Co-funded by the Erasmus+ Programme of the European Union

The Physics of Water

Respective blueprint	The Watermill
Description	In this pedagogical sequence students will learn the properties of water, and hydraulic energy using a home-made watermill.
Learning Objectives	Students will: - Learn how to create a home-made watermill - Understand the principle of hydraulic energy - Be able to create a water wheel and mill mechanism

Related curricular subject(s)	Physics, History
Prerequisites / preparatory actions for teachers	Teachers should gather the materials for the blueprint
Prerequisites / preparatory actions for students	Understand the basics of physics, know how to create and make a watermill work. Have basic knowledge on the principle of hydraulic energy.
Age of students	12-15
Duration	3-4 hours
Level of difficulty	**Hard**

Step by step description of the tasks

Step 1: The history of the watermill

Figure 1 Image Source: Photo by Drew Bae, 2020-06-02, Public Domain, https://unsplash.com/photos/gIl5b7JPREo

The teacher introduces the watermill and its story.

The watermill is a traditional machine, invented in ancient times, which uses hydraulic energy, i.e. the energy of watercourses, to grind grain, but also for all sorts of craft applications such as forges, sawmills and paper mills.

In the Middle Ages, the driving force of mills was used all over Europe to turn grain into flour, nuts into oil, hemp into scuttle. Mills became an essential part of village life, just like churches and castles, and were usually owned by lords, wealthy citizens or monastic institutions.

The golden age of water mills was between the 18th and 19th centuries. Small family or semi-artisanal mills multiplied on the smallest stream.

Step 2: How does a watermill work?

In order to operate, a mill must have a certain height of waterfall (except for the run-of-river wheels, which operate immersed in the current). Mills had to be close to the villages to allow everyone to grind their grain. They could not be built in an area that was too hilly, where there were waterfalls.

A small intake dam was therefore used to take part of the river's flow and then a feeder canal, also called a reach. It sometimes starts several hundred meters from the mill, almost horizontally, while the river has a natural slope. Thus, at the mill, the feeder channel is higher than the river. This difference is used to operate the horizontal and vertical water wheels (except for the run-of-river wheels). Sometimes there is a water body in the installation (at the end of the canal or across the river) which serves as a reservoir.

The wheel used depends on the available drop height. Above 3 meters, there are vertical wheels on top or horizontal wheels. Below 3 meters, chest wheels and side wheels are used.

Once the water has passed through the wheel, it passes through an outlet channel and is returned to the river. The wheel is usually connected to a set of gears, or to a dynamometer system (in the case of modern-day electricity turbines).
A typical watermill provides between 3,000 and 30,000 watts of power, depending on the flow rate it is able to harness and the height of the

waterfall (the difference between the level at which the water enters and the level at which it leaves).

Some old mills have been equipped to produce electricity or completely converted into small hydroelectric power stations. However, most hydroelectric power plants have been installed on new sites to exploit much greater power due to technical advances and the possibility of using energy elsewhere (remotely) with electricity.

Step 3: Technics

In most cases the impeller is vertical (horizontal axis).

- In a run-of-river mill, the water flowing in the river or reach drives the paddle wheel from below.

Figure 2 Source: Pixabay

- By leading the water over the wheel, it is the fall of the water that transmits its energy to the wheel; the use of bucket wheels allows a higher efficiency.

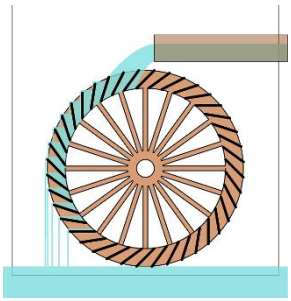

Figure 3 Source: Pixabay

- The water can also flow under the wheel, transmitting some of its kinetic energy to the wheel.

From the industrial revolution onwards, and more so in the 20th century, some mills use a horizontal wheel (with a vertical axis) also known as a "turbine", particularly in the case of "impoundment" mills,

which are generally of modest size. The water level is maintained at a sufficient height upstream of the mill by a weir.

Step 4: Different uses

Water mills were used for many purposes before the industrial era, such as:

- grinding grain, the oldest use;

- in the forestry industry, sawmills;

- for textiles: fulling machines, weaving looms;

- for metalworking: millstones, forges, hammer drills;

- to drive pumps.

- paper mill: from the 13th to the 18th century, the energy of the mill was used to reduce soaked rags into paper pulp by activating pestles fitted with spikes. In the 19th century, it also powered the continuous paper machine, but the term mill was abandoned in **favour** of the term paper mill.

Step 5: What is hydraulic energy?

Hydropower uses the kinetic force of the movement of water in all its forms (waterfalls, currents in rivers and other streams) to produce energy. This process is an indirect manifestation of solar energy and the Moon's force of gravity in the life cycle of water: solar energy causes water vapor in the oceans and seas to form clouds and be blown by the

wind into rain and snow, which then feed lakes, rivers, seas and oceans. Thus, it is the combination of several renewable energy sources that indirectly contribute to the production of hydropower.

The power of water has been used since ancient times via water mills to provide mechanical energy - direct energy without further processing - for making paper or grinding grain, drawing water, etc.

