PELTON TURBINE

1. The aim of the measurement

The aim of the measurement is the determination of the characteristic curves of an acid resistant Pelton turbine used as an energy recuperation device in chemical industrial processes. The characteristic quantities: Q, the water absorption rate, H, head, M_t, torque, η_t, turbine efficiency, n frequency. In case of turbines, specific quantities (corresponding to H = 1 m head and D = 1 m runner diameter) are used. In this measurement, for two different nozzle positions, we determine the following couplings:

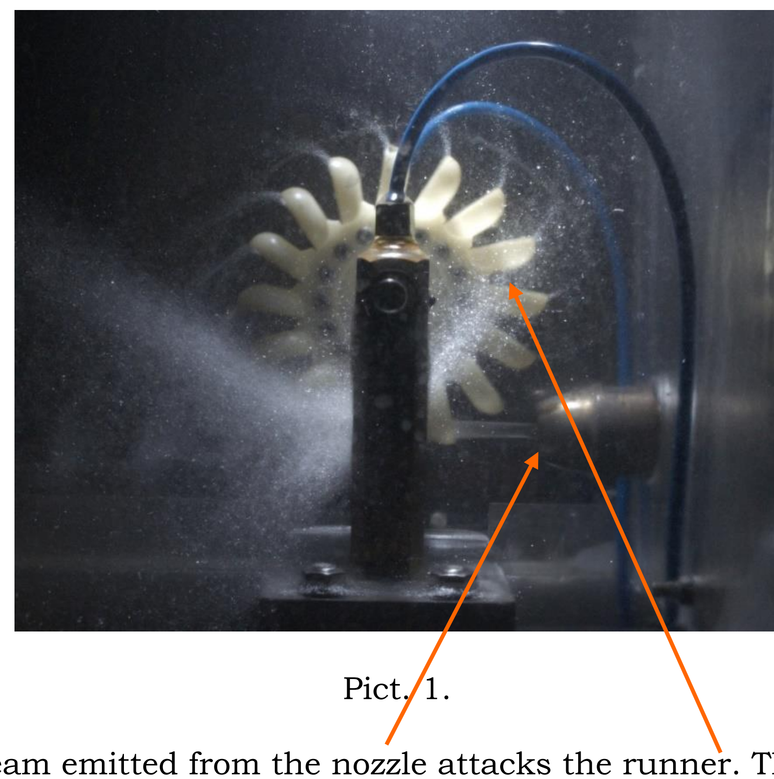
$M_{11} = f_2(n_{11})$ specific torque as a function of specific frequency,

$\eta_t = f_3(n_{11})$ turbine efficiency as a function of specific frequency,

$Q_{11} = f_1(n_{11,over})$ specific absorption rate as a function of specific overrun frequency.

2. The equipment

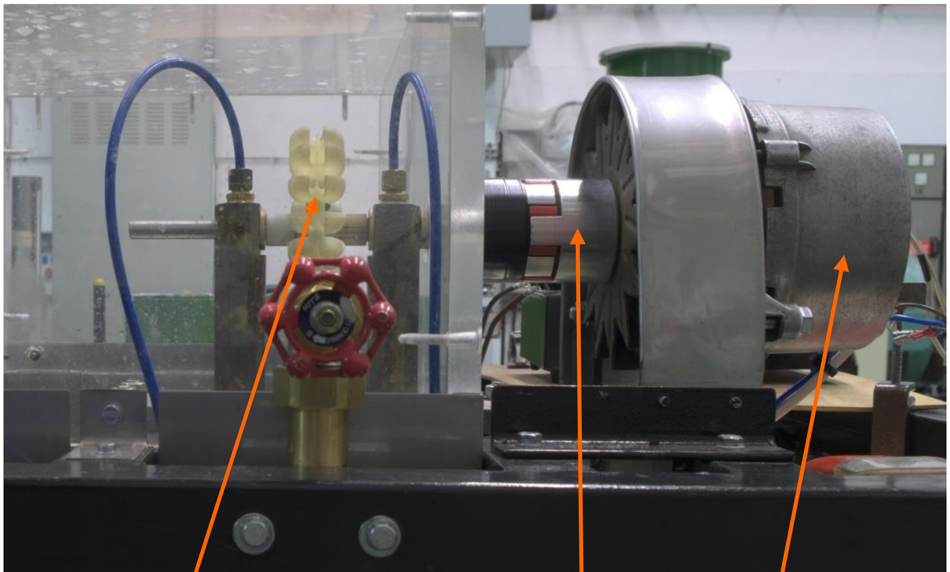
You can see the sketch of the equipment on Fig 1. and Pict. 3. The water beam attacking the runner of the turbine is sucked by the Wilo pump denoted by P, from the water reservoir denoted by W. Through the tube, water is pumped to the adjustable nozzle N, which it leaves as a well-directed free (i. e. atmospheric) water beam and attacks the runner R, see Pict. 1.



