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## Declaration

I hereby declare that this thesis is my own work, that I have not presented it elsewhere for examination purposes and that I have not used any sources or aids other than those stated. I have marked verbatim and indirect quotations as such.

Ingolstadt, 15 January 2024



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Rushabh Deepak Miyani

## Abstract

In this thesis, the designing and detailing of a patented hydroelectric energy storage system is documented. Hydropower has been one of the oldest sources of electricity for humankind. This thesis is focused on the idea of manufacturing a hydropower plant to a scale that would be feasible and useful for an average household of 4 people. It also includes the processes and guidelines to manufacture the parts of this energy storage. In current times, renewable sources of energy production are increasing, relevant to earlier years, to reduce the dependence of the world energy needs on fossil fuels. Storing this renewable energy is important and due to limited natural resources like Lithium, Nickel etc. for Battery storage, other viable storage technologies need to be developed such as HEES. Hydro-electric Energy Storage (HEES) is an innovative energy storage concept that utilizes hydropower as energy storage. This paper focuses on the design of the Pelton turbine and the nozzle for a prototype of the HEES. Specifically, the runner, the method used to fix the Buckets on a Pelton runner, and the casing for the runner are analyzed in detail. The HEES nozzle is a critical component responsible for precisely directing high-pressure water jets onto the turbine's rotating buckets.

The study explores the intricacies of Pelton turbine design, including considerations for bucket width, depth, and attachment methods. The importance of nozzle technology for creating ultra-thin water jets and the design of a casing for the high-speed Pelton turbine is also examined. Material selection is a critical aspect, involving stainless steels with varying properties, including corrosion resistance, strength, and weldability. The evaluation and comparison of these materials lead to informed decisions for prototype and final designs. In the context of manufacturing, various methods, such as CNC machining, forming, stamping, forging, and powder metallurgy, are assessed. A detailed analysis highlights the strengths and weaknesses of each approach. For the HEES prototype, a manufacturing method is chosen based on cost-effectiveness and suitability for aluminium, while the final design leans toward stainless steel and methods that ensure strength, precision, and durability. In the ever-evolving landscape of renewable energy, this thesis contributes to the development of a promising Hydro-Energy Storage System, laying the foundation for sustainable and efficient household energy storage solutions.

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## List of Abbreviations

HEES Hydro-Electric Energy Storage

HPP Hydropower power plant

NCM Nozzle clearance mechanism

SS Stainless Steel

HSS High strength steel

MIM Metal Injection Moldingg

$d_{jet}$  Jet diameter

$P$  Power

$\Delta p$  Operating pressure

$\beta_2$  Angle of deflection (Pelton bucket)

$\rho_w$  Water density

$V_{wasser}$  Volume of water

$t$  Time

$d_{jet}$  Jet diameter

# 1 Introduction

Energy is the lifeblood of human civilization, powering our homes, industries, and progress. It fuels the machinery of modernity, illuminating our cities, propelling our vehicles and igniting development overall. In an era marked by environmental consciousness and a fervent quest for sustainability, the thirst for clean and efficient energy solutions has never been more profound. The pages that follow embark on a journey into the heart of this quest, unveiling the potential of Hydro-Electric Energy Storage (HEES). Against the backdrop of mounting global energy demands and ecological imperatives, this thesis ventures into the intricate realm of HEES, where innovation, precision and sustainability converge to redefine our energy landscape. In this part of the thesis the basics of Hydropower and energy production is discussed briefly. The need for HEES for energy storage is explained.

## 1.1 Energy Requirements

Energy is one of the basic needs of human beings. It is used in various forms throughout the day including electrical, mechanical, chemical, heat and many more. The graph below represents global energy consumption and shows that energy consumption has increased over the last 20 years (Figure 1).

According to statistics from the Renewable Energy Agency, in Germany the gross electricity consumption was about 562 TWh in 2021. About 237 TWh consumed energy out of the 562 TWh was generated from renewable energies, which corresponds to an approximate percentage share of 42% of the total consumed energy [AEE 2022].

Renewable energy is energy derived from natural sources that are replenished at a higher rate than they are consumed. Sunlight and wind, for example, are such sources that are constantly being replenished. Renewable energy sources are plentiful and all around. [Mills, B. 2023]

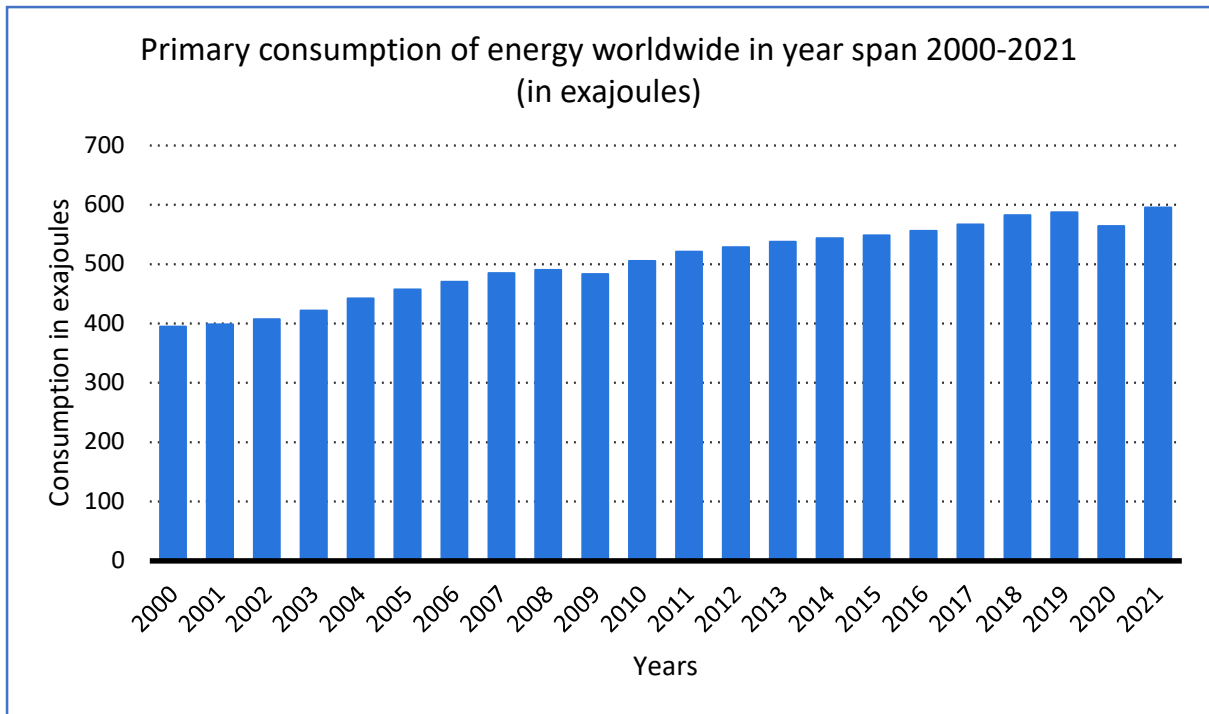


Figure 1: Primary consumption of energy worldwide in year span 2000 to 2021 [Statistical Review of World Energy 2022. (2022, July 1)]

However, renewable energy is flow limited. Renewable resources are theoretically inexhaustible in duration but limited in the amount of energy that is available per unit of time. [U.S. Energy Information Administration, 2022]

The energy produced through renewable sources has also increased over the years. The line graph in figure 2 shows the percentage contribution of renewable energy sources in Germany from year 1990 to 2021 (Figure 2).

The reason for the shift towards renewable sources, as shown in Figure 2, is the initiative towards a world with clean energy and to reduce the dependence on fossil fuels, which are non-replenishable and only available in fixed amounts.

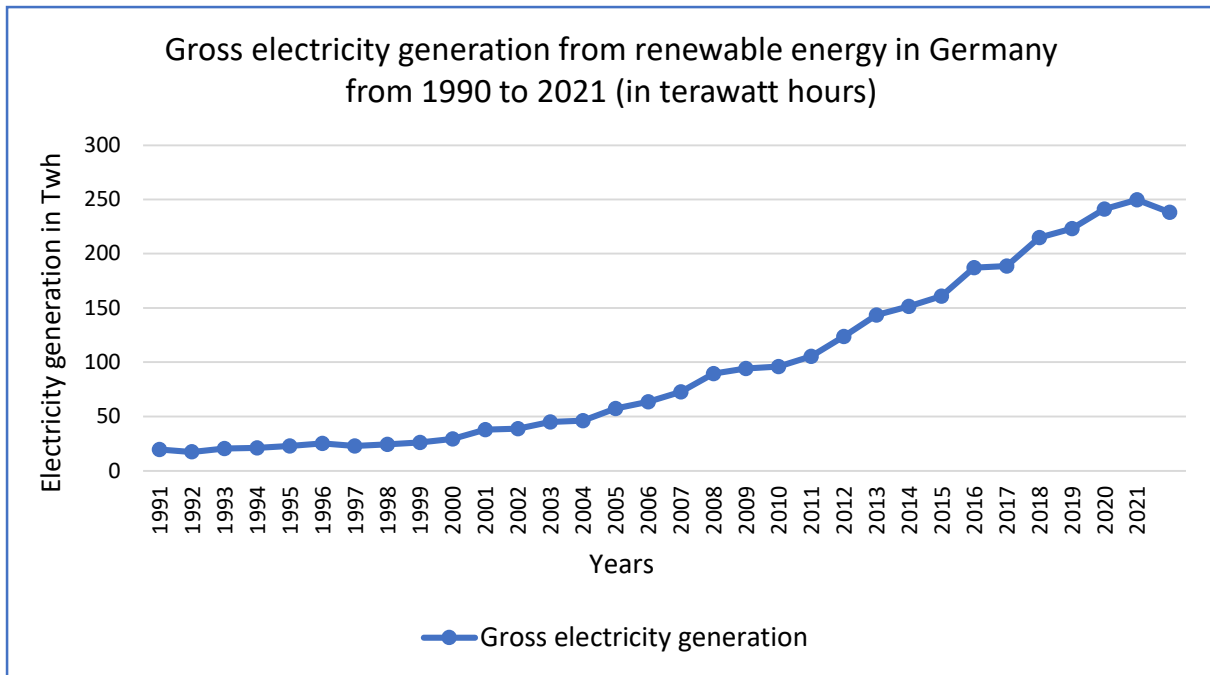


Figure 2: Gross electricity generation from renewable energy in Germany from 1990 to 2021 (in terawatt hours). Source [AGEB., 2023].

There are several renewable sources of energy production. The graph below shows the increasing contribution of different renewable sources between the years 2011-2021. (Figure 3)

The environmental goals set by Germany result in the increased production of energy from renewable sources in Germany. Considering 19.7 TWh Hydropower energy out of the total energy production for Germany of 237 TWh (Figure 2 and 3). Hydroelectric energy makes up around 8.3% of all renewable energy produced. Despite being one of the oldest sources of electrical energy, hydropower has a comparatively low contribution due to the factor of limited geographical locations for hydro-powerplants across Germany. Suitable sites for hydropower are mostly already developed and in use. Other renewable sources like solar and wind contribute significantly more due to scalability and lower cost of the technology per unit. However, wind and solar energy are not perfect sources of energy supply as they have the issue of security of supply.

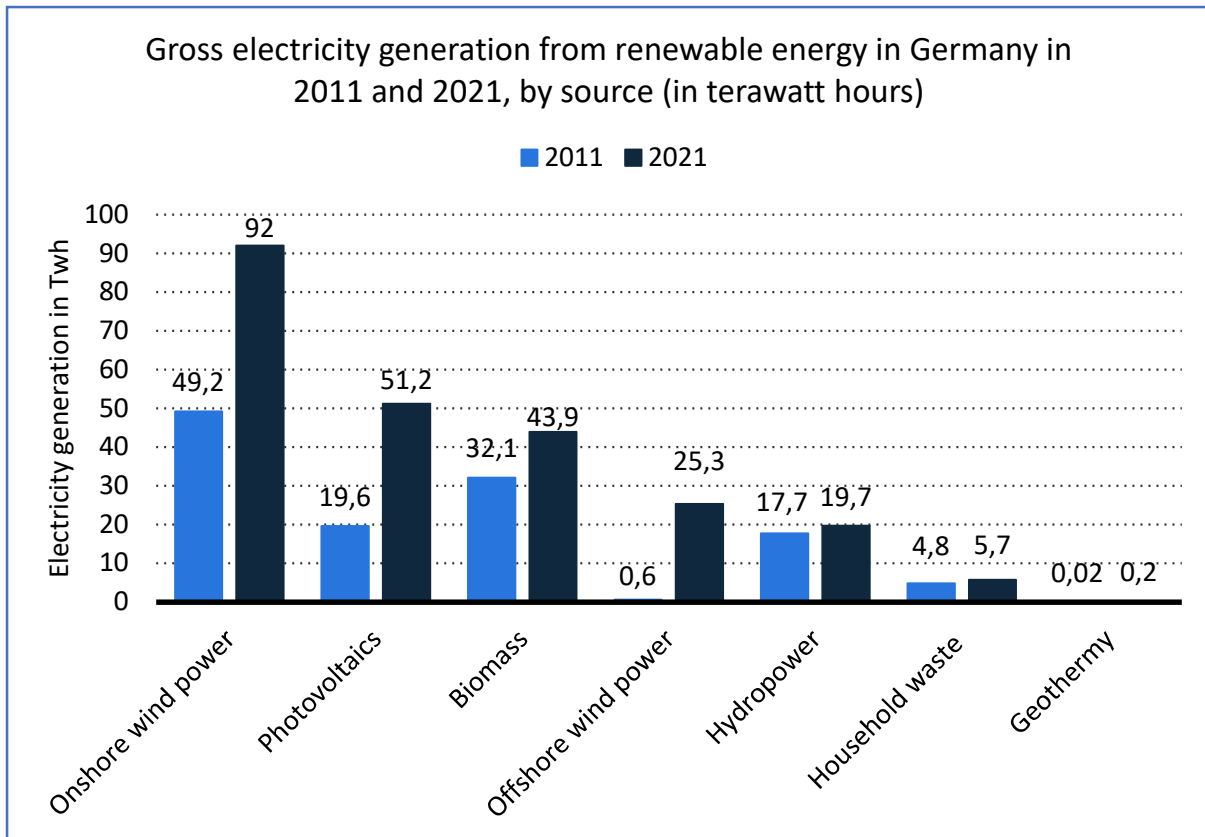


Figure 3: Gross electricity generation from renewable energy in Germany in 2011 and 2021, by source (in terawatt hours) Source [*Electricity generation from renewable energy Germany 2012-2022*, (2022)].

Solar and wind power have a high dependence on weather conditions, which are variable. Hence solar and wind power are irregular sources meaning that the energy supply generated is not constant thus the surplus energy must be stored during clear weather conditions, for other times of the year. As a result, energy storage systems have become very vital to the whole renewable energy production, distribution, and consumption system. Therefore, there is a need to research and innovate every possible potential technology to achieve the required climate targets. HEES is one of these potential technologies that could play a very important role in storing energy.

A big height difference between two water reservoirs is an ideal requirement for a hydro-powerplant. Head is the distance of the water level from its bed (Zhang, 2016). The high head required for hydro-powerplants is not available everywhere. One innovative approach, to further use the development of hydropower as energy storage, is to simulate the height difference by storing water in a hydropneumatic tank at

extremely high pressure. This high pressurized water flows through a small diameter nozzle to create a small water jet. In this way, the high efficiency of hydropower can be combined with the independent location of a pressure reservoir. [Niβl, 2022]

The basic idea behind the operation of the system is that a transfer medium (in this case water) is first stored in a hydraulic accumulator. This water is separated from the rest of HEES by valves, which is kept at very high pressure. A pump pressurizes the gas within the accumulator until a desired pressure difference is achieved. When a valve to a turbine is opened, the water flows through a nozzle, which produces a thin jet of water at high velocity.