The advent of the industrial era in the 19th century saw the first uses of waterpower through dams, produced by waterfalls in hydroelectric power stations.

Step 6: The physics of Converting Energy or improving efficiency

The principle of a waterwheel resides in the initial turns of the wheel caused by the force of water. The water wheel turns constantly, but how to harness the energy to the best of our ability? The original idea is that, thanks to a set of gears, the big water wheel turns a big gear on the same axel, which is attached to a small gear. Gears systems are based on the principle of mechanical advantage: the ratio of output force to input force in a system. In the case of gears ratio, this mechanical advantage depends on the ratio between the final gear's speed and the first gear's speed in a gear train.

The mechanical advantage is:

$$MA = \frac{\omega_A}{\omega_B} = \frac{r_B}{r_A} = \frac{N_B}{N_A}$$

Where:

- N is the number of teeth on the gear,
- ω is the angular velocity of the gear and
- r is the radius of the gear.

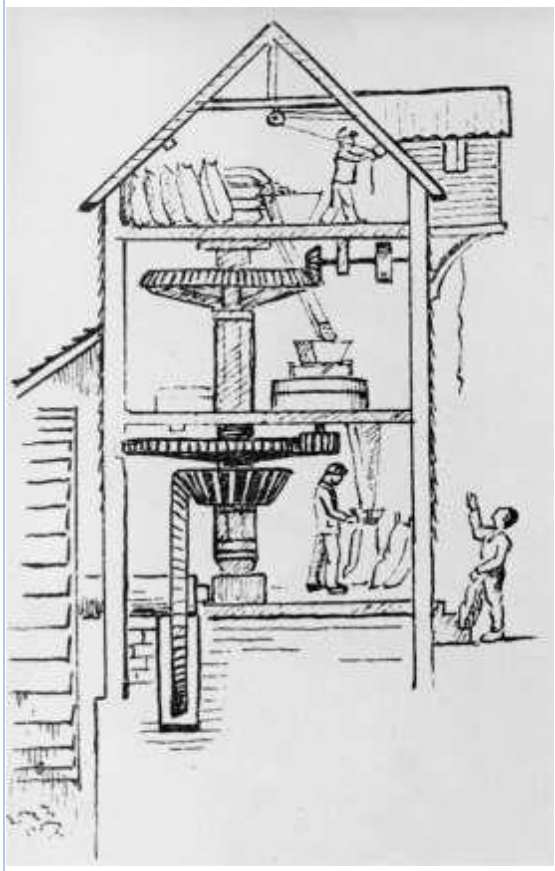

Figure 4 Image borrowed from Norfolk Mills at http://www.norfolkmills.co.uk/watermill-machinery.html

In the case of a waterwheel, the first big gear will make the small one will turn. For each revolution of the first big one, the small one will turn 3 times faster if its radius is 3 times smaller. On the same axel as the small gear, we have a big gear again at the other end. This big gear will make another small one turn which will usually be attached to the millstones. This way, the miller can have a gear system that exploits the water energy to make the millstones turn and create flour with nothing but the water energy.[1]

[1] J.M.K.C. Donev et al. (2018). Energy Education - Gear [Online]. Available: https://energyeducation.ca/encyclopedia/Gear. [Accessed: April 8, 2022].

Step 7: In which other situation can you imagine we use gears and a mechanical advantage?

Make a brainstorming session with the students and take note of all their suggestions. You can then complete the suggestions with you own.

Gears are used in:

- Cars
- Bicycles
- Clocks
- Mills
- Etc.

Conclusion

In this lesson the students learn about the different uses of watermills and the principle of hydraulic energy. They learn how to create a home-made watermill and make it work. They learn about mechanical advantage and gears systems.

Assessment activities

Activity 1. Find information about the different types of watermills and present them to the class.

Activity 2. Search for videos explaining the hydraulic energy principle.

Activity 3. Collect photos of elements created by waterpower/water mills and to integrate them with extraneous images. Ask the pupils which ones are correct.

References:

- Histoire pour tous - de France et du Monde (2021, 29 décembre). *Invention du moulin à eau (-200).* https://www.histoire-pour-tous.fr/inventions/700-invention-du-moulin-a-eau-200.html
- Selectra (2022, 31 mars). *Energie hydraulique : sa définition, ses avantages et inconvénients.* https://selectra.info/energie/guides/environnement/hydraulique
- Société d'Archéologie et d'Histoire de la Mayenne. *FICHE MOULIN A EAU.* (http://histoire.mayenne.53.free.fr/lexmoulinaeau.pdf
- Techno-Science. *Moulin à eau – Définition et Explications.* https://www.techno-science.net/definition/3421.html
- Vikidia (2021, 27 novembre). *Moulin à eau*. (https://fr.vikidia.org/wiki/Moulin_%C3%A0_eau

- J.M.K.C. Donev et al. (2018). Energy Education - Gear [Online]. Available: https://energyeducation.ca/encyclopedia/Gear. [Accessed: April 8, 2022].
- Figure 1: Public Domain, unsplash
- Figure 2 and 3: Pixabay
- Figure 4: borrowed from Norfolk Mills at http://www.norfolkmills.co.uk/watermill-machinery.html