Pict. 1.

Water beam emitted from the nozzle attacks the runner. The change in the momentum of water triggers a torque exerted on the axis of the runner.

A jaw coupling transmits torque from the runner to the generator *G*, see Pict. 2.



Pict. 2.
Turbine runner – jaw coupling– generator

The generator is excited by supply *S*, with excitement current I_{exc}. The effective/working circuit of the generator includes a tunable resistance *Res* where loss in tension denoted by *U* occurs in the presence of electric current I_{work}, the product of these quantities gives the effective power $P_{eff,g}$ of the generator. The frequency *n* of the rotating part (called armature) is measured by an optical tachometer *O*. The turbine is shielded by a plexiglass box, water falls directly back from the turbine into the water reservoir *W*.

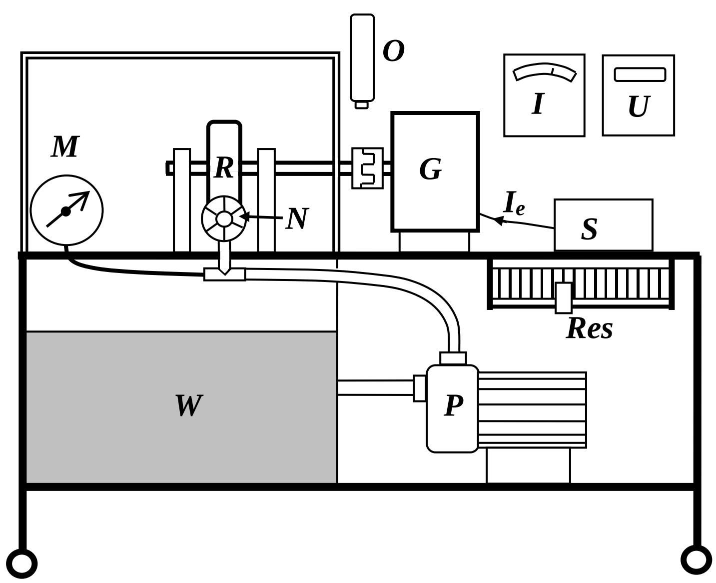
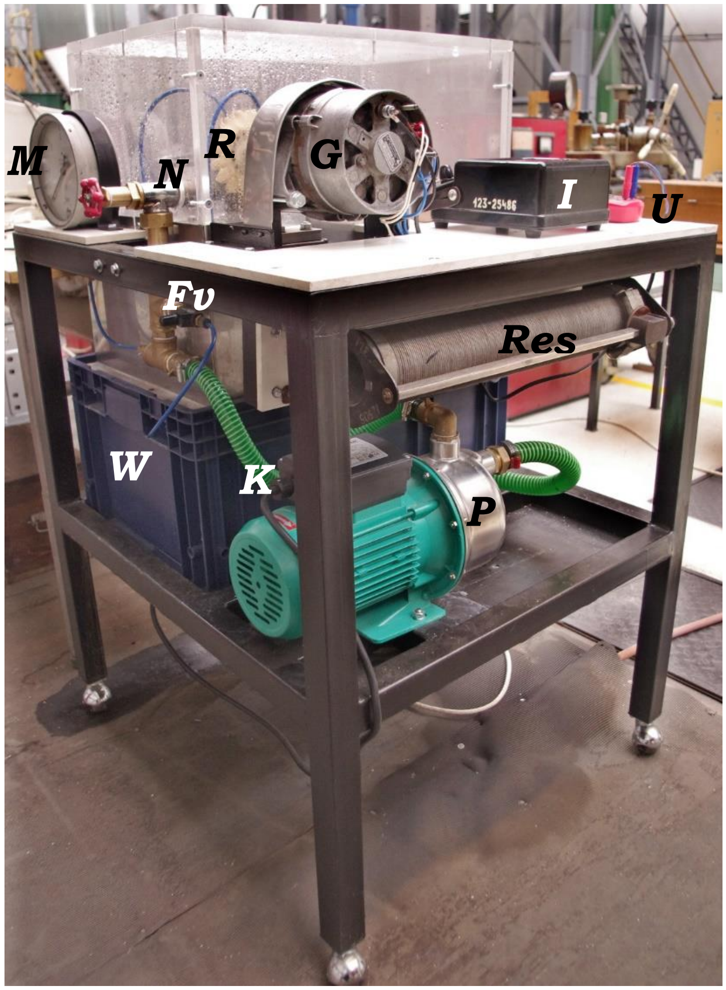