## 1.2 Pressurized water jet

The pressurized water in the tank is projected onto a Pelton turbine in the form of a waterjet through a nozzle. The waterjet has a high kinetic energy and with the help of a Pelton turbine this kinetic energy is converted into rotational mechanical energy. There is a shaft connected from the Pelton turbine to a generator which converts the rotational mechanical energy into electrical energy. This entire process converts the pressurized energy of the stored liquid (water) at high pressure into electrical energy using a Pelton turbine. The diagram below (Figure 4) illustrates the setup of the complete system.

In Figure 4, the Pelton turbine shown is a type of impulse turbine that uses the kinetic energy of moving water to generate electricity. Pelton turbines are often used in hydroelectric power plants. In the image, the water flows from a hydro-pneumatic tank through a pipe and into the Pelton turbine. The water hits the buckets on the turbine wheel, which causes the wheel to spin. The spinning wheel is connected to a generator, which generates electricity.

This setup allows a combination of the highly efficient hydroelectric power generation and the independence of location. The hydro-pneumatic tank is very important as it converts the height parameter into pressure difference.

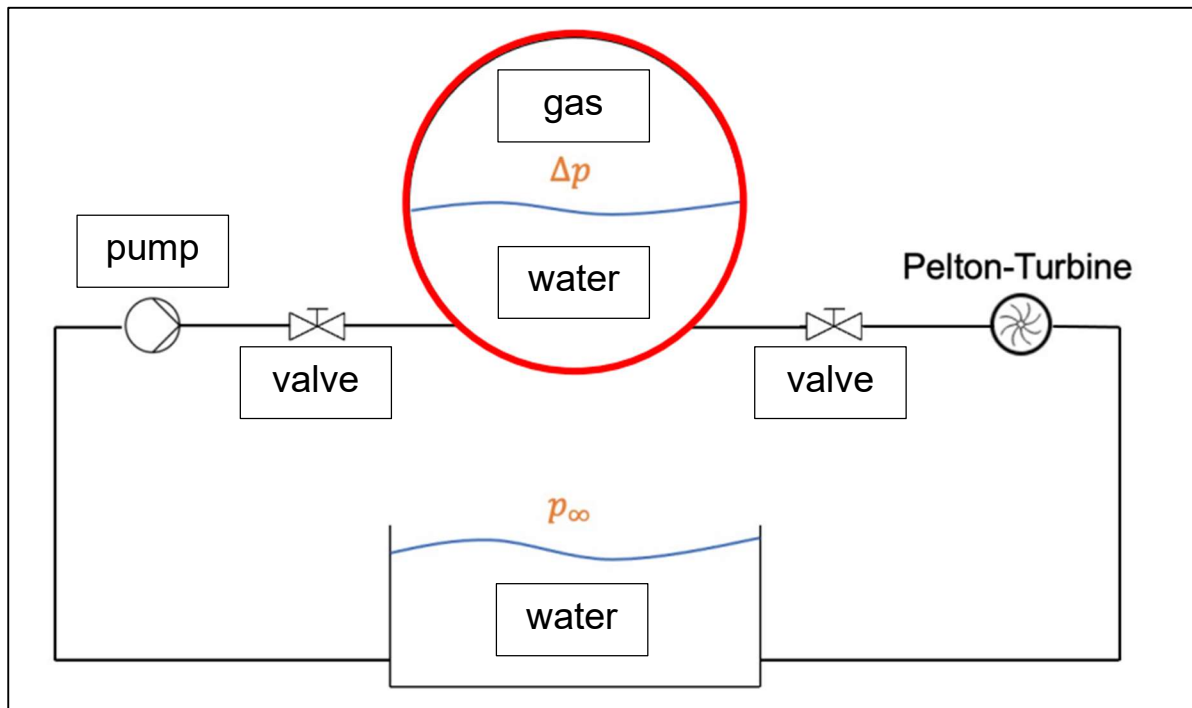


Figure 4: Layout of HEES [NiβI, 2022]

A system like this would have several applications depending on the energy storage capacity of the system. The energy capacity depends on the volume capacity of the high-pressure tank for the fluid medium. Therefore, the higher volume capacity results in a higher total energy storage. For example, windmills and big solar farms could use a HEES so that it would occupy less space and hence offers an alternative to the need of installing a big battery storage or connecting the energy source to the electric grid for offsite energy storage. The goal of the thesis is to design the HEES and determine the necessary dimensions and parameters of the individual parts required for a prototype manufacturing including the Pelton turbine and the nozzle. This includes the runner and the method used to fix the buckets on the runner for a safe and efficient setup that could be used to make the first prototype model of the HEES and be flexible to new changes that come during the testing and optimizing phase.



## 2 Explanation of the Technology

The HEES combines two major technologies. First being the hydroelectric power generation with a Pelton turbine and the second being the waterjet technology. These two technologies are described briefly and in necessary depth in the upcoming pages.

### 2.1 Hydroelectric Power

Hydroelectric power is an invention dated back to the 19<sup>th</sup> century. It was accidentally discovered by an American scientist named Lester Allan Pelton around the 1870s [Lester Allan Pelton,2023].

The basic principle behind it is simple. For example, the escape velocity of a water stream from a water column of certain height can be determined by the Torricelli equation [Zhang Z.,2016].

$$\Delta p = \frac{1}{2} \cdot \rho_w \cdot v^2 \quad (1)$$

$$\Delta p = \rho_w \cdot g \cdot h \quad (2)$$

$$v = \sqrt{2gh} \quad (3)$$

In the equation above, potential energy of the water jet is converted into kinetic energy. This water stream is directed towards a turbine e.g. a Pelton turbine. The stream hits the turbine buckets at the central cutting edge and splits up into two water flows that transfer momentum into the turbine. This transfer of momentum initiates the rotational movement of the turbine. This mechanical rotational energy is further converted into electrical energy by a generator connected to the rotating turbine.

Hydro-power plants (HPP) require certain geographical conditions, such as high height difference between the reservoir and the turbine to convert potential energy into kinetic

energy into electrical with a generator, and most of the compatible locations for plant construction have either been constructed or in progress. This is the reason why hydropower only contributes around 8.3% out of all renewable energy production in Germany. Whereas other renewable sources like solar and wind are more flexible and are also used by a lot of individuals compared to hydroelectric. However, HPP can stabilize the grid during power generation irregularities from solar and wind by serving as flexible energy reserve. When demand fluctuates or the output of intermittent renewables like wind and solar drops, hydropower can quickly be increased or decreased. It acts as a reliable source, bridging supply gaps and helping to maintain grid stability by responding swiftly to changes.

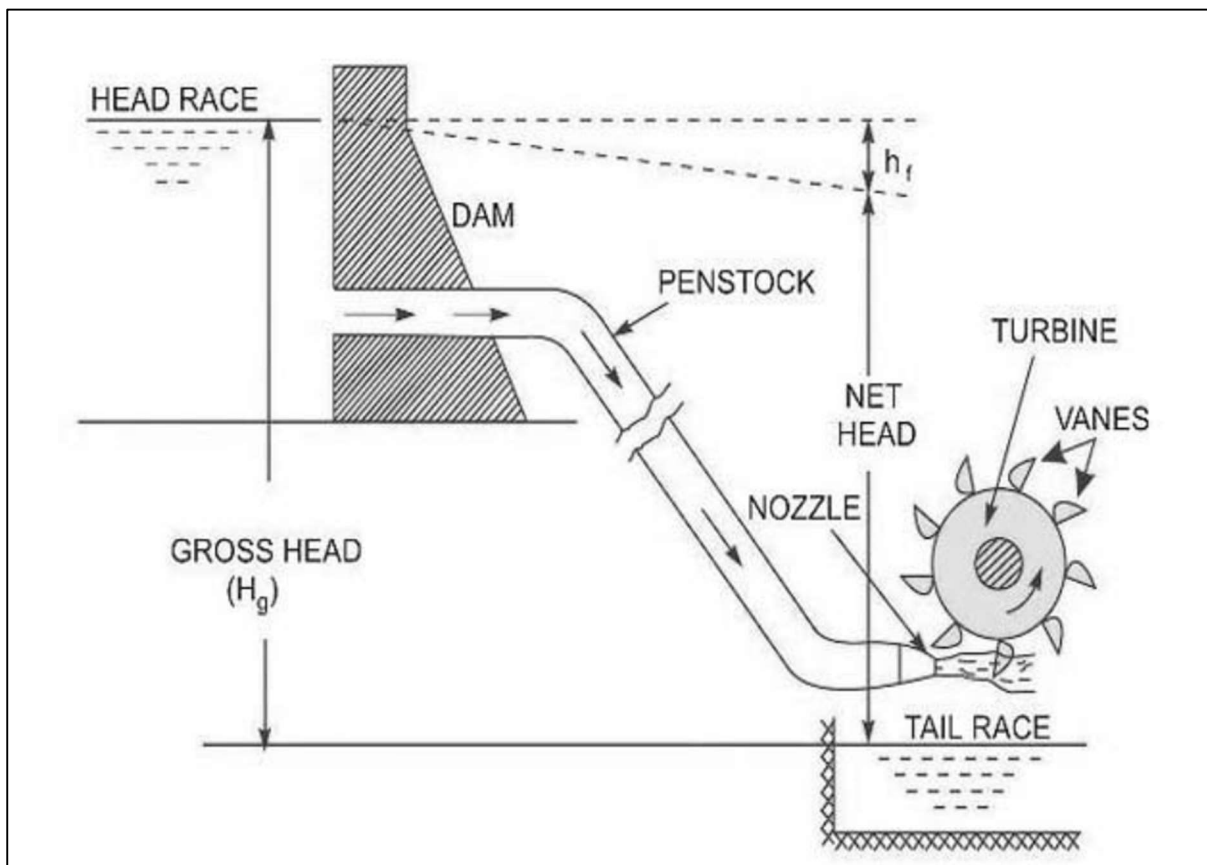


Figure 5: Hydro-electric power schematic diagram [Ishwaranand, 2020]

The image above shows a diagram of a hydroelectric power plant with a Pelton turbine. Pelton turbines are well-suited for high-head applications, such as hydroelectric dams [Figure 7]. The water in the reservoir is held back by a dam. The water then flows through a penstock, which is a large pipe that leads to the Pelton turbine. The penstock

controls the amount of water that flows through the turbine, which in turn controls the amount of electricity that is generated. The water jet from the penstock strikes the buckets of the Pelton turbine, which causes the turbine to rotate. The turbine is connected to a generator, which converts the mechanical energy of the rotating turbine into electrical energy. The electrical energy from the generator is then transmitted to the power grid, where it can be used to power homes and businesses [How Hydropower Works, 2023]. From understanding this working principle, it can be deduced that when there is a surplus in power production the water could be pumped back up with a pump in the high reservoir to store energy.

## 2.2 Water jet cutting

The pressurized tank creates a waterjet, which is impacting the Pelton bucket at very high speeds. This scenario is similar to waterjet cutting, where a very thin jet of water with abrasive material is shot at a material under high pressure to cut through it. When this jet hits the material surface, the kinetic energy is converted into impact-like potential energy. [Schulze and Fritz 2015, S. 408]

For HEES the use of pressurized waterjet and speed that does not have abrasive effects on the Pelton turbine is desired. When working with the high-pressure water jet, a distinction is also made between the two variants of clean water and the addition of an abrasive agent. The clean water jet can be used to cut soft materials such as rubber, leather, paper, or foam [Koether 2012, p. 186]. The figure below (Figure 6) shows the effects of a waterjet (without abrasive material) with increasing pressure. In the case of HEES, studying waterjet effects with abrasive material is not essential because HEES will be using just water. Furthermore, almost all surfaces can be cleaned, roughened, or abraded with pure water and at a suitable speed ablated, as described in the following figure. [Awiszus et al. 2020, p. 222]

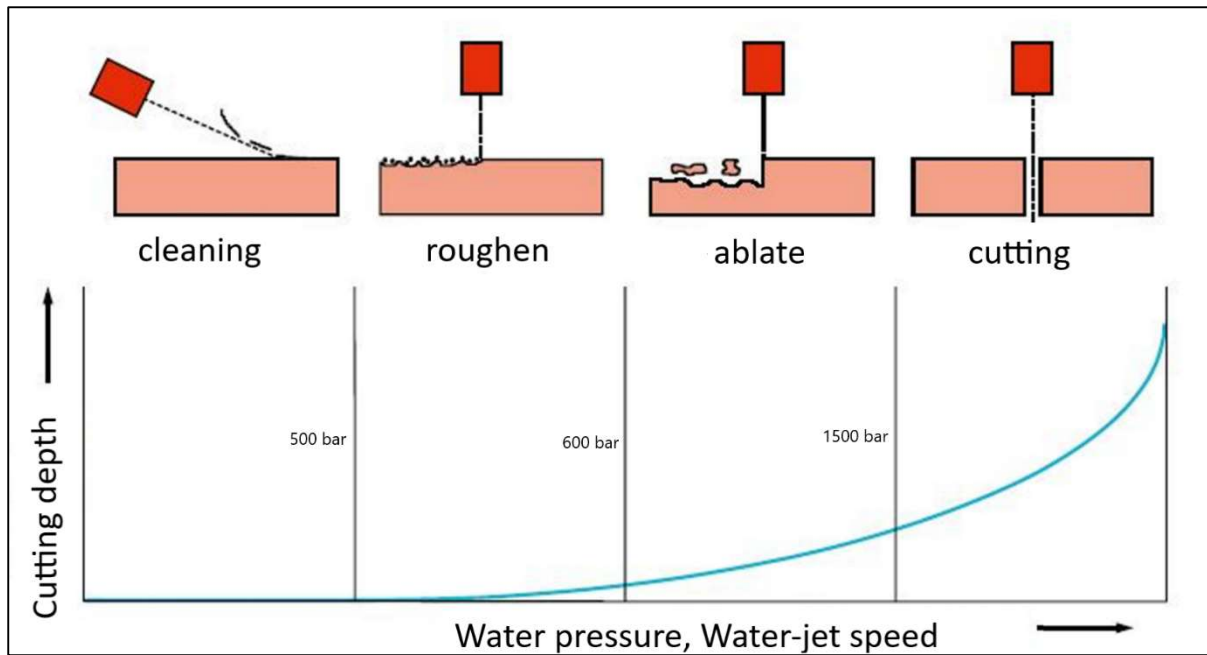


Figure 6: Waterjet pressure for different impacts on high tensile strength material like Steel. Based on [Hückel M., 2021].

For high-strength metallic materials or ceramics, a suitable maximum water pressure limit at the point of impact for water jet applications without inducing abrasion, roughening, or material removal can be set at 600 bar. Historically, cast steel was employed for turbine bucket blades attached to the impeller using bolting. However, with the contemporary trend of manufacturing Pelton turbines as monolithic structures, it is imperative to consider material effects stemming from manufacturing processes like welding, particularly within the context of energy storage and recovery systems [Hückel M., 2021].

Examination of water jet operations reveals a critical threshold: beyond 600 bar pressure, material removal ceases using pure water jets. Consequently, it is inferred that this pressure should not be surpassed at the bucket blades of the Pelton turbine runner. This condition imposes a restriction on the maximum allowable pressure differential within the hydropneumatic accumulator, which is calculated in research paper as  $\Delta p = 2400$  bar. This pressure is estimated for the specific purpose of HEES for household application. (Nißl, 2022)

## 3 HEES Components and their Functions

The HEES includes various parts like a turbine, pump, hydropneumatic tank and more. This section describes their functions and other attributes. The HEES focuses on storing and then providing energy when the need arises. Mentioned below is a brief explanation of the reasons and methods used to choose the appropriate components for HEES to achieve the required performance.

