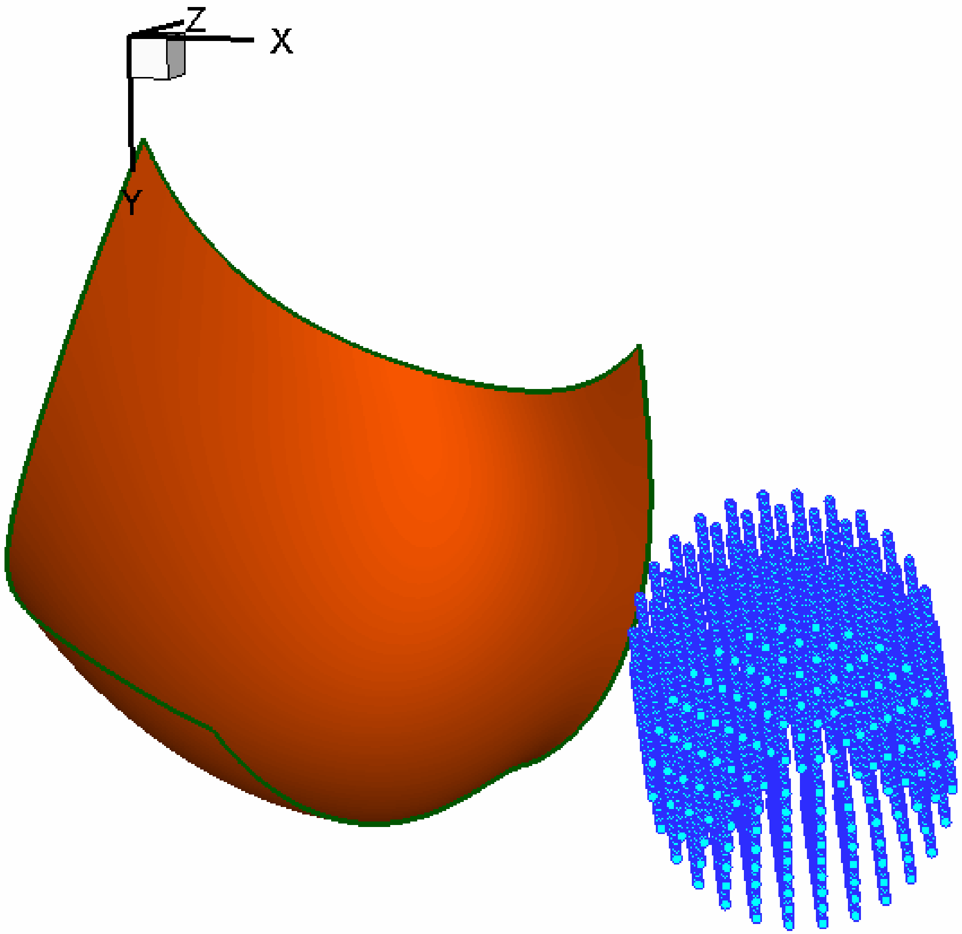


Turgo prototype model



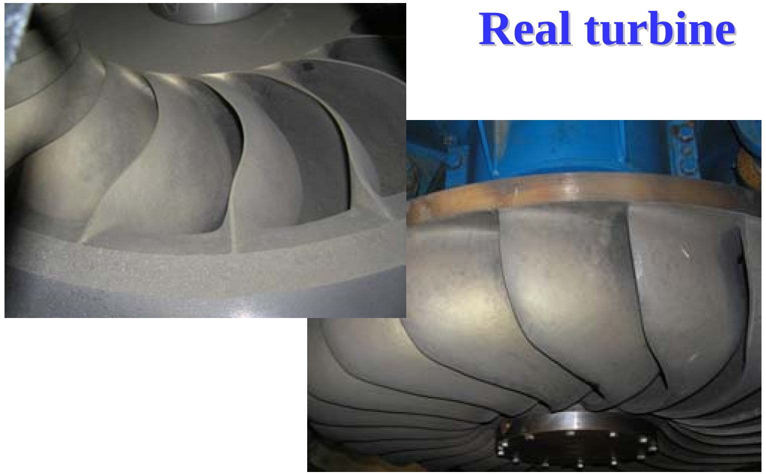
Comparison of free surface flow patterns during jet-runner interaction, as computed by the SPH (left) and by the FLS software (right), at two different angular positions after start of interaction: 36 deg (a, b), and 72 deg (c, d).