Fig. 1. Sketch of the Pelton turbine measuring equipment.



Pict. 3. The equipment with components denoted as above.

During measurement, we fix the nozzle (and thus the supply pressure p, shown by manometer M) in one position, and, by adjusting the resistance Res in the working circuit of the generator, we make one dataset by noting the U, I_{work} pairs together with frequency n. We make two separate datasets with two different nozzle positions for which the supply pressure lies in the 2,9 bar < p < 3,5 bar interval. After that, we measure the absorption rate as a function of overrun frequency. In this part of the measurement the circuit of the generator is interrupted which mimicks a station blackout of a real power plant. We vary the position of the nozzle in a way that the inequalities $p_{\min} < p <$ 3,9 bar hold for the supply pressure. Here $p_{\min}$ denotes the minimal pressure corresponding to a maximally open nozzle position, while 3,9 bar is the maximal supply pressure at which the water beam is capable of making the unloaded runner move. As the generator is unloaded, the turbine is only loaded by the frictional resistance of the bearings of the runner and the generator plus the resistance of the cooling ventilator of the generator.

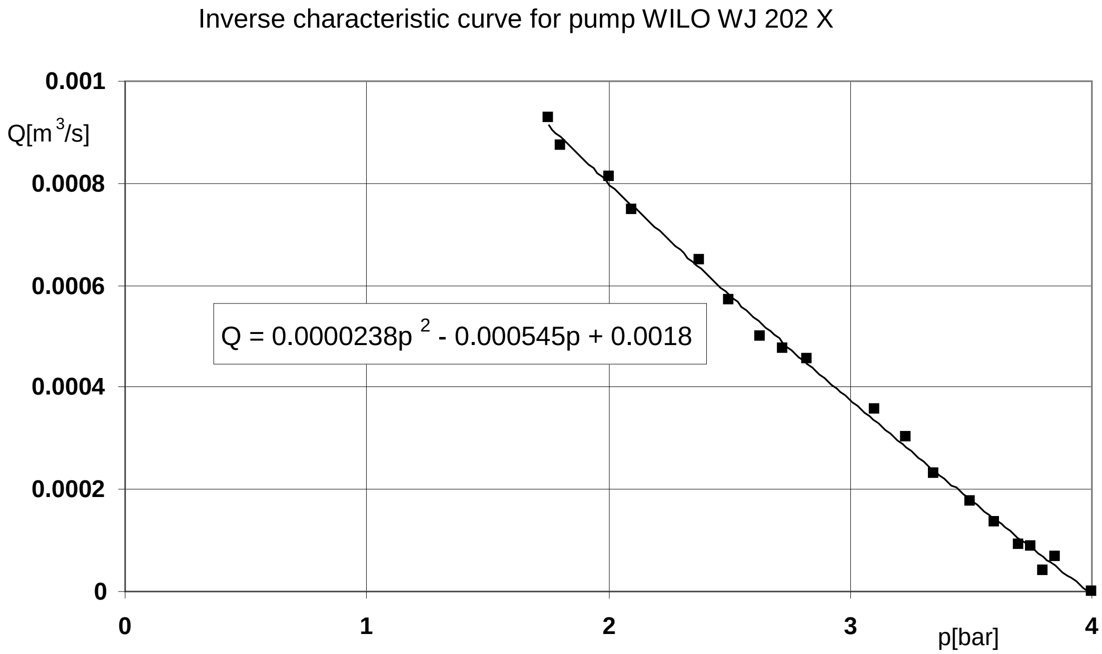


Fig. 2. Inverse characteristic curve $Q(p)$ of the pump-nozzle ensemble.