### 3.1 The Turbine

A turbine is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work. The work produced by a turbine is used for generating electrical power when combined with a generator (Munson, 2009). There are several types of turbines and materials that are studied in section 3.1.1 and 3.1.2 to decide the best suited components.

#### 3.1.1 Turbine design

Turbines are machines that convert fluid or gas energy into mechanical power by rotating blades, commonly used in power generation. Therefore, there are several different types of turbines with distinctive designs of the vanes but fundamentally the same working principle. Figure 7 determines the most suitable turbine type for different flow rates and head. HEES operates at very high-pressure heads. High pressure leads to high-speed waterjet and to keep the size of the HEES tank small and portable volume rate is low. It can be concluded from the graph that this criterion is met by Pelton turbines since they perform best in high head. The volume rate for HEES is determined using the formula given below: [NiβI, 2022].

$$\dot{V}_{(P,\Delta p)} = \frac{\rho_w \cdot \frac{\pi}{4} \cdot d(P, \Delta p)^2 \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho_w}}}{\rho_w} \quad (4)$$

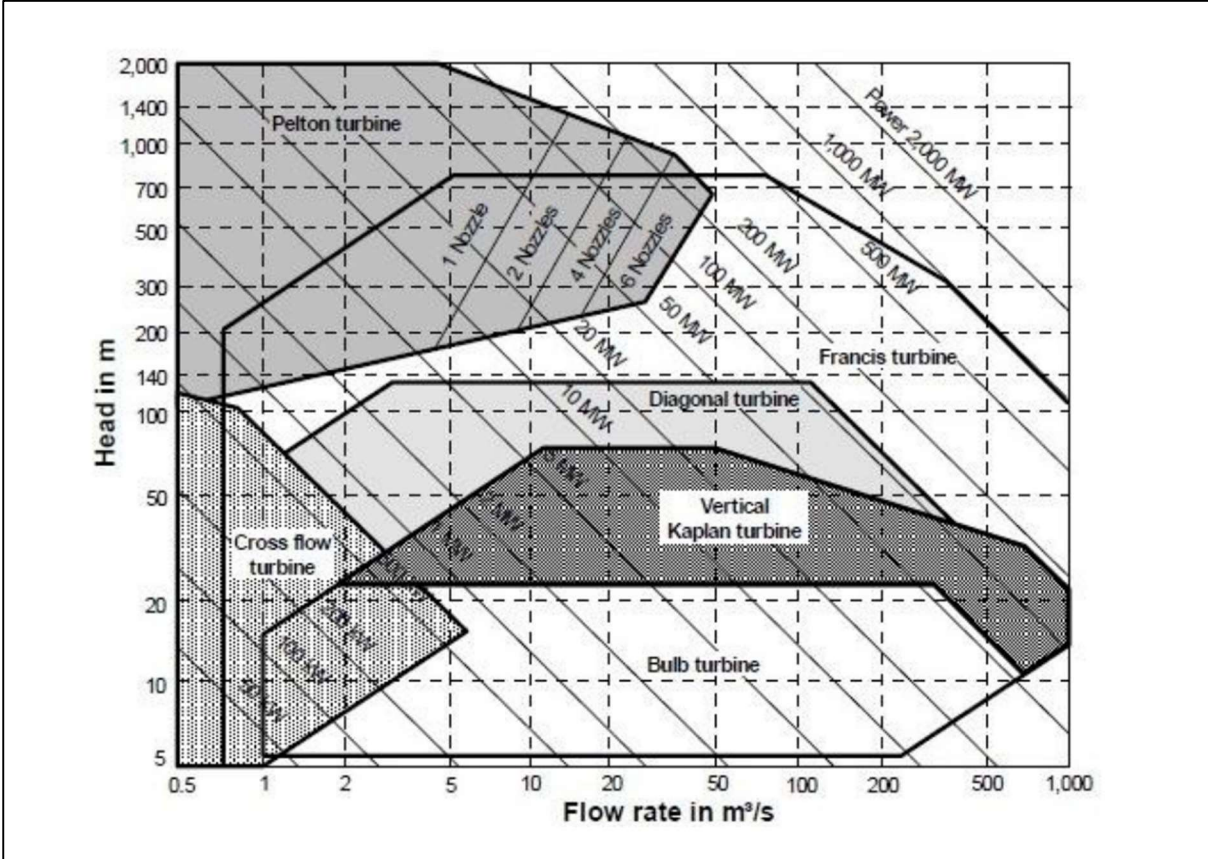


Figure 7: Selection ranges of different turbines related to head and flow rate (Kaltschmitt, Streicher, & Wiese, 2007)

The design of Pelton turbines has been developed for more than a century since its invention by Lester Pelton in 1880 (Audrius Židonis, 2016). Pelton turbines essentially consist of a Pelton wheel with blades in the form of a bucket and one or more injectors that generate the high-speed jets when leaving the nozzle. The energy transfer from the high-speed jet onto the Pelton wheel is performed through the interaction between the jet and the rotating buckets. (Zhang, 2016)

### 3.1.2 Material of the Turbine

Choosing materials for turbine components is a crucial decision, resting on two primary factors. First, the material must have exceptional tensile strength to endure the abrasive effects of the high-pressure waterjet, which can reach pressures of up to 600 bar, along with the associated high-velocity flow. This strength is essential not only for resisting material erosion and surface roughening but also for providing sufficient fatigue resistance to maintain long-term structural integrity. Second, the material must inherently possess corrosion resistance to protect against ongoing deterioration, considering its continuous and direct exposure to water [Hückel M., 2021].

Following the specified criteria, stainless steels emerge as a logical choice. These materials offer a dual advantage, combining corrosion resistance with impressive strength and thermal resilience. Stainless steels are also known for their machining ease and recyclability. A material earns the "stainless steel" classification when it contains at least 10.5% Chromium and no more than 1.2% Carbon. Increasing Chromium content and adding elements like Molybdenum (Mo) and Nickel (Ni) enhance corrosion resistance. However, excessive heat treatment can lead to specific corrosion types, such as intergranular corrosion, caused by Chromium carbide precipitation along grain boundaries. Incorporating Titanium (Ti) or Niobium (Nb) acts as a preventive measure. Additionally, introducing Nitrogen (N) can boost material strength [Hückel M., 2021].

The table below summarizes the materials and their properties, highlighting their corrosion resistance, strength, and weldability. The parentheses indicate the level of each property, with "(++)" denoting very high and "(+)" denoting moderate.

Description	Material	Properties
Stainless steel, duplex	X2CrNiMoN22-5-3	Corrosion resistance (++) Strength (+)
Stainless steel, Ferritic	X6CrMo17-1	Corrosion resistance (++) Weldability (+)
stainless steel, martensitic	X17CrNi16-2	Strength (+) Corrosion resistance (+) Weldability (+)
stainless steel, martensitic	X20Cr13	Strength (+) Weldability (+)

Table 1: Materials and Their Key Properties [Nißl ,2022]

### 3.2 The Nozzle

A Pelton turbine nozzle, in the context of hydroelectric systems, is a critical component responsible for precisely directing high-pressure water jets onto the turbine's rotating buckets. This nozzle ensures efficient energy transfer by controlling the placing and velocity of the water jets. By optimizing the water's impact on the turbine blades, the nozzle enhances the turbine's overall performance and power generation capabilities. It plays a pivotal role in converting the kinetic energy of flowing water into mechanical energy that drives a generator, producing electricity in hydroelectric power plants. This waterjet collides into the Pelton buckets and splits itself evenly on the Pelton bucket edge. The jet constructed by the nozzle has a diameter  $d_{jet}$ . The picture represents the diameter of the water jet expanding as the distance of the jet from the nozzle increases. [Zhang, 2015]



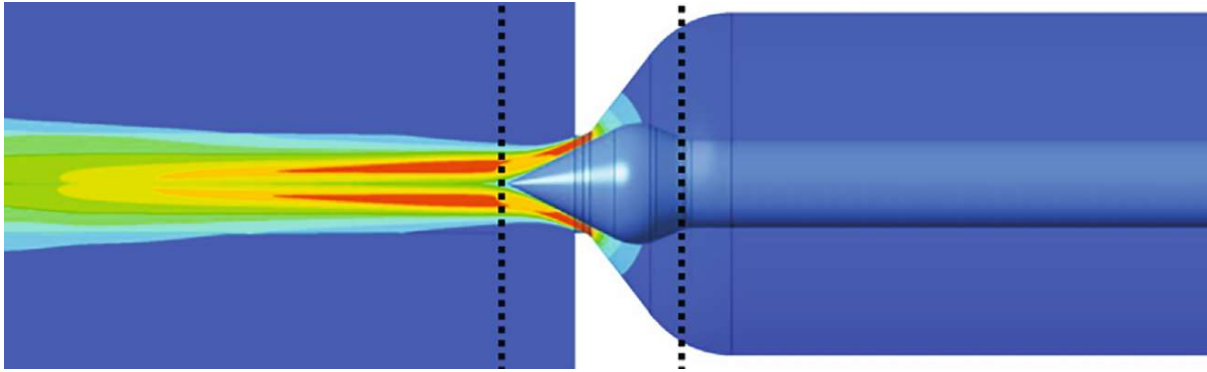


Figure 8: Waterjet diameter increasing after leaving spear needle nozzle [Bhajracharya, 2022]

Due to this increasing diameter effect of the waterjet exiting the nozzle the Pelton buckets should not be further than a specific distance from the nozzle. This phenomenon known as the Coanda Effect and the Nozzle is studied in more detail for HEES in section 4.2.2.

### 3.4 The Hydro-pneumatic Tank

Since the system is intended to operate at very high pressure, a hydro-pneumatic tank is used to store water at high pressure. A hydraulic accumulator - also referred to as a hydro accumulator - makes use of the compressibility of gas with the aim of enabling more favorable energy utilization with improved uniformity of energy transfer. Inside the accumulator, there is a piston separating gas and the liquid to avoid dissolution. If water is now added to the system the water-side pressure increases, compressing the air. If the system pressure sinks again, the expansion of the gas component forces the liquid out of the interior of the stored energy and is thus made available to the circulation system [Hückel M., 2021].

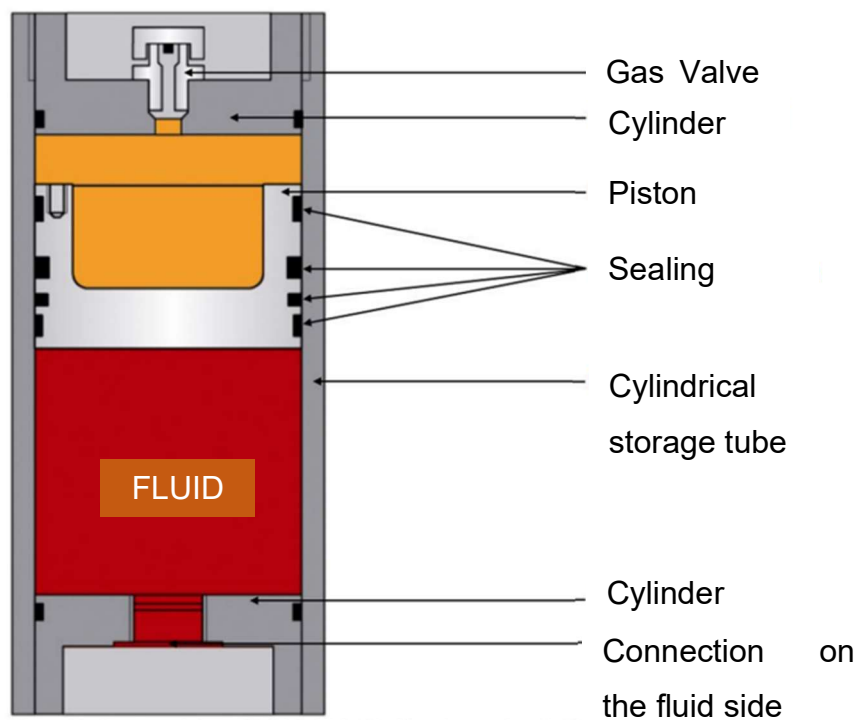


Figure 9: Structural diagram of Piston accumulator [Findeisen und Helduser 2015, S. 650]

The choice of compressible gas is an important consideration in the design of the hydraulic accumulator. On the one hand the dissolution behavior of the gas in the water under increasing pressure and fluctuating ambient temperature, and secondly, the influence of a possible phase change must be investigated. Possible gases to be considered are air and nitrogen. Figure 9 depicts the setup inside a cylindrical hydro-pneumatic piston tank. (Nißl, 2022)

Nitrogen is recommended, due to the critical point ( $T_c = 126\text{K}$ ,  $p_c = 33.9\text{ bar}$ ) and its compression and molecular properties. In conjunction with a piston accumulator, gas is also prevented from dissolving in the water as the pressure rises. [Nißl, 2022]

## 4 Designing the HEES prototype using 3D modelling

Designing a 3D software model is indispensable for gaining a more spatial perspective of the HEES system. Furthermore, a 3D model offers greater adaptability for implementing changes, a critical aspect given that this energy storage technology is still in its nascent stages and continues to evolve. The HEES model serves as a compelling tool for attracting potential investors who can contribute to further research and development of this innovative energy storage concept. The 3D model could be helpful for any further simulations to examine the feasibility performance of the system. The 3D model has been meticulously crafted using Fusion 360, a 3D modeling software developed by Autodesk Inc. The subsequent section provides a detailed account of the component's construction.

The 3D model will include the following parts:

1. Pelton buckets
2. Pelton runner
3. Nozzle

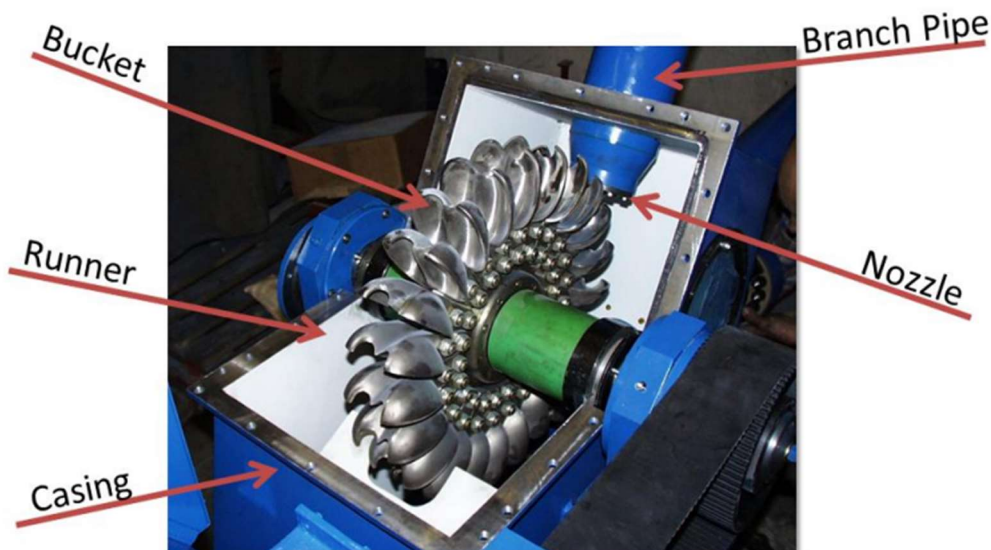


Figure 10: Typical layout of a modern Pelton turbine [Zidonis A., 2015]

The image above shows the fundamental parts of a Pelton turbine. It includes a nozzle that directs a jet of water to the buckets on the runner. The runner is a wheel with buckets on its rim. The Pelton buckets are attached to the rim of the runner. They are designed to catch a jet of water from the nozzle and spin the runner. A shaft (Green colored axle in the center of the Pelton runner) is connected to the runner and transmits the rotational energy to the generator. The casing is a housing that surrounds the runner and other parts of the turbine. It protects the turbine from the elements and helps to contain the water.