More accurate estimation of mechanical losses in part loads

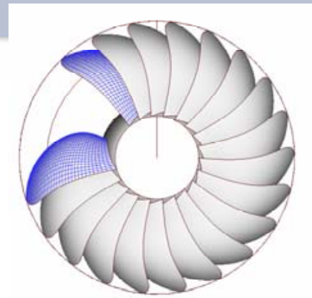


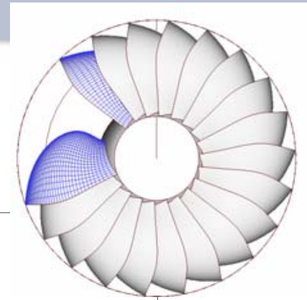
Improved runner performance

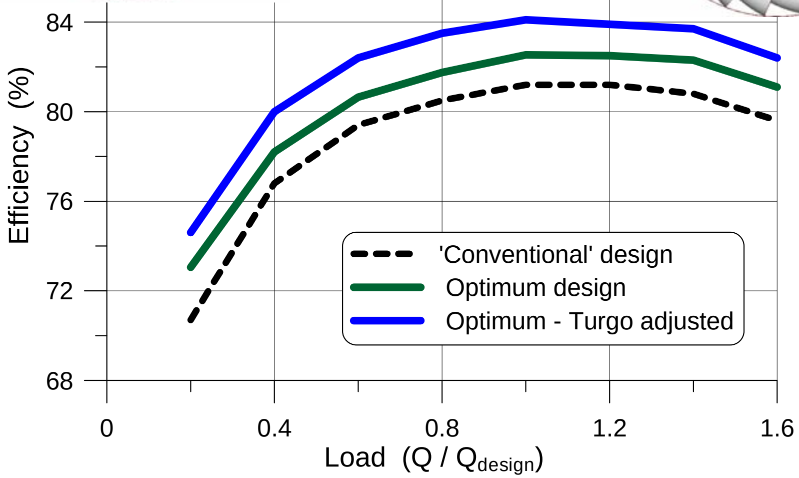
Real turbine

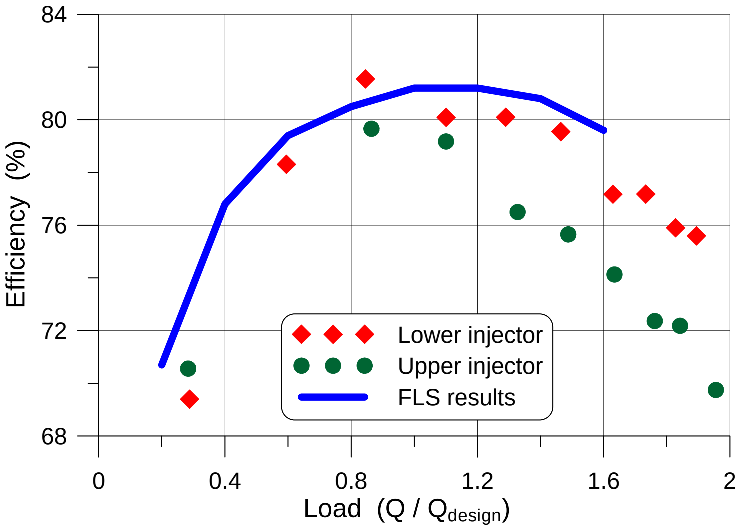


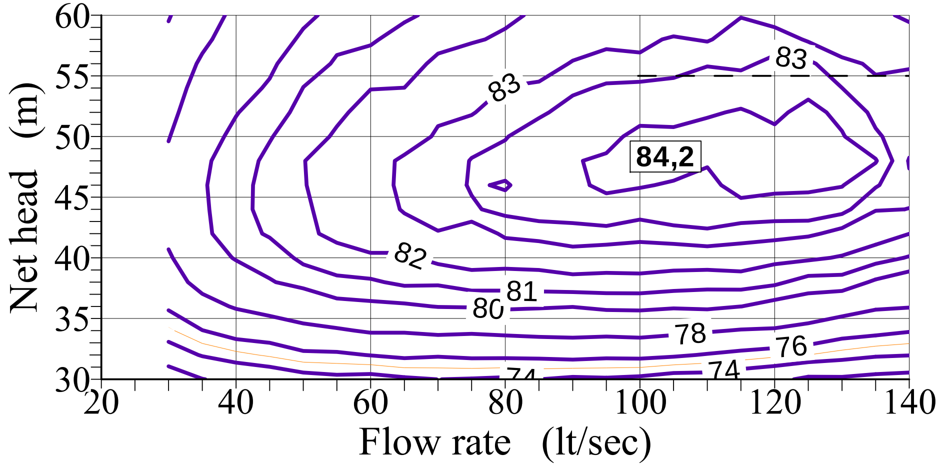
Improved designs