As can be figured out from the above mentioned description, we do not measure the absorption rate directly. We can do so, as the (inverse) characteristic curve $Q(p)$ of the water supply equipment has been determined previously, when the $Q - p$ pairs of the pump-nozzle ensemble have been determined. This curve is shown in Fig. 2. The obtained dataset enables us to define the function $Q(p)$. Fig. 2. contains the equation of the trendline $Q(p)$ as well.

The power input into the turbine is equal to the effective power of the supply pump, as the dissipation in the flexible tube between the pump and the nozzle can be neglected. This power can be calculated as $P_{in,t} = Q \cdot p$ as the pressure shown by manometer M is equal to the pressure supplied by the pump. As the unit of Q (see Fig. 2.) is m^3/s, which requires a pressure in Pa in order to obtain power in W, thus

$$P_{in,t}\,[W] = Q[m^3/s] \cdot p[bar] \cdot 10^5[Pa/bar]. \tag{1}$$

From the point of view of power transmission, the jaw coupling (see Pict. 2.) can be considered as rigid, thus the effective power of the turbine can be taken equal to the input power of the generator. However, we can only measure directly the effective power $P_{eff,g} = U \cdot I_{work}$ of the generator. U is directly shown in Volts on a digital voltmeter, current is shown in units as,

$$I_{work}[A] = c_I[A/unit] \cdot I'_{work}[unit]. \tag{2}$$

(Comma in the superscript of I_{work} serves as a distinction against dimensional discrepancies.)

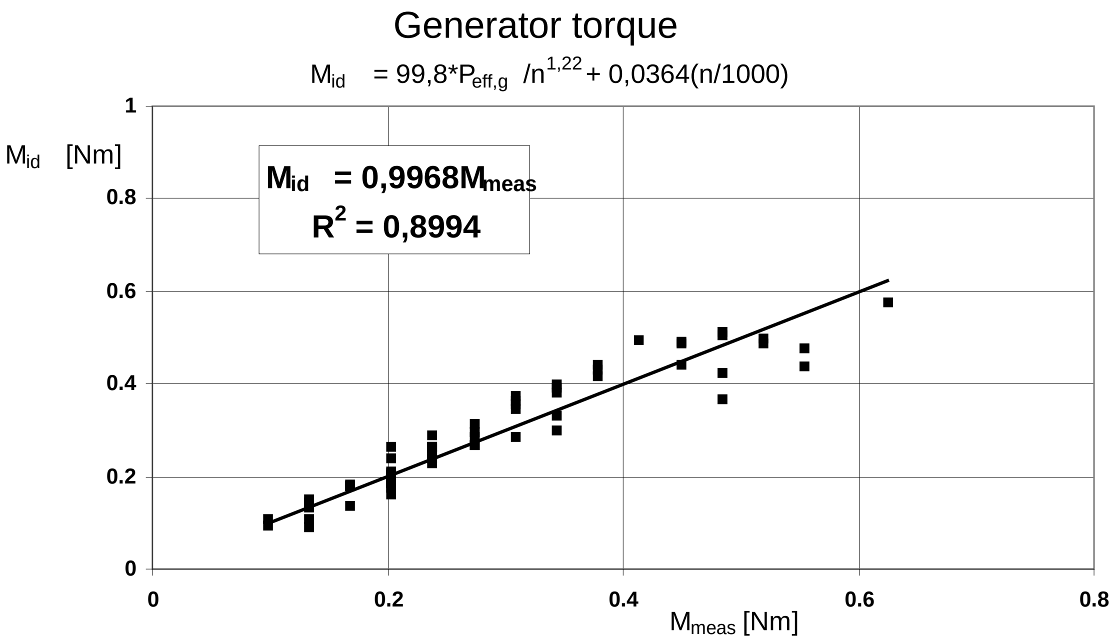


Fig. 3. Approximation of the torque acting on the generator as a function of effective power and armature frequency
Measurement intervals: $1280/min < n < 3000/min$; $0 < P_{eff,g} < 55\ W$

Multiplicator c_I is shown on the amperemeter.