The runner consists of a circular disc on the periphery on which several buckets are evenly spaced and fixed. The shape of the buckets is of a double hemispherical cup or bowl. Each bucket is divided into two symmetrical parts by a dividing wall which is known as the Splitter. Pelton Buckets have several dimensions which are measured for HEES in section 4.1. The general shape of a Pelton bucket and a bucket mounted runner is illustrated in Figure 11. [Prajapati P.V.M. et al. 2015]



Figure 11: Pelton Bucket (Left) and Pelton runner with buckets bolted (Right) [Mane M., 2020]

#### 4.1 Pelton Bucket design

The shape of the bucket inside is crucial to transfer the energy from the waterjet into rotational energy by rotating the Pelton impeller. The interior profile of the Pelton buckets must be configured so that the water spreads as smoothly and steadily as

possible. The profile should have no discontinuity. This is required not only because of hydraulic aspects but also because of concerns of the mechanical process of manufacturing the buckets, for instance, by milling machines. (Zhang, 2016)

The HEES has a unique set of challenges for all its parts including the buckets. Here are some challenges which will be the focus of the thesis:

1. A requirement for the bucket design is to incorporate individual attachment mechanisms, like tongs with holes for bolts to securely attach them to the Pelton turbine.
2. The suitable manufacturing process for this component will be selected and may involve CNC machining, but due to the proximity of the two consecutive buckets on the Pelton runner, machining the individual splitter on each bucket may be obstructed by the front bucket if the whole Pelton wheel is constructed from a single block of metal. To overcome this challenge, alternative production and machining methods for the buckets are considered in this thesis in section 5.
3. The diameter of the jet would vary according to the pressure difference at nozzle and the volume rate would also change accordingly. Figure 12 depicts the partially hyperbolic relation between the  $d_{jet}$  (Left y-axis) and  $V_{water\ 24}$  represents usage for 24 hours (Right y-axis). This is relevant for this thesis as the goal is to construct a Pelton turbine that performs efficiently throughout the life cycle of HEES. Hence understanding how the tank behaves during usage is necessary.

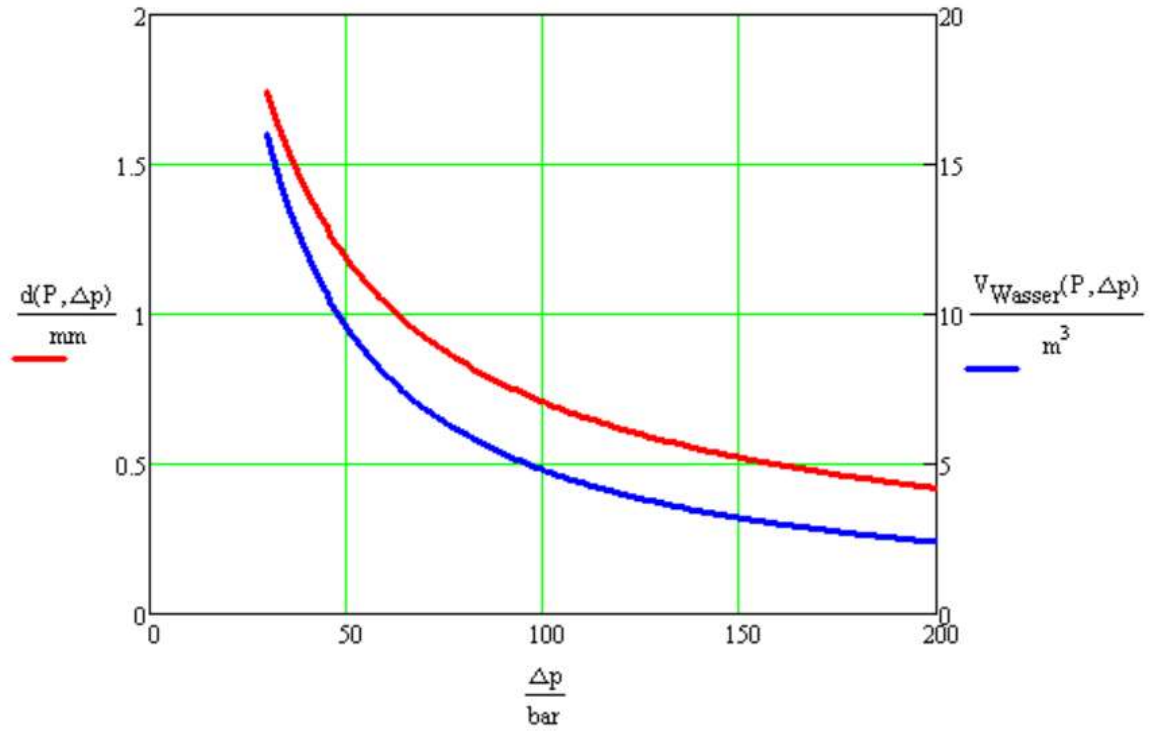


Figure 12: Relation between the jet diameter and the water volume usage per day corresponding to varying relative pressure differences and the power produced. [Költzsch,2021]

The graph mentioned above gives a clear image of how much volume of the tank is required for different pressures and diameter of nozzle for HEES.

The equations (5) and (6) [Költzsch,2021] mentioned below are used to plot the graph above:

$$d_{jet}(P, \Delta p) = \sqrt{\frac{P \cdot 8}{\pi \cdot \left(\sqrt{\frac{2 \cdot \Delta p}{\rho_w}}\right)^3 \cdot \rho_w \cdot \sin\left(\frac{\beta_2}{2}\right)^2}} \quad (5)$$

$$V_{wasser}(P, \Delta p, t = 24hrs) = \frac{\rho_w \cdot \frac{\pi}{4} \cdot d(P, \Delta p)^2 \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho_w}}}{\rho_w} \cdot t \quad (6)$$

The average household power consumption determines the power needed to be generated by the HEES because it is designed for Household use in this thesis. The

average power for a 4-person household in a single-family house is calculated as  $P_{avg} = 571W$ . The pressure difference is equal to  $\Delta p = 2400bar$  for the mentioned calculations. [Niklas,Niβl]. The  $P_{min} = 200W$  and  $P_{max} = 10KW$  are the minimum and maximum power consumption requirements from HEES for the mentioned Household. [Költzsch,2021].

From the equations 5 and 6 the value of the parameters (Jet diameter, Volume rate, Volume per day) are determined and shown in the table below:

	$P_{min}$	$P_{avg}$	$P_{max}$
$d_{jet}$ (waterjet)	0.06 mm	0.07 mm	0.28 mm
Volume rate	0.10 kg/min	0.15 kg/min	2.54 kg/min
V per day	146 L /day	209 L /day	3662 L /day

Table 2: Range of  $d_{jet}$  (waterjet), Volume rate, V per day for HEES [Niβl, 2022].

It is noticeable that the nozzle outlet diameters range from 0.06 to 0.28mm. These are very small dimensions which, as already explained in section 1.3.1.2, are found in the waterjet cutting industry. Furthermore, the daily water demand, for coverage at constant minimum or average load, is between 146 L and 209 L. At constant peak load, this value is 3662 L. However, since a constant consumption at peak load is unrealistic anyways, this value is only for calculating the extremities for HEES.

The Pelton buckets can be constructed in the Fusion 360 software as 3D models. The basic structure and dimensions for the Pelton bucket which need to be determined are shown in figure 13.

For the basic structure, among various mathematical functions, an ellipse model is very suitable for a Pelton Bucket for better distribution of the waterjet after it hits the splitter and diverges and spreads out (Zhang, 2016).



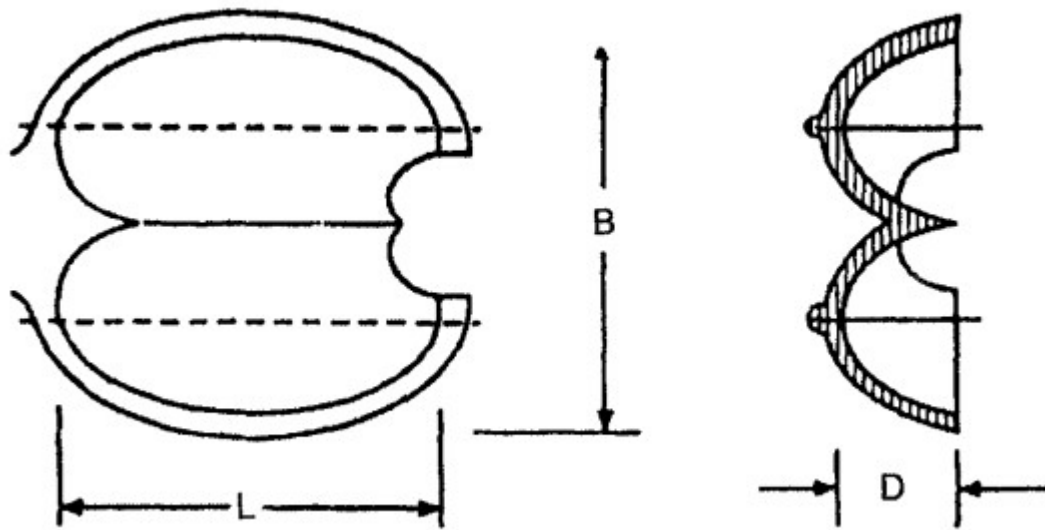


Figure 13: Top view (Left) showing the length and breadth parameter of a bucket. Front view (Right) marking the depth of the bucket. [Husain Z.,2008]

#### 4.1.1 Dimensions of the Pelton Bucket

The dimensions of a bucket are shown above and can be calculated with formulas. The following equations are established from research paper [Prajapati P., 2015].

$$B_w = 3.4 * D_j \quad (1)$$

$$B_t = 3 * D_j \quad (2)$$

$$B_d = 1.2 * D_j \quad (3)$$

$B_w$	Bucket width
$B_t$	Bucket radial length
$B_d$	Bucket Depth
$D_j$	Jet diameter at the nozzle
$v_{wj}$	Waterjet speed

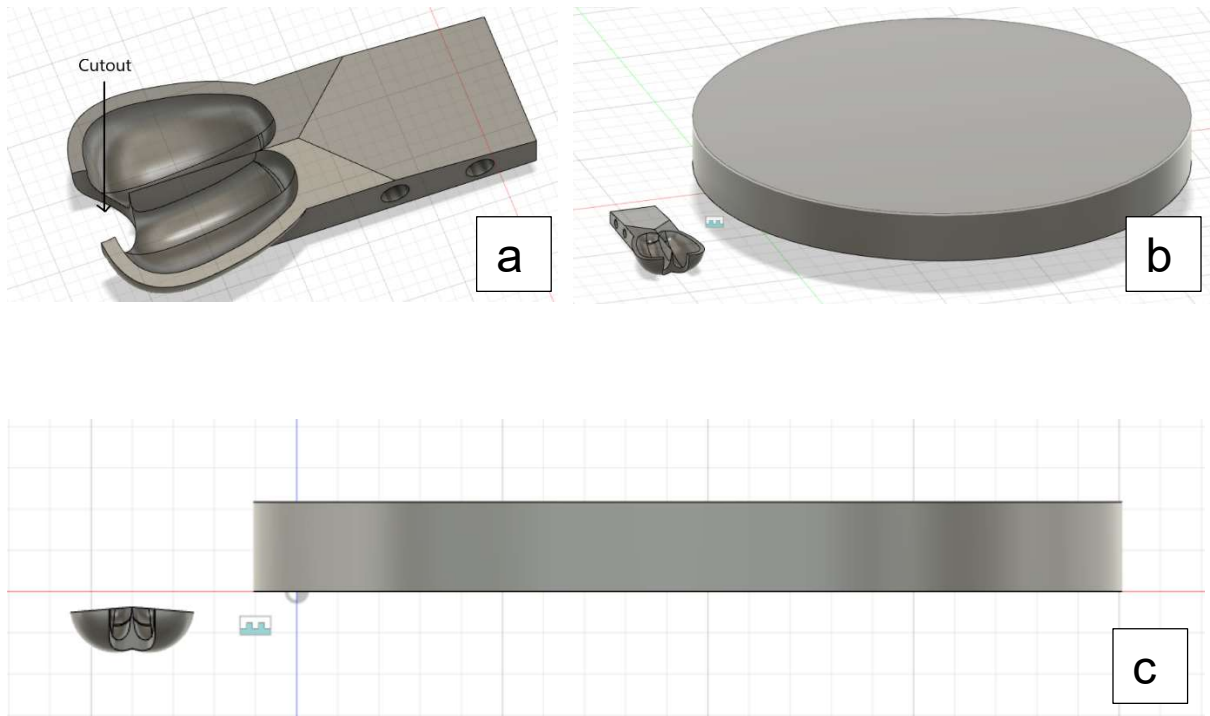
Table 3: Parameters of the Bucket dimensions equations

To find out the bucket parameters, the waterjet diameter is needed which is shown in Table 2. Calculating the dimensions for the three power levels minimum, average, and maximum is done separately.

	B <sub>width</sub> (in mm)	B <sub>length</sub> (mm)	B <sub>depth</sub> (mm)
P min	0.204	0.18	0.072
P avg	0.238	0.21	0.084
P max	0.952	0.84	0.338

Table 4: Bucket dimensions for different Power requirements

From the table above the values of the dimensions for the Pelton bucket are theoretically justified. It is observed that the size of the Pelton bucket that would be ideal from the theoretical point of view has very small dimensions. A model is created in the Fusion 360 software using the Bucket dimensions corresponding to P<sub>max</sub>. P<sub>max</sub> provides the biggest dimensions compatible for HEES buckets. Despite this, the P<sub>max</sub> dimensions of the bucket is very small. The image below shows the created 3D model of a Pelton bucket and the comparison of the Pelton bucket to a 1 cent coin to provide a better perspective for its size.



a) 3D model of a Pelton bucket constructed using Fusion 360. The cutout in the design is explained below.

b) 3D model size comparison of the Pelton bucket with a one cent coin in fusion 360

c) Pelton bucket size comparison to one cent coin thickness

Figure 14: (a, b, c ) Size comparison between Pelton Bucket and one cent coin.

The size of the bucket is much smaller than the buckets used in hydro power plants due to the very high pressure and low volume rates of HEES. Machining these buckets would require precision tools and a precision method which will be discussed in section 5 - Manufacturing Method.

#### 4.1.2 Cutout in the Pelton Bucket design

The circular cutout in the Pelton bucket as shown in figure 14a is an important design element. It appears from the numerical simulation [Peerig A., 2006] that the bucket backside does contribute to the bucket torque. This is linked with the interaction between the water jet and the bucket cutout profile. The Coanda effect causes the

waterjet to adhere to the curved surface due to reduced pressure on the concave side, creating a favorable environment for the jet to follow the curvature. This phenomenon enhances energy transfer efficiency in the Pelton turbine. The Coanda effect leads to the creation of a lift force, and from that an angular momentum in the sense of rotation which is developed, contributing to the runner torque. The diameter of the cutout is kept at  $2 \cdot d_{jet}$  (diameter of the jet) to allow the jet to pass through the Pelton bucket and use the Coanda effect to increase the contribution to performance by 7.5%. [Peerig A., 2006]

#### 4.1.3 Bucket exit angle

Another important Pelton bucket dimension is the exit angle. As shown in Figure 15 and 16 the Pelton bucket determines the angle of exit for the water jet. The theoretically ideal exit angle is 180 degrees, but this could result in the water jet colliding with the preceding bucket. Therefore, the exit angle is typically kept between 170 to 160 degrees [Peerig A., 2006].