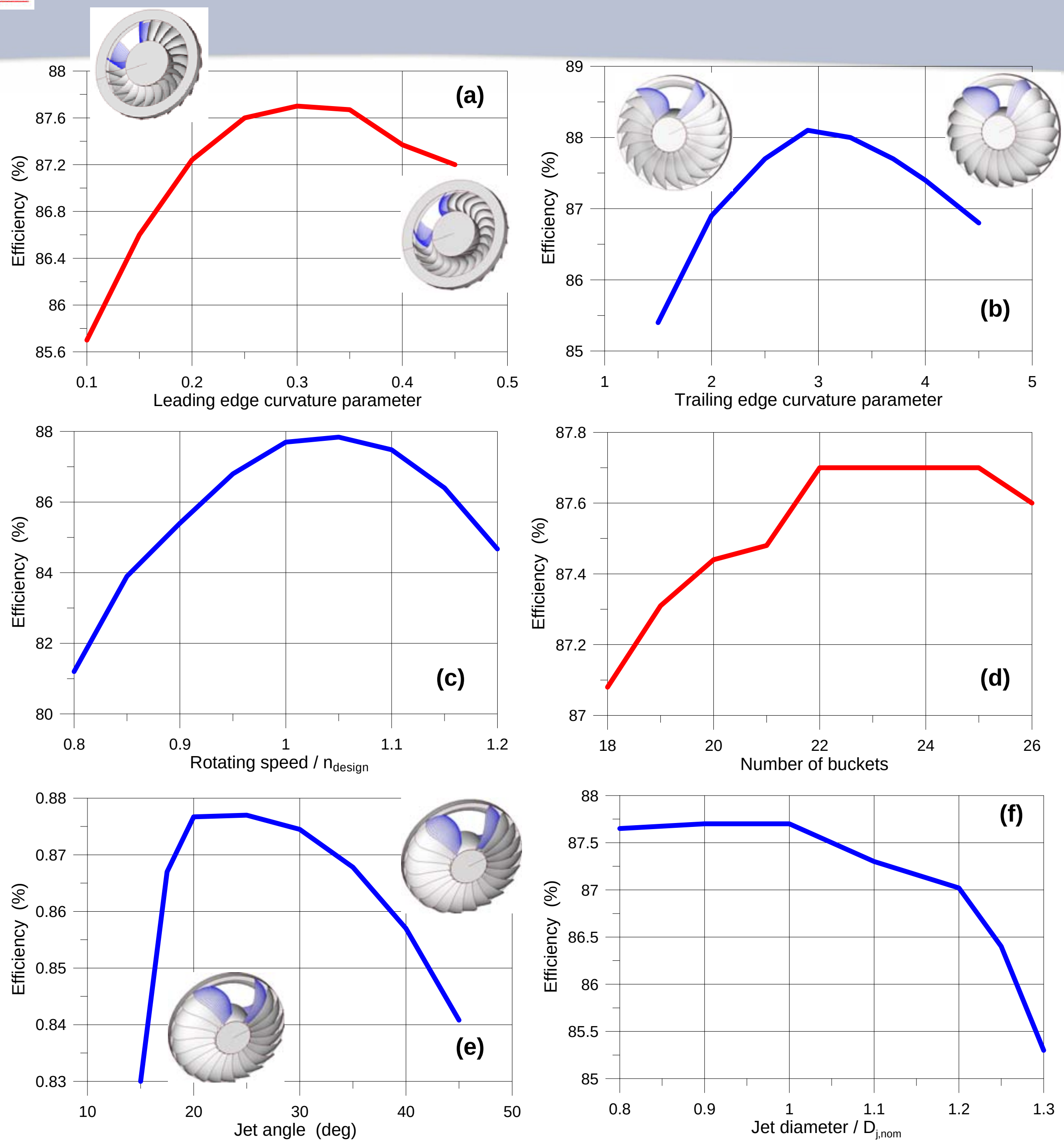




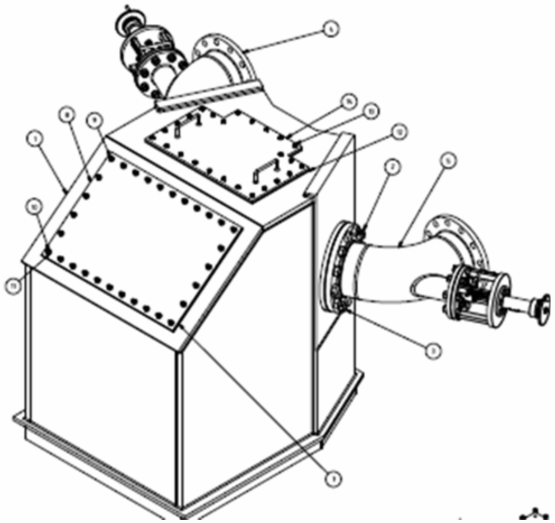


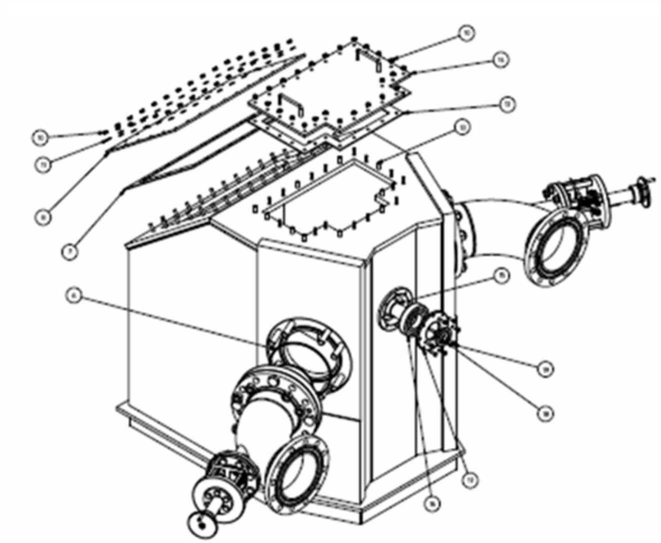
FLS results

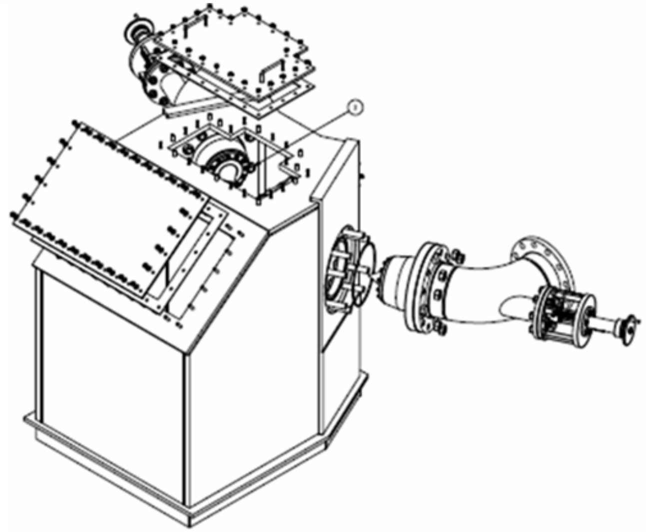
Parametric & Sensitivity design studies

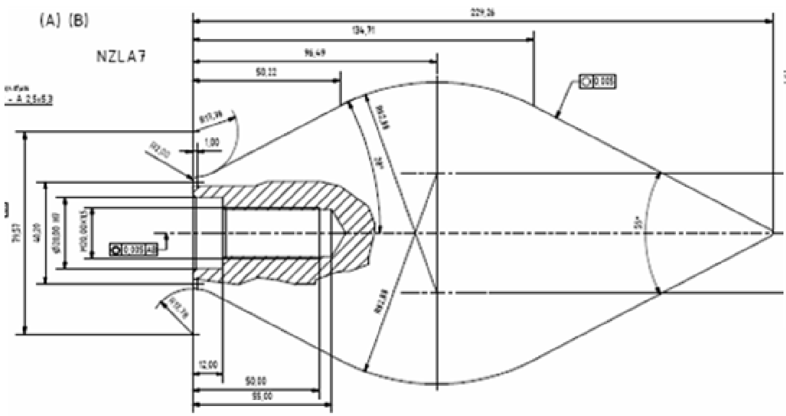


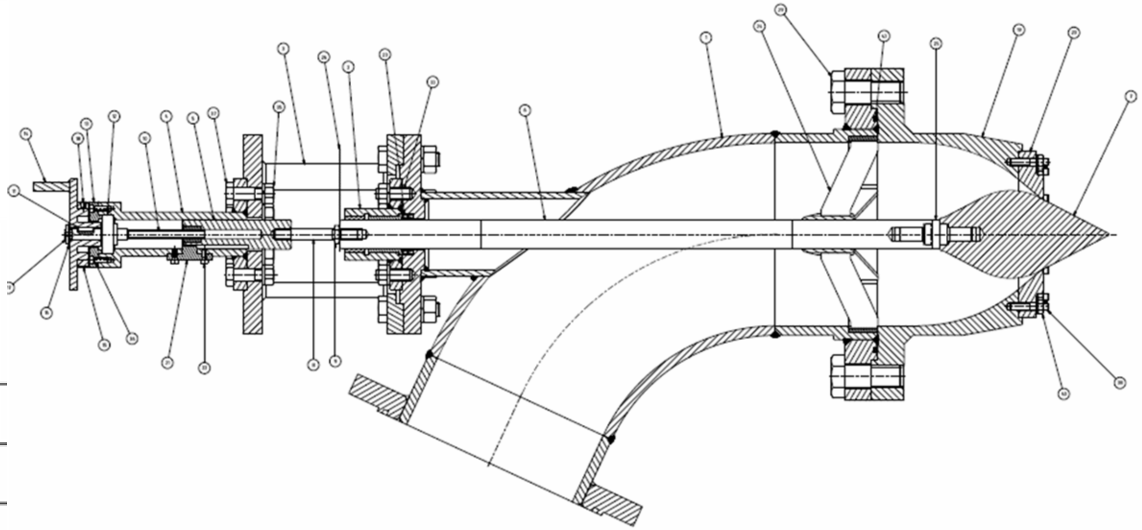
Model turbine construction drawings