A coupling can be observed between the torque M acting on the generator's axis, the effective power $P_{eff,g}$ and the armature frequency n. We have quantified this coupling with motors equipped with lever arms, in a manner identical to No. 2. measurement in the subject "Introduction to Mechanical Engineering". We have measured the balancing mass, armature frequency, the current and tension of the generator, while varying the resistance *Res* of the working circuit of the generator. The result is shown in Fig. 3., the approximative value of M_{id} as a function of armature frequency n $[1/min]$ and effective power $P_{eff,g}\ [W] = U{\cdot}I_{work}$:

$$M_{id} = M_{eff,t} = 99{,}8 \cdot \frac{P_{eff,g}}{n^{1{,}22}} + 0{,}0364 \frac{n}{1000}. \quad (3)$$

A linear function with a slope close to unity is a good approximation. We have indicated the correlation constant R (see subject Analysis of Technical and Economical Data) on Fig. 3. as well.

With the help of these previous measurements, students can easily calculate the torque exerted by the turbine, by measuring tension U, current I_{work}, and frequency n of the generator. From torque M_t and frequency n, the effective power $P_{eff,t}$ of the turbine is:

$$P_{eff,t} = M_t \cdot \omega = \left(\frac{99{,}8 \cdot P_{eff,g}}{n^{1{,}22}} + 0{,}0364 \cdot \frac{n}{1000}\right) \cdot \frac{2\pi \cdot n}{60} \quad (4)$$

The efficiency of the turbine from Eqs. (1) and (4):

$$\eta_t = \frac{P_{eff,t}}{P_{in,t}}. \tag{5}$$

3. Specific turbine characteristics

Characteristics of turbines are usually given by specific quantities. Specific quantities are transformations of genuine ones, corresponding to a runner diameter of $D = 1$ m, and water head of $H = 1$ m. Indices 11 refer to these values. Describing turbine properties in terms of specific quantities is a useful approach as it makes the comparison of runners working under different circumstances possible. This holds for a runner working at the basis of a high mountain, for a runner of a mill using the water of a creek, or for the runner of the department operating at different nozzle positions.

During transformations, we assume geometrical and fluid mechanical affinity. That is, we assume all speeds to be proportional to tangent velocity, which is proportional to the speed $\sqrt{2gH}$ of the water beam emitted by the nozzle. As gravitational acceleration is practically constant on the surface of Earth, the tangent velocity $u = \frac{D\pi n}{60}$ is proportional to $\sqrt{H}$,that is $u = \frac{D\pi n}{60} \approx \sqrt{H}$. We obtain $n \approx \frac{\sqrt{H}}{D}$, that is, $\frac{n \cdot D}{\sqrt{H}} = \text{const.} = \frac{n_{11} \cdot 1m}{\sqrt{1m}}$. We can finally write

$$n_{11} = \frac{nD}{\sqrt{H}}. \tag{6}$$

The absorption rate Q is the product of the speed of the water beam and its cross-sectional area, this latter quantity is proportional to D^2, according to the assumption mentioned above, velocity is proportional to $\sqrt{H}$, thus $Q \approx D^2 \cdot \sqrt{H}$, that is $\frac{Q}{D^2 \cdot \sqrt{H}} = \text{const.} = \frac{Q_{11}}{(1m)^2 \sqrt{1m}}$. We obtain the specific absorption rate as

$$Q_{11} = \frac{Q}{D^2 \sqrt{H}}. \tag{7}$$

Assuming efficiency η and water density ρ to be independent of transformation, $Mn \approx M\omega = P_{eff,t} \approx P_{in,t} = Q \cdot \rho g \cdot H \approx D^2 \sqrt{H} \cdot H$. Considering $n \approx \frac{\sqrt{H}}{D}$ on the left side, we obtain $M \frac{\sqrt{H}}{D} \approx D^2 \sqrt{H} \cdot H$, that is $M \approx D^3 H$. Finally, we get the specific torque as

$$M_{11} = \frac{M}{D^3 H}. \tag{8}$$

The head H of the turbine can be obtained from the pressure shown by manometer M as:

$$H[m]=\frac{p[Pa]}{\rho g}=\frac{10^5\ p[bar]}{\rho g}=\frac{10^5}{9810}p[bar]=10,2\cdot p[bar]. \qquad (9)$$