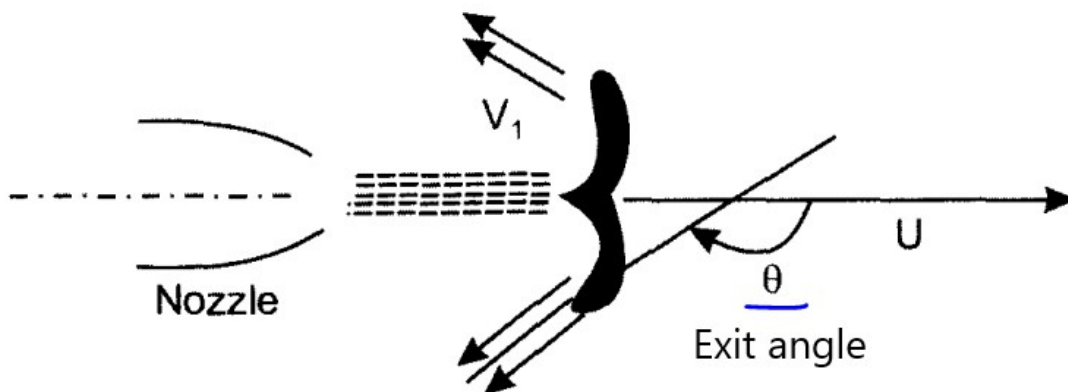


Figure 15: Exit angle for the diverted waterjet [Peerig A., 2006]

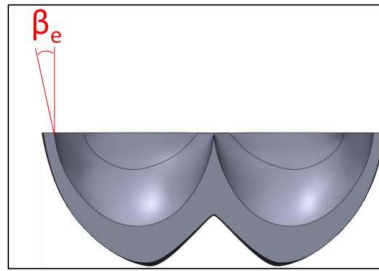


Figure 16: Bucket exit angle [Zidonis A., 2015]

To determine the perfect exit angle for HEES, such that it does not collide with the previous bucket and is the closest to 180 degrees, it would require constructing an entire CFD simulation and conducting a numerical simulation of the water jet interacting with the rotating Pelton turbine. This process of simulating a working model of HEES would be very time and resource intensive. Nevertheless, this angle can be estimated using the 3D model construction. In this thesis, the exit angle was calculated by using the Fusion 360 model of the Pelton buckets on the Pelton runner, and by measuring the distance between the buckets, the exit angle was estimated to be approximately  $170^\circ$  after rendering the appropriate number of Pelton buckets. Figure 17 explains this phenomenon where a 3D construction is shown of two Pelton buckets in Fusion 360 and placed consecutively next to each other on a Pelton runner. It seems that  $170$  degrees is appropriate for this thesis.

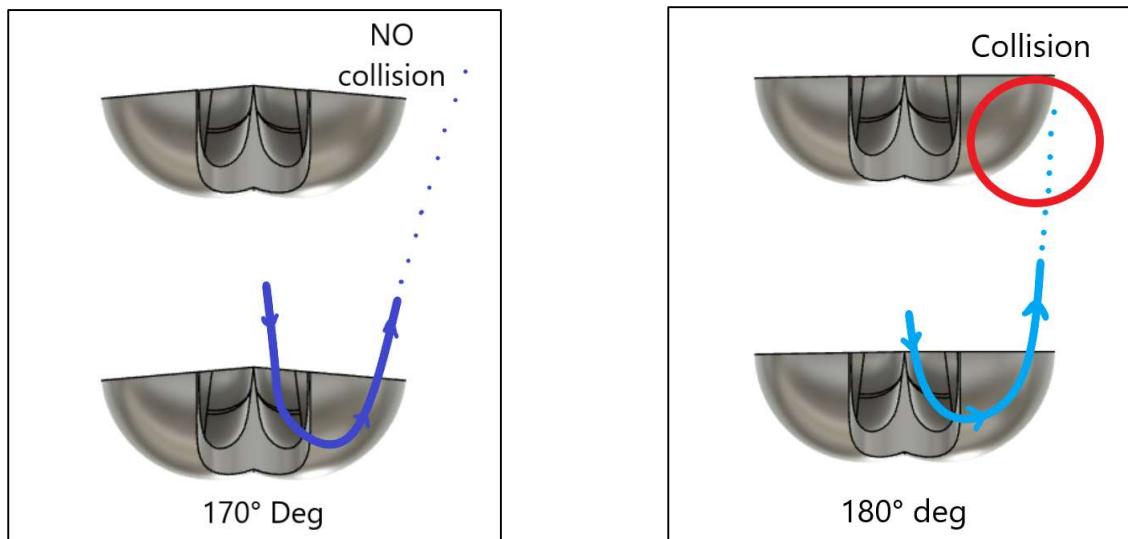


Figure 17: 3D model of two consecutive Pelton buckets

## 4.2 Pelton runner

The Pelton runner is the heart of a Pelton turbine, comprising of a series of curved buckets or cups on a rotating wheel. It is a key component that extracts energy from high-velocity water jets. Requirements include robust construction, efficient shape, and precise alignment with the jet to maximize energy transfer. The runner's function is to receive the water jet's kinetic energy and convert it into mechanical energy, spinning the turbine's shaft to generate electricity or perform mechanical work. Its design ensures optimal energy conversion in hydropower applications. The diameter of the Pelton runner can be determined by using the formula mentioned below.

$$d_{runner} = \frac{v_{bucket}}{\pi \cdot \omega_{max}} \quad (4)$$

The diameter used for this thesis is 1.7m for a rotational speed of 3000 min<sup>-1</sup> and the speed of the buckets  $v_{bucket} = 267 \text{ ms}^{-1}$  [Nißl, 2022]. In the design and construction of the turbine, a more precise approach is necessary than just treating the Pelton turbine as a solid rotating disk. Additionally, careful consideration should be given to the method used for attaching the buckets. Significant variations exist in this regard, whether the buckets are secured through bolting or welding, or if the turbine is manufactured as a unified component or an entirely different method of attachment [Nißl, 2022].

### 4.2.1 Bucket attachment method to the Pelton runner

Attaching many small Pelton buckets to a Pelton runner with precision is a critical task. Several methods can be employed:

#### 1. **Bolting:**

- Process: Each Pelton bucket is individually drilled with holes, and corresponding holes are machined or cast into the Pelton runner. Bolts or

screws are then inserted through these holes and tightened to secure the buckets in place on the Pelton runner. [Norton, R. L., 2005]

- Advantages: Provides precise control over bucket placement, easy to assemble and disassemble for maintenance or adjustments.



- Considerations: Time-consuming for a large number of buckets, requires meticulous alignment and torque control. Additionally, the size of the buckets for HEES is around a few millimeters. This also affects the size of the screws that are used.

Figure 18: Bolted Pelton buckets on runner. [Guglielmi Alessandro, 2020]

## 2. Adhesive Bonding:

- Process: A strong adhesive, typically epoxy or specialized bonding agents, is applied to the contact surfaces of both the Pelton buckets and the runner. The buckets are then positioned and pressed firmly against the runner until the adhesive cures. [Lee, L. H. (Ed.), 2013]
- Advantages: Creates a strong and durable bond, can handle high stresses and vibrations, suitable for non-metallic buckets.
- Considerations: Requires precise alignment, curing time, and proper surface preparation.

## 3. Welding:

- Process: Suitable for metal buckets and runner materials, welding involves melting the edges of the buckets and the runner to fuse them together. Common methods include TIG (Tungsten Inert Gas) or MIG (Metal Inert Gas) welding. [Gourd, L. M., 1986]
- Advantages: Provides a robust and permanent connection, suitable for high-stress applications.
- Considerations: Requires skilled welders, careful heat control to prevent distortion, and can be challenging for non-metallic materials.

#### 4. Casting:

- Process: During the casting of the Pelton runner, the buckets are integrated into the runner structure. This result is a seamless connection between the buckets and the runner. [Kafle, A. et al., 2020]



- Advantages: Ensures a strong and integrated design, with no additional attachment required. Casting for metals like steel and aluminum is viable.
- Considerations: Requires specialized casting processes and molds, limited flexibility for design changes.

Figure 19: Casted Pelton turbine [saVRee, 2020]

#### 5. 3D Printing:

- Process: Modern additive manufacturing technologies can directly print the Pelton runner with integrated bucket structures, layer by layer, using materials suitable for the turbine's operational conditions. [ Takagi, M. et al., 2014]
- Advantages: Offers design flexibility and precise control over bucket placement.
- Considerations: Requires access to advanced 3D printing equipment and materials suitable for high-stress applications.

#### 6. Micro spot welding:

- Process: Micro spot welding involves the creation of tiny, well-defined welds by applying localized heat using small electrodes. These electrodes press against the materials, and an electric current pass through, creating precise, controlled welds. [ *Micro Welding Explained* ,2020]
- Advantages: Micro spot welding offers a secure and strong connection, especially suitable for delicate or small components. It ensures accuracy in the welding process.



- Considerations: This method demands precision in electrode placement, tight tolerances, and specialized equipment for micro-scale welding. Accuracy in the process is crucial for reliable and effective results.

#### 4.2.2 Attachment critical factors

Selecting the best attachment method for the HEES (which has a Pelton turbine with extremely small buckets) requires considering several critical factors:

##### 1. **Bucket Material:**

The material of the buckets plays a crucial role in determining the suitable attachment method. Some methods, like welding and micro spot welding, perform best when used for specific materials, such as metals.

##### 2. **Precision Requirements:**

The HEES design demands high precision due to the small bucket size. The level of accuracy needs to be high because this ensures efficient water jet interaction and splitting. The precision must be high enough to make sure the jet with the smallest possible diameter being  $d_{jet} = 0.06\text{mm}$ , is split by the splitter. The alignment of the jet on splitter is important for better overall performance.

##### 3. **Production Volume:**

The number of HEES buckets to be manufactured can influence the choice. High-volume production requires more automated and efficient attachment methods.

##### 4. **Operational Conditions:**

Evaluating the turbine's operational environment, including factors like temperature, pressure, and vibration are necessary, as these can impact the attachment method's durability.

##### 5. **Maintenance and Repairs:**

The ease of maintenance and repairs is vital since the HEES will be operated under several conditions, which will induce damage and possible repairs and changes to the HEES design. Methods like bolting facilitate easier bucket replacement compared to methods like welding or adhesive bonding.

#### 6. **Cost and Budget:**

The overall cost of implementing the attachment method, including material costs, labor, and equipment needs to be as low as possible. Ensuring it aligns with the project budget is essential.

#### 7. **Design Flexibility:**

This refers to how each attachment method accommodates design changes or modifications, as well as the adaptability for different bucket geometries.

#### 8. **Skilled Labor:**

Some methods, like welding, may require skilled welders. Considering the availability of qualified personnel for such methods is vital. The maintenance cost would be driven up by more skilled labor. However, in case of mass production in the future the cost of automation might be lower than labour.

#### 9. **Environmental Impact:**

Assessing the environmental implications of the chosen method, including waste generation and material sustainability is vital.

### 4.2.3 Attachment Method Comparison for HEES:

#### 1. **Bolting:**

*Advantages:* Bolting offers versatility in material compatibility, making it well-suited for the diverse needs of the HEES project. It maintains a moderate cost, aligning with the project's budget constraints, and ensures ease of maintenance.

*Disadvantages:* The method demands skilled labor for implementation, requires a moderate precision that should meet the HEES specifications, and entails a production speed that aligns with the project timeline.

#### 2. **Adhesive Bonding:**

*Advantages:* Adhesive bonding, relevant for prototyping in the HEES development phase, exhibits good material compatibility and ensures ease of maintenance.

*Disadvantages:* This method incurs moderate to high costs, which the HEES budget needs to accommodate. Additionally, skilled labor is required, as well as precision, which needs to be lower compared to some other methods though.

### **3. Welding:**

*Advantages:* Welding, with its high precision, ensures strong bonds necessary for the robustness required in HEES operational conditions.

*Disadvantages:* It is limited to metal materials. Welding presents challenges in the repair process and high production volume that is needed for HEES.

### **4. Casting:**

*Advantages:* Casting allows for integral design, a feature beneficial for HEES operational conditions. It incurs a moderate cost, which is favorable for HEES budget considerations.

*Disadvantages:* Despite these advantages, casting comes with limitations in design flexibility and moderate precision.

### **5. 3D Printing:**

*Advantages:* 3D printing, with exceptional precision, aligns with HEES requirements for precision engineering. It provides high design flexibility, a crucial aspect of meeting HEES design variations, and only requires 3D software skills.

*Disadvantages:* The trade-off includes a high cost, which needs to be justified by the benefits and it has material limitations.

### **6. Micro spot Welding:**

*Advantages:* Micro spot welding, chosen for its high precision, ensures versatile material compatibility, aligning with the diverse materials used in HEES. It is easy to maintain, which is a crucial factor for reliability.

*Disadvantages:* However, it requires skilled labor, demands consideration for design flexibility within HEES specifications, and involves a moderate cost that HEES needs to accommodate.

Here is a table evaluating various attachment methods for HEES on the factors mentioned:

Attachment Method	Bolting	Adhesive Bonding	Welding	Casting	3D Printing	Micro spot Welding
<b>Bucket Material Compatibility</b>	Versatile	Material-Specific	Metal Only	Material-Specific	Material-Specific	Metal Only
<b>Precision Requirements</b>	±50 µm	±100 µm	±30 µm	±200 µm	±10 µm	±20 µm
<b>Production Volume</b>	Moderate to High	Moderate	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate
<b>Operational Conditions</b>	Typically, Suitable	Generally Suitable	Typically, Suitable	Typically, Suitable	Typically, Suitable	Typically, Suitable
<b>Maintenance &amp; Repairs</b>	Easier Maintenance	Moderate	More Complex Repairs	Integral Design	Easy to Replace	Moderate Maintenance
<b>Cost &amp; Budget</b>	Moderate	Moderate to High	Moderate to High	Moderate to High	High	Moderate to High
<b>Design Flexibility</b>	Good	Good	Limited	Limited	Excellent	Limited
<b>Skilled Labor</b>	Required	Required	Required	Required	Not Required	Required
<b>Environmental Impact</b>	Low	Low to Moderate	Low	Low to Moderate	Low to Moderate	Low to Moderate

Table 5: Comparison of the attachment methods. [Norton, R. L., 2005] [ *Micro Welding Explained* ,2020] [ Takagi, M. et al., 2014] [Kafle, A. et al., 2020] [Gourd, L. M., 1986] [ Lee, L. H. (Ed.), 2013]

#### 4.2.4 Comparison Conclusion:

For the specialized application of HEES characterized by its notably diminutive bucket size and stringent precision requisites, bolting, especially with screws like M1.6 cup point grub screws (Figure 20), emerges as the most favourable attachment method. Demonstrating versatility, cost-effectiveness, ease of maintenance, and compatibility with a broader spectrum of metallic materials, bolting aligns seamlessly with the distinct requisites of HEES. This choice is reinforced by insights from the comparison table, where bolting exhibited competitive advantages over other methods.

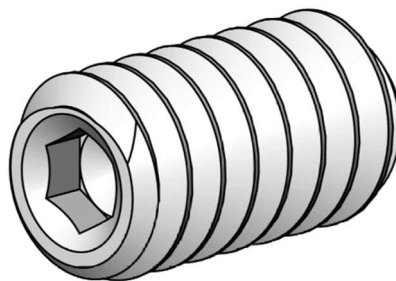


Figure 20: Grub screw M1.6 [Cup Point Grub Screw M1.6x5mm, DIN 916., 2023]

However, for a smaller scale prototype of an operational HEES model, the transition towards 3D printing techniques may assume a more fitting disposition. While Bolting retains its competitive stance, 3D Printing stands out for its adaptable design possibilities, simplified maintenance, and cost-effectiveness in testing scenarios, offering flexibility for design modifications, and reducing costs associated with testing and prototyping.