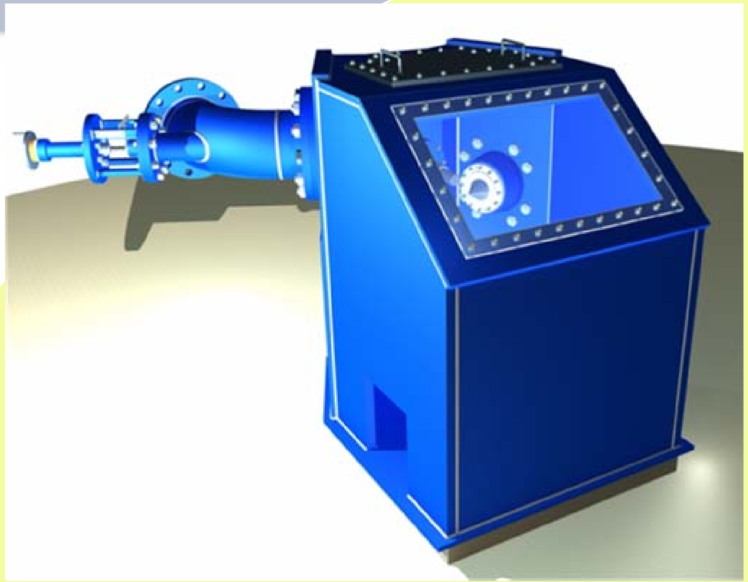


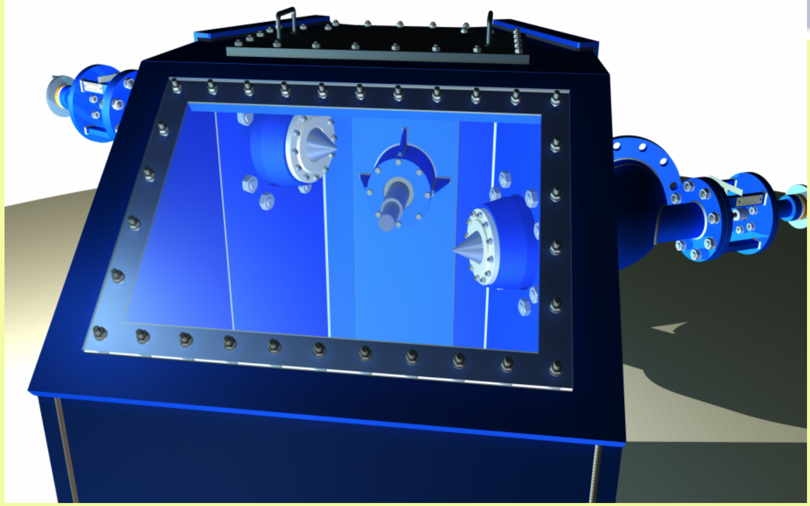


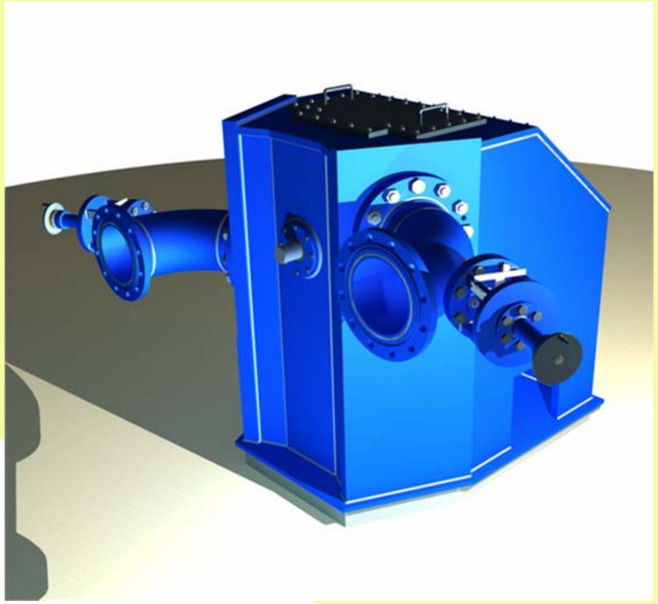


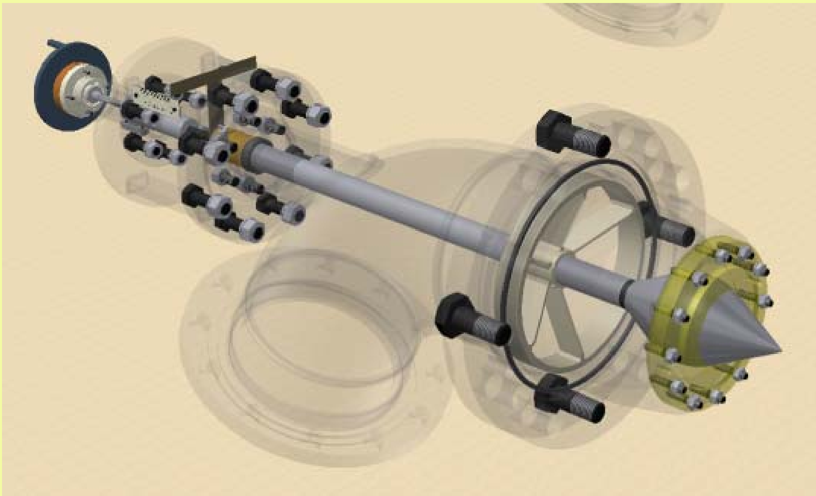


Model turbine computer views









Design of the casing and of the injectors of the model of Turgo turbine

Runner fabrication

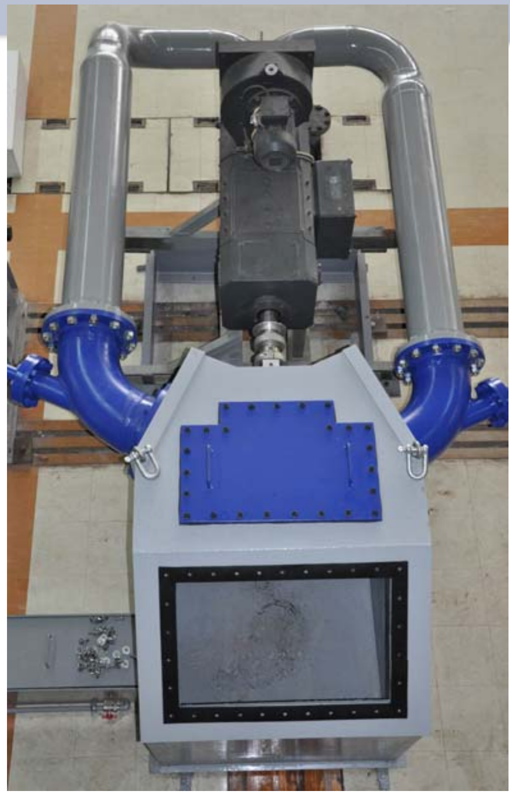