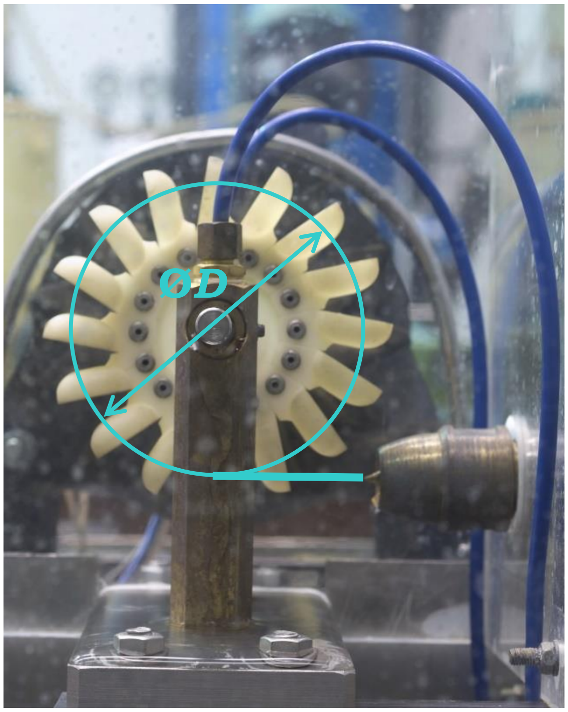
The characteristic frequency n_q is also applied for turbines. With the values of the optimal working point belonging to maximal efficiency, $n_q=\frac{n\cdot Q^{0,5}}{H^{0,75}}$, units are $1/min$, m^3/s, and m respectively. By substituting n from Eq. (6), Q from Eq. (7), we get: $n_q=\frac{\frac{n_{11}\sqrt{H}}{D}\cdot\left(Q_{11}D^2\sqrt{H}\right)^{0,5}}{H^{0,75}}$. After rearrangement, we obtain a more simple form for n_q from specific quantities as:

$$n_q=n_{11}\sqrt{Q_{11}}\ . \qquad (10)$$

4. Technical data of the experimental equipment, material properties

Diameter D of the runner consisting of 16 blades – the diameter at which water beam attacks the runner	83 mm
Type of pump	WILO WJ 202 X
Density ρ of water at measurement temperature	1000 kg/m^3
Type of generator	VEM 8042.401/2

Diameter D is twice the distance of the point of action of the water beam's centerline and the axis of the runner. (see Pict. 4.)



Picture 4. Runner of a Pelton turbine (left), and a Pelton blade (right). Water beam emitted by the nozzle reaches the runner at its nominal diameter **ØD**.

5. Preparations, delineation of measurement points

Before starting measurement, turn electric supply on. We switch nozzle N off. After that, we turn pump *P* on, by its switch K shown in Pict. 3. We open lubricating fine valve Fv for a short time (see Pict. 3.). If water appears around the bearings of the runner, we can switch the valve off as splashing water provides sufficient lubrication during measurement. We open nozzle N, and adjust the supply pressure as mentioned is Sec. 2. We measure the first point with an unloaded generator:

$$p\,[bar], n\,\left[\frac{1}{min}\right], U[V], I'_{work}\,[unit]\,. \tag{11}$$

After that, we switch the excitement circuit of the generator with current I_g on, and set about 10 measurement points until maximal load according to the instructions of the professor. Caution! Maximal load (i.e. maximal current I_{work}) may not occur at the end position of the adjustable resistance *Res*, but slightly before! Measurement points should be adjusted in more or less equal increments of current I_{work}. We note all quantities of Exp. (11) for each measurement point in a table. Meanwhile, the verification diagram should be drawn *simultaneously* in order to enable the professor to verify the progress of the measurement *live* (see below).

After the completion of a measurement at supply pressure p_1, we perform a new measurement and a dataset at supply pressure p_2 (again, with respect to the interval prescribed in Sec. 2, and the instructions of the professor.) We note the required quantities again, and insert the points of the new set into the same verification diagram with different symbols and/or colour.

We put the effective power of the generator ($P_{eff,g} = U \cdot I_{work}$) into the diagram instead of the efficiency as a function of specific armature frequency n_{11}, both curves representing different nozzle pressure in the same diagram. Fig. 4. shows an illustration without scales, in which the first dataset has been introduced. Points shown in red are invalid, they should be replaced by points measured at different positions of resistor *Res*!