### 4.3 Nozzle Clearance

The minimum distance between the waterjet and the bucket in a Pelton turbine is commonly referred to as the "nozzle-to-bucket clearance" or simply "nozzle clearance." This distance is crucial to prevent interference between the water jet and

the rotating bucket, ensuring effective energy transfer without causing damage to the system. It plays a key role in maintaining the efficiency and proper functioning of the Pelton turbine [Hoyt, J. W.,

1948]. As the Pelton runner rotates at high angular velocities, centrifugal stress can cause the Pelton runner diameter to increase. The necessary maximum distance between the nozzle to the bucket splitter is  $z_a = 3,3\text{mm}$  for  $d_{\text{jet}} = 0.07\text{mm}$  (considering  $P_{\text{avg}}$ ). [Nißl, 2022]

The reasoning for this maximum distance is the high exit velocity of the waterjet from the nozzle. As the distance from the nozzle augments, the diameter of the waterjet correspondingly enlarges. Notably, the waterjet quality is most optimal near the nozzle. [Nißl, 2022]

#### 4.3.1 Nozzle Clearance Mechanism (NCM)

To maintain an optimal distance between the nozzle and the buckets and compensate for any diameter expansion of the Pelton runner, an adjustable or variable nozzle position mechanism must be employed. This is due to the centrifugal forces that change diameter of the Pelton turbine under load. Here's an overview of such mechanisms:

##### 1. Hydraulic Actuation:

A hydraulic system can be used to adjust the position of the nozzle. By varying the hydraulic pressure, the HEES control system can control the extension or retraction of the nozzle from the Pelton runner. This allows adjustments based on the turbine's operating conditions. [Stone E. B., 2008]

##### 2. Pneumatic Actuation:

Similar to the hydraulic systems, pneumatic actuators can move the nozzle in response to changes in nozzle clearance and the rotating buckets. By regulating the air pressure, the HEES control system can control the position of the nozzle relative to the Pelton runner. [Stone E. B., 2008]

### 3. Servo Motors:

Electrical servo motors equipped with feedback sensors can be employed for precise positioning of the nozzle. These motors can automatically adjust the nozzle's position to maintain the optimal distance from the buckets as the Pelton runner diameter changes with rotational speed. [Sussman, H. J., Williams, R. S, 1999].

### 4. Variable Pitch Nozzles:

Some Pelton turbines incorporate variable pitch nozzles that can be adjusted manually or automatically. By changing the pitch angle of the nozzle vanes, the HEES control system can control the jet's impact point on the Pelton runner's buckets, compensating for changes in diameter due to centrifugal forces. [Boening J. J., 1992]

### 5. Feedback Control Systems

Advanced control systems with sensors monitoring the Pelton runner's diameter and rotational speed can provide real-time feedback to adjust the nozzle position. These systems can maintain an optimal distance for maximum turbine efficiency. This feedback system will be connected to one of the NCMs, in order to get the ideal nozzle clearance while HEES is under operation. [Ogata K., 2002]

#### 4.3.2 Comparison Criteria

The choice of mechanism depends on factors such as the response time, accuracy, reliability, lifetime, and performance. The priority requirements for the HEES are:

1. **Accuracy:** It evaluates how precise the mechanism can control the nozzle position. The specified accuracy indicates the precision in controlling the nozzle position for each mechanism. It is expressed in millimeters (mm) and micrometers ( $\mu\text{m}$ ). For example,  $\pm 0.1$  mm means the mechanism can control the nozzle position within a range of 0.1 mm. The tolerance for precision would have to be smaller than approximately 3mm as that is the length of stable waterjet. [Niβl, 2022]

2. **Response times:** The Pelton buckets on the runner are moving with a maximum speed of approximately  $350 \text{ ms}^{-1}$  [Nißl, 2022] Hence the nozzle must have a response time that is suitable for such a high-speed machine and is able to accomplish movement requirements with the lowest latency. This factor assesses how quickly the mechanism can adjust the nozzle position.
3. **Lifetime:** Nozzle and turbine in a HEES system are vital parts. The nozzle position mechanism must function for long periods of time. Longer lifetime means better quality and lower maintenance cost.
4. **Reliability:** If the NCM (Nozzle clearance mechanism) does not function, it would lead to a collision of the nozzle and the turbine buckets or even the Pelton runner. Hence the NCM must be reliable. This factor considers the likelihood of system failures or breakdowns.
5. **Performance:** This aspect assesses how well the mechanism contributes to the overall turbine performance. The performance of the mechanisms listed in Table 7 has been assessed based on their general attributes and how well they align with the HEES requirements in the context of adjusting the nozzle position in a Pelton turbine.
6. **Agility:** Agility refers to the mechanism's ability to adapt to changing conditions or requirements. Feedback control systems and servo motors offer high agility, allowing for precise and rapid adjustments. Variable pitch nozzles can also be agile. Hydraulic and pneumatic systems have a slightly lower agility due to the dependence on fluid pressure adjustments.

Table 6 on the next page is a comparison table of the five mechanisms for adjusting the nozzle position in a Pelton turbine based on various factors. [Stone E. B., 2008] [Sussman, H. J., Williams, R. S, 1999] [Boening J. J., 1992] [Ogata K., 2002]



Mechanism	Response Time	Accuracy	Reliability	Life-time (Years)	Performance	Agility
<b>Hydraulic Actuation</b>	5-20 milliseconds	±0.1 mm (100 µm)	High	20+	Good	Moderate
<b>Pneumatic Actuation</b>	2-10 milliseconds	±0.5 mm (500 µm)	High	15+	Moderate	Moderate
<b>Servo Motors</b>	1-100 microseconds	±0.01 mm (10 µm)	Very High	30+	Excellent	High
<b>Variable Pitch Nozzles</b>	5-20 milliseconds	±0.1 mm (100 µm)	High	20+	Good	High
<b>Feedback Control Systems</b>	1-100 microseconds	±0.01 mm (10 µm)	Very High	35+	Excellent	Very High

Table 6: Nozzle clearance mechanisms comparison. [Ogata K., 2002] [Boening J. J., 1992] [Sussman, H. J., Williams, R. S, 1999] [Stone E. B., 2008]

#### 4.3.3 Summary of Mechanism Comparison:

For a Pelton turbine with a high rotational speed of  $2000 \text{ min}^{-1}$ , a very small waterjet diameter of 0.7mm, and a maximum nozzle-to-bucket distance of not more than 3mm, the following considerations apply:

##### 1. **Response Time:**

Servo motors and feedback control systems offer the fastest response times in microseconds, making them suitable for rapid adjustments. Hydraulic and pneumatic actuators have moderate response times within milliseconds.

## 2. **Accuracy:**

Servo motors and feedback control systems provide the highest accuracy, with micrometer precision. Hydraulic actuators offer high accuracy in the sub-millimeter range, while pneumatic actuators have slightly lower accuracy.

## 3. **Reliability:**

All mechanisms are highly reliable, but servo motors, feedback control systems, and hydraulic actuators are slightly more reliable due to their established technology.

## 4. **Lifetime (in Years):**

The mechanisms offer long lifetimes, with servo motors and feedback control systems potentially lasting the longest. This also defines the turbine's expected operational duration, and also makes sure of very probability of maintenance required.

## 5. **Performance:**

Servo motors and feedback control systems excel in maintaining optimal performance, followed by hydraulic actuators and variable pitch nozzles. Pneumatic actuators have a slightly lower performance. The servo motors can be combined with a feedback system to activate a feedback loop for the best nozzle clearance at all times of operation.

## 6. **Agility:**

Feedback control systems and servo motors offer a high agility, while variable pitch nozzles can also be agile. Hydraulic and pneumatic actuators may have slightly lower agility due to fluid adjustments. Feedback control systems and servo motors together provide high agility for adapting to changing conditions.

In conclusion, considering the specific requirements of a Pelton turbine with a high rotational speed, a very small waterjet diameter, and a tight nozzle-to-bucket distance, the best mechanism is likely to be a combination of servo motors and feedback control systems. These mechanisms offer the necessary speed, accuracy, and agility to control the nozzle position precisely, ensuring optimal energy conversion and efficiency in such a demanding operating environment.

## 4.4 Optimal number of Buckets on the Pelton runner

The number of Pelton buckets on a Pelton runner significantly impacts the turbine efficiency. Each bucket receives a high-velocity water jet, converting kinetic energy into mechanical energy. An optimal number of buckets ensures balanced water distribution and maximizing energy extraction. Too few buckets can lead to energy loss, while an excessive number can hinder efficient jet utilization. Finding the right balance is crucial for peak performance. Additionally, more buckets can increase mechanical complexity and maintenance needs. Thus, selecting the ideal number of buckets is a key design consideration to achieve the highest efficiency and overall effectiveness in operation. [Židonis A., 2016]

M. Eisenring suggests the equation below to calculate the optimum number of buckets  $N_{pb}$  by relating the diameter of the pitch circle  $D_{pc}$  to the optimum jet diameter. [Eisenring M., 1991]

$$N_{pb} = \frac{\pi \cdot D_{pc}}{2 \cdot d_{jet}} \quad (5)$$

By employing the equation and substituting the specified values, with a pitch circle diameter of 2.2 meters. The length of the Pelton bucket is relatively negligible; thus the pitch circle diameter is approximated from 2.2004m to 2.2m for this calculation. The jet diameter is 0.07mm. (Niβl, 2022).

The calculated result reveals that the theoretical optimal number of buckets required is 49367.8  $\approx$ 49367. This number is immensely huge. This is due to the size of the Pelton runner that is 22000mm compared to the jet diameter of 0.07mm. Thus, in order to surround the circumference of the Pelton runner with micro-Pelton buckets the quantity required skyrockets. Figure 21 shows the perspective of these many buckets on a Pelton runner.

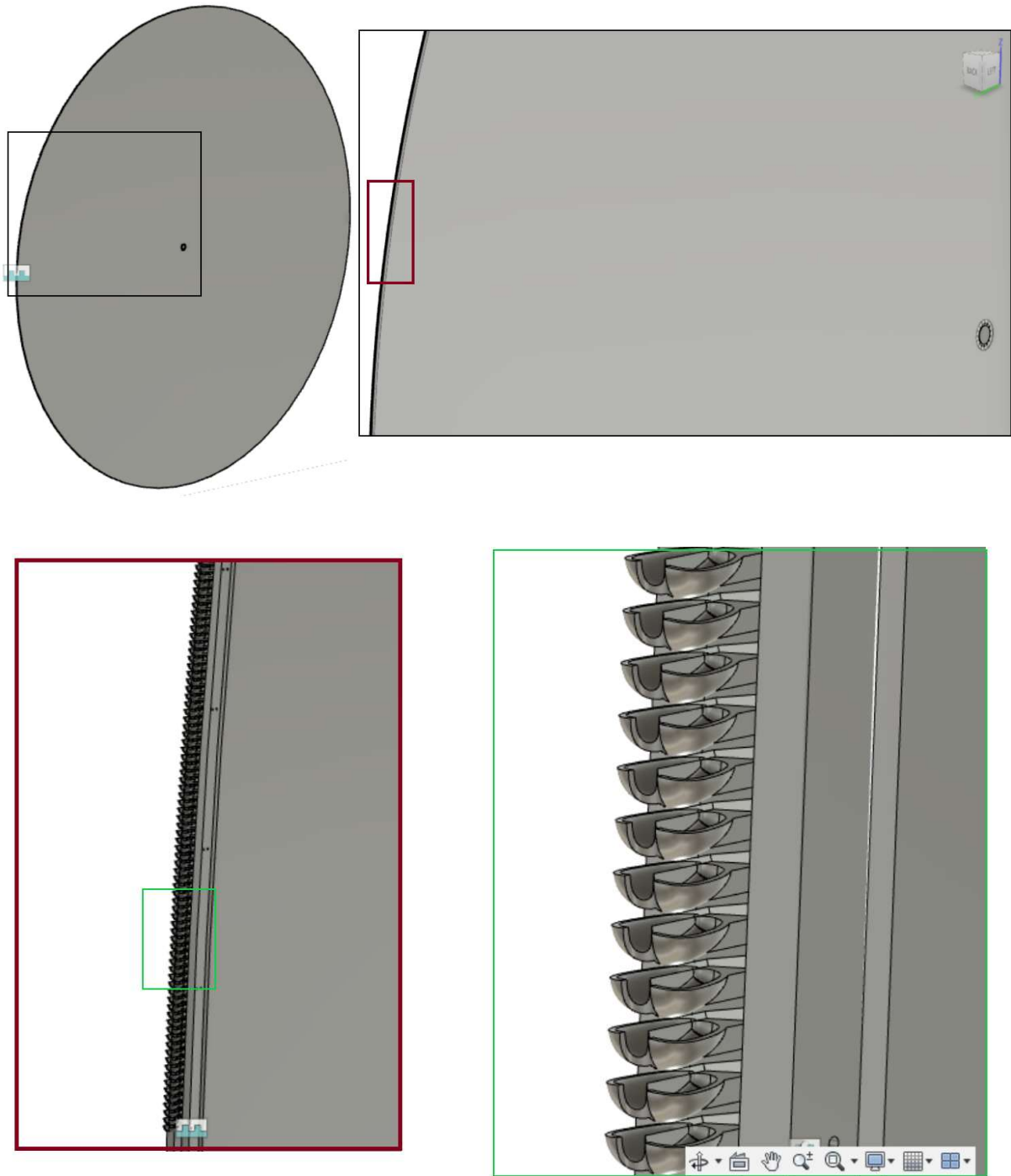


Figure 21: 3D view of Pelton buckets on the Pelton runner.

## 4.5 Nozzle

The concept of creating a water jet with a diameter of 0.06 mm for the HEES is remarkably similar to the technology used in water jet cutting machines, albeit on a much smaller scale. Water jet cutting machines are designed to precisely focus and accelerate water to cut through various materials. In the following paragraphs this technology is leveraged and modified for HEES.

### 4.5.1 Nozzle Technology

Water jet cutting machines use specialized nozzles to control and shape the water jet. These nozzles are engineered to maintain a consistent and narrow diameter for precise cutting. Similarly, for HEES, it could be adapted and miniaturized for this nozzle technology to produce the ultra-thin water jet required. The figure below shows the typical design and parts of a water jet cutting machine nozzle.