<u>*Separate fabrication of runner parts (blades, hub and shroud)*</u>

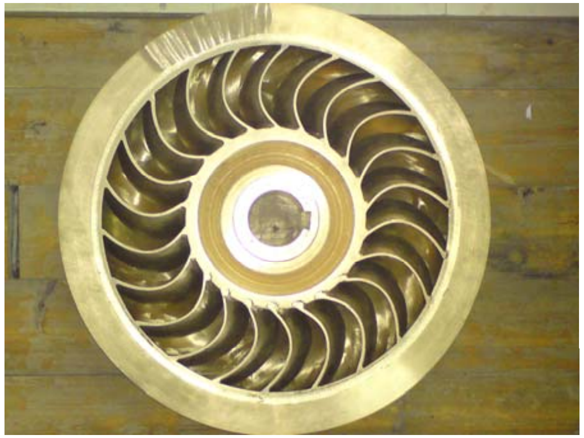
- Hub and Shroud with precision machining.
- Proper slots for blades fitting.
- Prototype blade constructed by composites using 3D-printing
- Use of plastic prototype to produce aluminium prototype
- Blades fabrication by bronze casting
- Internal blade surface polishing
- Final blade assembly with bronze welding
- Runner balancing

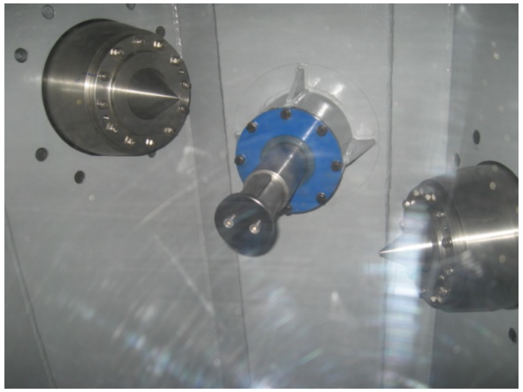
<u>*Features*</u>

More complex but more accurate construction methodology
Enhanced axial symmetry of the runner
Capability for particular mechanical manufacturing of the hydrodynamic profile of each separate blade if necessary

Test rig construction / adaptation







Closure

Flow analysis and design of action hydraulic turbines is a challenging and demanding task

Combination of numerical and experimental tools is required

The FLS model proved to be a reliable and handy tool. Further development and improvements are being considered.

Thank you!