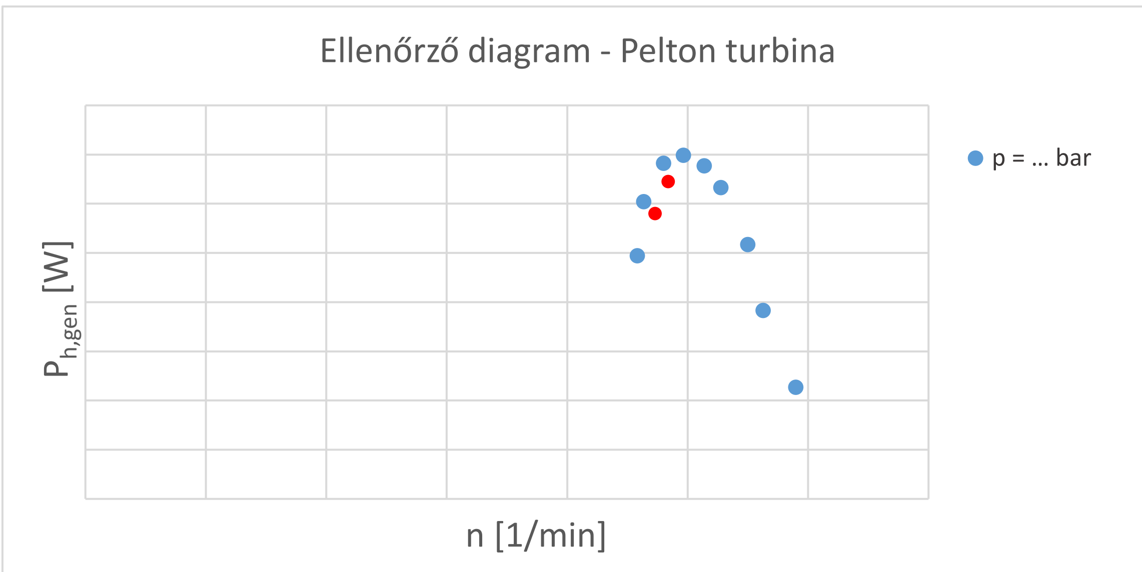


Fig. 4. Example for a verification diagram with false measurement points

Finally, we determine the coupling between overrun frequency n_{max} and supply pressure *p*. Absorption rate *Q* can be obtained from supply pressure *p* with the help of the trendline of Fig. 2. Knowledge of the overrun frequency is a must due to security reasons. In case of a sudden loss of load in the working circuit of the generator (as it may occur in a station blackout), the runner accelerates to overrun frequency so suddenly that shutdown processes of water supply cannot inhibit overrun. Therefore, weldings, screws, blades and all other components of the turbine should bear such a load without damage and considerable risk of accident.

6. Evaluation of the measurement, form of the evaluation report

All requirements concerning format and content (evaluation process, calculation of error propagations, etc.) are available on the hompage of the Department of Hydrodynamic Systems (**http://www.hds.bme.hu/oktatas.php?sm=1&lang=EN&xml=BMEGEVGBX01**).

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After a brief description of the equipment, the data should be evaluated according to Eqs. (1)-(5) in a table management software. After this, points of the curves $M_{11} = f_2(n_{11})$, $\eta_t = f_3(n_{11})$, $Q_{11} = f_1(n_{11,over})$ can be calculated from Eqs. (6)-(9), and curves can be plotted by the software. In the final diagrams, **two separate diagrams** should be drawn for the **two** different nozzle positions (unlike in the case of verification diagrams mentioned before), but the curves $M_{11} = f_2(n_{11})$ and $\eta_t = f_3(n_{11})$ for identical nozzle position should be plotted into the same diagram. For presenting two different quantities in the same graph, use the secondary axis as well! Backgroud should be white, different curves should have different colouring. Use thin, appropriate polynomial trendlines for a smooth approximation of measurement points. The **third diagram** is the one representing the $Q_{11} = f_1(n_{11,over})$ coupling. **Do not forget to give units for axes (and for all quantities of the entire document), even for specific quantities, with somewhat unconventional dimensions that can be figured out from Eqs. (6)-(8)!**