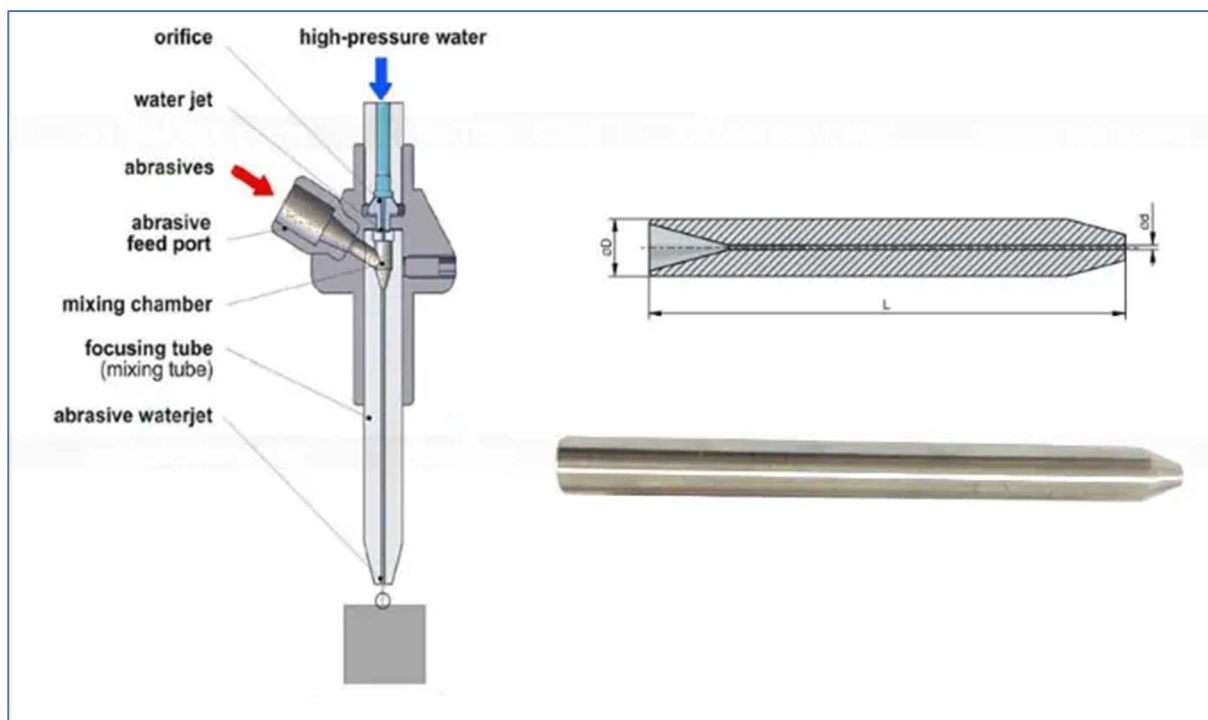


Figure 22: Waterjet cutting nozzle design [Zhuzhou, 2022]

#### 4.5.2 Orifice Design

The orifice of a water jet cutting nozzle is a critical component. It is typically made from materials like sapphire or diamond to withstand the abrasive nature of the cutting process. The orifice is designed to be extremely small, allowing for precise control over the water jet's diameter. For HEES the diameter of the orifice can be calculated using the following formulas [White F. M., 1990]:

$$D_{orifice} = \sqrt{\frac{4 \cdot Q_{jet}}{\pi \cdot p_{avg}}} \quad (12)$$

$$Q_{jet} = \pi \cdot d_{jet}^2 \cdot v_{jet} \quad (13)$$

$D_{orifice}$	orifice diameter
$Q_{jet}$	the flow rate calculated with equation (13)
$p_{avg}$	pressure of the waterjet in the HEES (= 2400 bar)

The flow rate  $Q_{jet}$  with  $d_{jet} = 0.07\text{mm}$  is  $0.15\text{Kg/min}$  (Table 3). Converting the volume rate to SI units ( $\text{m}^3$ ) using the density of water ( $997 \text{ Kg/m}^3$ ) leads to a value of  $2.5075 \cdot 10^{-6} \text{ m}^3\text{s}^{-1}$ . So, the calculated orifice diameter is approximately  $1.15 \times 10^{-7} \text{ m}$ , which is equivalent to 115 nanometers. Manufacturing such small orifices requires advanced techniques such as laser drilling, electron beam machining, or other specialized processes. The material properties of sapphire and diamond, known for their hardness and toughness, make them challenging to machine precisely at such small scales [McGeough J. A., 2013].

### 4.5.3 Focus Tube

Beyond the orifice, water jet cutting nozzles often have a focus tube. This tube narrows and focuses the water jet, helping to maintain a consistent and narrow diameter. The function of a focusing tube in waterjet cutting machines can be divided into three sub-functions for abrasive applications:

1. **Constriction:** The focusing tube narrows the water jet, reducing its diameter. This constriction enhances the jet's cutting ability by concentrating the energy into a smaller area.
2. **Stability:** It helps to stabilize the water jet by preventing divergence, ensuring that the jet remains coherent and maintains a consistent diameter over a longer distance. When water exits the orifice of the nozzle, it typically has a turbulent flow pattern with uneven velocities across the jet's cross-section. The focusing tube narrows the water jet's diameter, creating a more confined space for the water to pass through. As the water flows through this constriction, it tends to transition from a turbulent flow to a laminar flow state. Within the focusing tube, the water accelerates, resulting in a more uniform velocity profile across the jet's cross-section. The laminar flow, combined with the uniform velocity profile, stabilizes the water jet. The water molecules move in parallel, reducing chaotic motion and turbulence. This stability helps to maintain the jet's coherency and consistent diameter over longer distances, as it encounters fewer disturbances that would otherwise cause the jet to diverge or lose its shape.
3. **Protection:** In abrasive water jet cutting, the focusing tube also helps to protect the interior components of the nozzle from wear caused by abrasive particles, extending the nozzle's lifespan. It protects the interior of the nozzle from the high velocity abrasive particulates that bounce from the cutting surface and could harm the nozzle.

To understand the function of a focus tube in HEES the effects of absence of abrasive material are studied. In the case of HEES application, where abrasive material is not involved, the need for a focusing tube is different:

1. **Constriction (Diameter Control):** While constriction can help to control the water jet's diameter, achieving a 0.07 mm jet diameter is primarily dependent on a precise orifice design, high-pressure pumps, and flow control. The focusing tube's role in diameter control may be less critical in this case. The diameter control could be executed without the focusing tube since there is no addition of abrasive material after the waterjet leaves the orifice.
2. **Stability:** Stability remains important for ensuring that the water jet maintains coherency as it interacts with the Pelton buckets. However, other design factors and flow control mechanisms can contribute to this stability without relying solely on a focusing tube.
3. **Protection (Optional):** In HEES, there might not be a need for protection against abrasive wear. However, the focusing tube can serve as a protective barrier against external elements or contaminants that could affect the water jet's performance or inflict any wear on the orifice.

In summary, the use case of HEES's need for a focusing tube on the nozzle depends on the accuracy requirement of the end water jet diameter. Achieving and maintaining a 0.07 mm jet diameter is critical for the system's performance, thus a focusing tube would be a must. A HEES with a nozzle similar to a waterjet cutting machine would not allow for variance in jet diameter from 0.06mm to 0.28mm. It will be fixed to one waterjet diameter. On the other hand, it may have more flexibility in omitting the focusing tube and using a spear nozzle design while still achieving the desired results. However, in practice, it is very difficult to achieve such a small diameter with a spear nozzle and also give it the ability to change diameter due to the limitations of current technology. [Singh, S., 2011]. This would dictate that the nozzle with variable waterjet diameter is not possible for the HEES.

Additionally, water jet cutting systems include sophisticated pressure control mechanisms to adjust the force of the water jet. This allows operators to vary the cutting speed and power as needed. Precise control of the water flow rate is also essential for maintaining consistent performance of HEES. Thus, drawing inspiration from water jet cutting technology and miniaturizing its components, a highly precise and controlled water jet system can be created for HEES. This approach leverages



the proven principles of water jet cutting while adapting them to suit the specific requirements of our miniature Pelton turbine design.

## 4.6 Casing

Designing the casing for a Pelton turbine involves ensuring the structural integrity and safety of the turbine assembly while accommodating the rotating components. The casing in a project like a Hydro Electric Energy Storage (HEES) system, which incorporates a Pelton turbine, acts as a protective barrier around the Pelton turbine, which can spin at extremely high speeds. Safety is of the highest priority due to metal parts rotating at such speeds. Additionally, it prevents debris, water, or any other objects from entering the turbine, reducing the risk of accidents or damage to the system. The casing adds structural support to the Pelton turbine. It helps to maintain the alignment and balance of the turbine components, ensuring smooth and efficient operation even at high rotational speeds.

### 4.6.1 Material selection

The following criteria are important for choosing the best material for the casing:

1. **Tensile Strength:** Tensile strength is crucial because the casing material needs to withstand the mechanical stresses it will experience during operation. High tensile strength ensures the casing can handle the forces generated by the high-speed rotation of the Pelton turbine without deforming or failing.
2. **Density:** Density affects the overall weight of the casing. On the one hand a heavier Pelton turbine can help dampen vibrations and stabilize the system. This can contribute to smoother operation and potentially reduce wear and tear on the turbine components. On the other hand, a heavier system can be more challenging to transport to the installation site and may require more robust infrastructure for mounting. During initial stages safety is a high priority due to high speeds and heavy metal involved.

3. **Corrosion Resistance:** The casing will be certainly exposed to water and moisture in hydropower applications. Corrosion resistance is vital to prevent degradation of the casing material over time, ensuring long-term durability and safety.
4. **Cost:** Cost is a practical consideration, particularly for projects with budget constraints like HEES. Balancing material performance with affordability is essential to maintain the project's economic viability for household or commercial use.
5. **Thermal Conductivity:** Thermal conductivity can impact the ability of the casing to dissipate heat generated during operation. Efficient heat dissipation helps to maintain the casing's structural integrity and prevents overheating.
6. **Fatigue Resistance:** The casing will experience cyclic loading due to the rotation of the Pelton turbine. High fatigue resistance ensures that the casing can endure millions of loading cycles without developing cracks or failures.
7. **Machinability:** Machinability is essential because it influences the ease with which the casing can be manufactured and fabricated. Materials that are easy to machine can reduce manufacturing complexity and cost.

Material selection for the casing of the Pelton turbine in the HEES system is a critical decision. Table 7 on the next page evaluates potential material candidates based on various factors to help choose the most suitable material:

Criteria	High Strength Steel (HSS)	Aluminum Alloys	Stainless Steel (SS)	Composite Materials	Titanium Alloys
<b>Tensile Strength (MPa)</b>	900-1600	150-450	500-1200	200-1400	900-1400
<b>Density (g/cm<sup>3</sup>)</b>	7.8	2.7	7.9	1.5-2.0	4.5
<b>Corrosion Resistance</b>	Moderate to High	High	High	Variable	High
<b>Cost</b>	Moderate to High	Moderate	Moderate to High	Variable	High
<b>Thermal Conductivity (W/m·K)</b>	Moderate to High	Moderate	Low to Moderate	Low to Moderate	Low to Moderate
<b>Fatigue Resistance</b>	High	Moderate	High	Moderate	High
<b>Machinability</b>	Moderate	High	Low to Moderate	High	Low to Moderate

Table 7: Casing material properties comparison [Matweb, 2023] [McMaster-Carr., 2023]

In the following the different casing materials for the Hydro-Electric Energy Storage (HEES) system are compared and analyzed in more detail:

### 1. High Strength Steel (HSS) (AISI 4340):

HSS exhibits the highest tensile strength among the materials, making it robust and able to withstand mechanical stresses. Its high density adds weight to the system, potentially aiding in vibration dampening. It offers moderate to high corrosion resistance, which is essential for long-term durability in a water-based environment. The cost of HSS is moderate to high, which could impact the overall project budget. HSS has moderate to high thermal conductivity, aiding in heat dissipation. High fatigue resistance ensures long-term reliability. Machinability is moderate, affecting manufacturing complexity. [Appendix 9.1]

### 2. Aluminum Alloy (7075):

An Aluminum alloy, while exhibiting an average tensile strength, could be restricted in high-stress applications. Its lightweight nature diminishes the overall system weight, impacting vibration dampening. Notably, it provides high corrosion resistance, enhancing longevity, and is cost-effective, aligning with budget considerations. The moderate thermal conductivity necessitates supplementary measures for effective heat management. Considering its moderate fatigue resistance, meticulous design is essential for prolonged use. However, the alloy's high machinability streamlines the manufacturing process. [Appendix 9.2]

### 3. **Stainless Steel (SS) (AISI 316):**

Stainless steel (SS) boasts significant tensile strength, ensuring mechanical durability. With a higher density, it aids in vibration reduction. SS offers crucial corrosion resistance for longevity in a water environment, although costs can be moderate to high, impacting budgets. Moderate thermal conductivity may require additional heat management. Its high fatigue resistance ensures long-term reliability, but its machinability is low to moderate, potentially affecting manufacturing complexity. [Appendix 9.3]

### 4. **Composite Material - Carbon Fiber Reinforced Polymer (CFRP):**

Composite materials present a variable tensile strength dependent on their specific composition. Carbon fiber reinforced polymer (CFRP) is an advanced composite material that consists of carbon fibers embedded in a polymer matrix. Their lightweight nature might impact vibration dampening. The corrosion resistance varies, demanding careful material selection. Costs fluctuate widely based on the composite composition. Composite materials typically exhibit low to moderate thermal conductivity. Fatigue resistance varies, requiring precise material choice and design. Nevertheless, their generally high machinability simplifies the manufacturing process. [Sobri S. A., et al., 2020]

### 5. **Titanium Alloy (Ti-6Al-4V):**

Titanium alloy boasts high tensile strength, ensuring mechanical durability. With a moderate density, it potentially strikes a balance between weight and vibration. High corrosion resistance is a key feature for longevity. However, its high cost might impact the project's budget. Low to moderate thermal conductivity

necessitates additional heat management. The alloy's high fatigue resistance ensures long-term reliability, although machinability is low to moderate, impacting manufacturing complexity. [Appendix 9.4]

As a conclusion, while considering the specific requirements for the HEES casing, which include high tensile strength, corrosion resistance, and the potential for vibration reduction, stainless steel AISI 316 (SS) emerges as a suitable choice. SS combines robust mechanical properties, excellent corrosion resistance, and the potential for weight that aids in vibration dampening. Its overall benefits align with the critical needs of the HEES system, making it a strong candidate for the casing material.

However, for a prototype of the casing in the HEES system, where the primary focus is on cost-effective testing and functional validation, aluminum alloy 7075 appears to be a suitable choice [High-Strength 7075 Aluminum Sheets and Bars, 2016]. High machinability of aluminum alloys simplifies the manufacturing process, allowing for quicker prototype development, such as creating entries and exits for sensors and measuring devices for the testing. While aluminium alloys may not have the same mechanical robustness as stainless steel or titanium alloys, it's well-suited for building a functional prototype for testing and initial validation of the HEES system's design and performance.

## 5 Manufacturing process selection

Choosing the best manufacturing method for Pelton buckets in the HEES system is crucial for several reasons. Pelton buckets rotate at extremely high speeds, and any manufacturing defects or material weaknesses can lead to catastrophic failures. The right manufacturing method ensures structural integrity, reducing the risk of accidents. The precision and quality of the manufacturing method directly impact the efficiency and performance of the Pelton turbine. Irregularities or imbalances in the buckets can lead to energy losses and reduced power generation. Pelton buckets must withstand the forces exerted by high-speed water jets over an extended period. Choosing the right manufacturing method ensures the buckets' longevity and resistance to wear and tear.

## 5.1 Manufacturing methods

Some manufacturing methods would be more suitable for prototyping with aluminum alloy 7075 and some other methods for producing the final product with stainless steel AISI 316. Hence in this section the best method for both is investigated thoroughly.

### 5.1.1 Aluminium Prototype:

There are a lot of varied manufacturing methods available, but the four methods mentioned below are selected due to the ease and availability of tools for the methods.

#### **1. CNC Machining:**

CNC (Computer Numerical Control) machining involves the precise removal of material from an aluminium block using computer-controlled cutting tools. CNC machining requires aluminium stock compatible with CNC machining and suitable for producing detailed and accurate prototypes.

Pros and cons: The Technical University of Ingolstadt has CNC machines at its disposal, hence lower prototype manufacturing costs.

#### **2. 3D Printing:**

3D printing builds the prototype layer by layer using aluminium powder or filament. It is highly flexible and can create complex geometries like Pelton buckets. Specialized aluminium 3D printing material and postproduction heat treatment is required for printing. However, it is ideal for rapid prototyping and customization.

#### **3. Forming and Stamping:**

Aluminium sheets are shaped through plastic deformation, either by forming or stamping. It requires suitable aluminium alloys for forming processes. It is very cost-effective for bulk production of simple shapes.

#### **4. Powder Metallurgy:**

Aluminium powder is mixed with a binding agent, compacted into shape, and then sintered at high temperatures to create the prototype. Specialized aluminium powders and binders for the specific powder metallurgy process are necessary. Additionally complex shapes can be formed with this method.