7. Preparation for the measurement

You should prepare for the measurement as follows:

- You should know the content of this document! The measurement starts with the verification of your knowledge.
- You should provide a prepared sheet in a table management software before measurement with a header containing all quantities of Exp. (11). The sheet should contain at least 20 lines. We will note the p – $n_{\max}$ pairs in another sheet in the $p_{\min} < p < 4$ bar interval mentioned in Sec. 2. This sheet should contain 12 lines!
- You should provide a graph paper as well for the preparing the verification diagram during measurement! The armature frequency should be the horizontal axis between 0-4000/*min,* the vertical axis should be that of the effective power of the generator in the range of 0-30 *W*.

8. Verification questions

1. Define specific quantities n_{11}, Q_{11} and M_{11}!
2. How can we measure the effective power of the turbine itself (without generator)?
3. Why is it sufficient to know the pressure shown by manometer M in order to determine the water absorption rate?
4. How can you define the efficiency of the turbine itself (without generator)?
5. What are the measurement devices used for obtaining the raw data?
6. Draw the sketch of the side view of a turbine runner when the axis of rotation of the runner is perpendicular to the plane of the drawing! Indicate the water beam together with the nominal diameter of the runner!

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7. Specify the aim and the process of the measurement and the settings of the equipment for the different datasets!
8. What kind of bearing does the runner axis have? How is it lubricated?
9. Pelton turbines operating in high mountains operate with permanent head, independent of water absorption rate. However, in the experimental equipment, while nozzle is adjusted, head varies together with absorption rate. Nevertheless, how can we compare results obtained from the equipment with characteristics of runners operating in power plants?
10. Why do we have to know the overrun frequency as a function of absorption rate?

9. Individual excercises

1. Calculate the nominal diameter and expected effective power in the optimal workingpoint of a Pelton-turbine that we obtain as a scaling of the experimental turbine, if we the following data are prescribed for the real scale runner:

a) n = 500 1/min, H = 625 m;

b) n = 750 1/min, H = 169 m!

2. Calculate the characteristic frequency of the measured turbine according to Eq. (10)! Give estimation for the optimal workingpoint with the help of the workingpoint of maximal efficiency on the basis of the dataset with

a) lower,

b) higher

absorption rate! (Caution! Higher absorption rate *Q* belongs to lower supply pressure *p*, and vice-versa!)

3. We want to empty a container filled with water of absolute pressure p_a, to atmospheric pressure in a way that its energy is recuperated by a Pelton turbine. The turbine would serve as the engine of a compressor operating at frequency n_{comp}. Specify the nominal diameter of the upscaled runner if we want the turbine to function at maximum efficiency in case of the following prescriptions:

a) p_a = 14 bar, n_{comp} = 1000 1/min;

b) p_a = 12 bar, n_{comp} = 1000 1/min?

10. Support for calculation of error propagation

Making marginal neglections in the function of *Q(p)*, we can estimate the absolute error in the absorption rate as $E_Q = 4\cdot10^{-5}$ m^3/s. Furthermore, *uniquely for calculation of error propagation*, we can approximate the torque of the turbine with $M_t = 100 \cdot P_{eff,g}/n^{1,2}$.Substituting this into Eq. (4) and then into Eq. (5), we obtain:

$$\eta_t[-] = \frac{\pi}{3 \cdot 10^4} \cdot \frac{P_{eff,g}[W]}{Q[m^3/s] \cdot p[bar] \cdot \sqrt[5]{n[1/min]}}. \tag{E1}$$

During this measurement, error propagation should be calculated uniquely for curve $\eta_t = f_3(n_{11})$, the absolute error of efficiency should be calculated from Eq. (E1).

The precision of the measured data:

- Optical tachometer: ± 0,2% of the measuring limit (20000 1/min)
- Amperemeter: Precision class 2 (measuring limit = 10 units)
- Voltmeter: ± 0,2% of the measuring limit (m.l. = 20 V)
- Manometer: Precision class 1,6. (m.l. = 6 bar)
- The diameter of the runner can be considered error-free.

Precision class gives the absolute error of a device valid for the entire measuring range in percents of the measuring limit. For example the absolute error of an amperemeter of precision class 2,5 with measuring limit of 20 A is equal to E_{ampere} = 20 [A]·0,025 = 0,5 [A].