### 5.1.2 Methods for the stainless-steel final product

The methods like CNC machining, forming, stamping, 3D printing, and powder metallurgy are also considered for SS. Some additional methods to be evaluated are:

#### **1. Casting:**

Molten stainless steel is poured into a mold to create the final shape. Suitable for large and intricate parts and for mass production. It requires high-quality stainless-steel alloys compatible with casting.

#### **2. Forging:**

Stainless steel is heated and shaped by applying force through forging hammers or presses. This process ensures strong, durable parts. It requires thick SS sheets suitable for forging along with appropriate heavy forging equipment to produce heavy-duty components.

#### **3. Metal Injection Molding (MIM):**

Stainless steel powder is mixed with a binding agent, injected into molds, and sintered to create the final product. Specialized stainless-steel powder and binder materials suitable for small, complex components for MIM required.

### 5.1.3 Key requirements for manufacturing methods

Selecting the right manufacturing method for the final design and prototype of a Pelton turbine made from stainless steel and aluminum respectively involves considering a

range of factors to ensure the best results. The key requirements and considerations for choosing a manufacturing method are enlisted below:

**1. Complexity of Design:**

The Pelton turbine design is intricate and requires precise geometry. CNC machining, 3D printing, powder and powder metallurgy might be a suitable choice due to its ability to create complex shapes with high accuracy.

**2. Precision and Tolerances:**

Pelton turbine buckets require precise dimensions to optimize energy conversion. Methods like CNC machining can provide tight tolerances, ensuring consistency and performance.

**3. Customization and Iterative Design:**

Prototyping often involves design iterations. Methods like CNC machining and 3D printing offer the flexibility to quickly adjust the design without requiring new tooling or molds.

**4. Material Efficiency:**

Considering methods that minimize material wastage, as stainless steel can be costly, is crucial. CNC machining and some additive manufacturing methods are efficient in this regard.

**5. Surface Finish:**

The surface finish of the Pelton turbine buckets can impact water flow dynamics. CNC machining and certain additive manufacturing methods with post processing can provide excellent surface finishes.

**6. Strength and Durability:**

For stainless steel and its mechanical properties, it must be ensured that the selected manufacturing method maintains the strength and durability of the material.

**7. Prototype Quantity:**

For limited number of prototype Pelton turbine buckets, CNC machining and additive manufacturing methods can be cost-effective for small production runs.

**8. Cost Considerations:**



The cost of each manufacturing method, considering factors like material, labor, tooling, and equipment, should be evaluated. 3D printing would be cost-effective for smaller quantities and complex designs.

#### **9. Post-Processing and Finishing:**

Some methods might require additional finishing steps. The chosen method should align with the desired surface finish and any required post-processing.

#### **10. Expertise and Equipment:**

The availability of expertise and necessary equipment for each method is considered. Some methods might require specialized skills and machinery.

#### 5.1.4 Conclusion for aluminum prototype:

In the context of HEES, where precision and customization are paramount for prototype development, the choice of the manufacturing method becomes critical. Among the evaluated processes, CNC Machining emerges as the most favorable option. This technique provides a remarkable balance of precision, surface finish, and material strength, making it ideal for creating intricate components and conducting thorough testing.

The benefits of CNC machining for HEES aluminium prototypes are multifaceted. Firstly, its high precision ensures that each component meets the exact design specifications, minimizing the risk of errors during testing and optimization. Secondly, CNC machining delivers an excellent surface finish, crucial for the hydrodynamic efficiency of the Pelton buckets and the overall performance of the energy storage system. Lastly, while CNC machining may entail higher costs and lead times, these aspects align with the project's goals of achieving the best possible results during the prototype phase.

## Manufacturing methods for aluminium prototype comparisons

Factor	CNC Machining	3D Printing	Forming/Stamping	Powder Metallurgy
<b>Complexity of Design</b>	High	High	Low	High
<b>Precision and Tolerances</b>	High	Medium	Medium	Medium
<b>Customization and Iteration</b>	High	High	Low	Medium
<b>Material Efficiency</b>	Medium	High	High	High
<b>Surface Finish</b>	High	Medium	Low	Medium
<b>Strength and Durability</b>	Medium	Medium	Medium	Medium
<b>Prototype Quantity</b>	Low-Medium	High	High	High
<b>Cost Considerations</b>	Medium	Low	Low	Medium
<b>Post-Processing &amp; Finishing</b>	Low	High	Medium	Medium
<b>Expertise and Equipment</b>	Common	Specialized	Common	Specialized

Table 8: Manufacturing Methods for Aluminium Prototype [Kalpakjian, S., & Schmid, S. R., 2009] [Callister Jr, W. D., & Rethwisch, D. G., 2020] [Budinski, K. G., & Budinski, M. K., 1999] [Bobade, S. S., & Badgujar, T. Y., 2017]

### 5.1.5 Stainless steel final design manufacturing comparison

Factor	Casting	Forging	CNC Machining	Metal Injection Molding	Sheet Metal Fabrication	Powder Compacting & Sintering
<b>Complexity of Design</b>	High	High	High	High	Low	High
<b>Precision and Tolerances</b>	Medium	High	High	High	Medium	Medium
<b>Customization and Iteration</b>	Low	Low	High	Medium	High	High
<b>Material Efficiency</b>	Low	Medium	Medium	Medium	Medium	Medium
<b>Surface Finish</b>	Medium	Medium	High	Medium	Low	Medium
<b>Strength and Durability</b>	High	High	High	High	Medium	Medium
<b>Prototype Quantity</b>	High	High	Low-Medium	Medium	Medium	Low-Medium
<b>Cost Considerations</b>	Low	Medium	Medium	Medium	Medium	Medium
<b>Post-Processing &amp; Finishing</b>	High	Medium	Low	Medium	Medium	High
<b>Expertise and Equipment</b>	Common	Common	Common	Specialized	Common	Specialized

Table 9: Manufacturing Methods for Stainless Steel Final Design [Callister Jr, W. D., 2007] [Dieter, G. E., & Bacon, D., 1976] [Barbero, E. J., 2010] [Joshi, V. A., 2006] [Upadhyaya, G. S., 1997] [Bobade, S. S., & Badgujar, T. Y., 2017]

### 5.1.6 Conclusion for stainless steel final design manufacturing

When it comes to manufacturing the final design of HEES components from stainless steel, precision, strength, and durability are paramount. In this regard, CNC machining stands out as the optimal choice. CNC machining offers exceptional precision, ensuring that components meet stringent design specifications. Moreover, its capability to achieve a superior surface finish is crucial for the hydrodynamic efficiency of the Pelton buckets and the overall performance of the energy storage system.

The benefits of CNC machining for the stainless-steel final design of HEES extend beyond precision and surface finish. CNC-machined components boast high material strength and durability, essential for withstanding the extreme forces and conditions experienced during energy conversion. While CNC machining may involve higher costs and lead times compared to some other methods, these investments align with the project's commitment to safety, longevity, and performance.

## 6 Conclusion

In the pursuit of sustainable energy solutions, this thesis has delved into the intricate world of Hydroelectric Energy Storage (HEES). Through a comprehensive exploration of design, manufacturing, and engineering considerations, the foundation for a Hydroelectric energy storage system has been laid.

The Thesis commenced with an examination of the Pelton turbine, a fundamental component of HEES. Extensive discussions elucidated the critical factors influencing the design of Pelton buckets, encompassing aspects such as bucket width, depth, and curvature. The investigation into bucket design helped decide the size and culminated in a 3D modelling process using the software Fusion 360, ensuring hydrodynamic efficiency and energy conversion optimization.

Manufacturing methods were meticulously evaluated to bring these designs to fruition. The discerning choice of CNC machining for Pelton bucket production emerged as the ideal solution, combining precision, strength, and surface finish essential for HEES performance. In a parallel endeavour, attachment methods for Pelton buckets were scrutinized, yielding insights into the feasibility of bolting methods.

The quest for hydraulic efficiency ventured into nozzle and orifice design, which carried implications for jet diameter, orifice diameter, and water jet control. Innovations in water jet cutting technology were explored to harness the potential of ultra-thin water jets, reaching diameters as minute as 0.06 mm.

As the HEES system took shape, the casing emerged as a critical component, demanding strength, durability, and material considerations. After a rigorous evaluation of material options AISI 316 and aluminum alloy 7075 fulfilled, underscored the importance of CNC machining for precision and structural integrity.

In the culmination of this research, a comparative analysis of manufacturing methods for both prototype and final designs underscored the supremacy of CNC machining. This versatile method promises the precision, surface finish, strength, and durability indispensable for HEES. These characteristics align harmoniously with the project's commitment to safety, longevity, and performance.

In the final analysis, the Hydroelectric Energy Storage system envisaged herein stands as a testament to the potential of sustainable energy solutions. Through meticulous design, cutting-edge manufacturing, and innovative engineering, this thesis advances the forefront of renewable energy storage. As the world grapples with the challenge of sustainable energy generation, HEES emerges as a compelling answer, capable of revolutionizing the way we store and harness power.

This thesis is not merely the culmination of rigorous research; it is a catalyst for future innovation, a beacon guiding the path towards a greener, more sustainable future. The HEES system, with its meticulously designed Pelton buckets, precision manufacturing, and hydraulic advancements, represents a paradigm shift in renewable energy. As a conclusion of this thesis, towards realizing the full potential of Hydroelectric Energy Storage, a journey that promises a brighter, cleaner future for generations to come.

## 7 Outlook

The journey embarked upon in this thesis marks not an end but a profound beginning. As Hydroelectric Energy Storage (HEES) stands on the precipice of transforming the energy landscape, the path forward brims with promise and potential.

The immediate trajectory involves practical implementation. The 3D models of Pelton buckets, meticulously designed and validated in the digital realm, are primed for physical realization. Prototypes can be manufactured using CNC machining, offering tangible insights into their real-world performance. These prototypes will serve as crucial testbeds, allowing us to assess the design's efficacy in actual hydrodynamic conditions.

Simultaneously, the nozzle technology, instrumental in the creation of ultra-thin water jets, must undergo further refinement and scaling. Collaborations with experts in the field of water jet technology can accelerate progress, pushing the boundaries of what's achievable.

Environmental and economic impacts are also central to the future of HEES. Comparative life cycle assessments, in-depth economic analyses, and sustainability

evaluations are essential steps toward optimizing this technology for real-world deployment.

In this ongoing journey, international collaboration will be pivotal. Sharing insights, research, and practical experiences can accelerate the adoption of HEES as a global energy storage solution. Furthermore, partnerships with industries and energy companies will facilitate the integration of HEES into existing energy grids and infrastructure.

The ultimate vision is a world where sustainable energy storage systems like HEES underpin a clean and efficient energy future. This journey requires the collective efforts of researchers, engineers, policymakers, and innovators dedicated to the ideals of sustainability, energy efficiency, and environmental responsibility. The chapters of this thesis have paved the way, and the outlook for HEES is one of transformation, innovation, and sustainable energy solutions, forging a path towards a cleaner, greener tomorrow.

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# 9 Appendix

## 9.1 HSS AISI 4340

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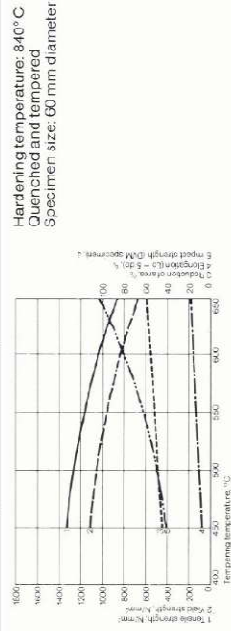
### AISI 4340 High tensile steel

Typical Analysis (Ave. values %)	C	Si	Mn	Ni	Cr	Mo	S	P
	0.40	0.25	0.70	1.80	0.80	0.25	0.025	0.025
NEAREST STANDARD	AS 4340	DIN 1.6565 34CrNiMo6	BS ~EN24 ~ 817/M 40	AISI 4340				

**DESCRIPTION**  
Nickel, Chromium, Molybdenum steel for applications requiring high tensile strength and toughness values, particularly in large cross sections in the quenched and tempered condition. The addition of Molybdenum prevents the steel from being susceptible to temper brittleness. Higher tensile and yield strength than 4140

**APPLICATIONS**  
Components for the aircraft, automotive and general engineering industries eg. Propeller shafts, connecting rods, gear shafts, and other automobile parts. Heavy forgings, eg. Rods, shafts, discs.

HEAT TREATMENT	Temperatures / Conditions
Forge	850-1050°C, slow furnace cool.
Normalize	850-880, air cool.
Anneal	650-700, Cool slowly in controlled furnace
Stress relieve	In the quenched and tempered condition, about 30-50°C below the tempering temperature. Air cool.
Harden	In the annealed condition, 600-650°C. Air cool.
Temper	630-660°C, oil quench
Nitride	540-680°C hold for 1 hour min. at temperature, air cool. (See tempering chart)
	Suitable for both liquid and gas nitriding.



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**WELDING**  
Parts should be welded in the hardened and tempered condition. Strength properties of the joint will not be the same as the base metal.  
Preheat 300-400°C. Temper after welding to about 35-50°C below the recommended tempering temperature.  
Filler metal: - Fox DCMS: KB electrodes or DCMS-G wire.  
For advice in connection with difficult welding, please consult our engineers.

MECHANICAL PROPERTIES Heat Treated Condition	Condition	Ruling section mm	Tensile Strength MPa	Yield Strength MPa	Elong. %	Izod Impact J	Brinell Hardness
T	250	850-1000	685	13	40	248-302	
	150	850-1000	685	13	54	248-302	
U	100	930-1080	740	12	47	289-331	
	63	1000-1150	835	12	47	293-352	
W	30	1080-1230	925	11	41	311-375	
X	30	1150-1300	1005	10	34	341-401	
	30	1230-1380	1080	10	24	363-429	
Z	30	1555-	1725	5	10	444-	

HIGH TEMPERATURE STRENGTH	Diameter	Yield strength MPa						
		Over	Up to 20°C	100°C	200°C	250°C	300°C	350°C
250	500	540	505	471	451	412	383	353
	1000	490	466	441	422	392	363	343

PHYSICAL PROPERTIES	Value
Density (kg/dm <sup>3</sup> )	7.85
Modulus of elasticity (GPa)	210
Thermal conductivity (W/m.K)	42
Electric resistivity Ohm.mm <sup>2</sup> /m	0.19
Specific heat capacity J/(kg.K)	460
Modulus of elasticity	100°C 200°C 300°C 400°C 500°C

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## 9.2 Aluminum Alu 7075



### 7075 Aluminum Alloy: Properties

#### General Characteristics

Characteristic	Appraisal
Strength	High
Corrosion Resistance	Average
Weldability & Brazability	Poor
Workability	Poor
Machinability	Fair

#### Chemical Composition

Element	Minimum %	Maximum %
Silicon	No Min	0.4
Iron	No Min	0.5
Copper	1.2	2
Manganese	No Min	0.3
Magnesium	2.1	2.9
Chromium	0.18	2
Zinc	5.1	6.1
Titanium	No Min	0.2
Other Elements	No Min	0.05 each, 0.15 in total

#### Physical Properties

Property	7075-O	7075-T6, -T651	7075-T73, -T7351
Density	2.81 g/cc   0.102 lb/in <sup>3</sup>	2.81 g/cc   0.102 lb/in <sup>3</sup>	2.81 g/cc   0.102 lb/in <sup>3</sup>

#### Mechanical Properties

Property	7075-O	7075-T6, -T651	7075-T73, -T7351
Tensile Strength	228 MPa   33000 psi	572 MPa   83000 psi	505 MPa   73200 psi
Yield Strength	103 MPa   15000 psi	503 MPa   73000 psi	435 MPa   63100 psi
Modulus of Elasticity	71.7 GPa   10400 ksi	71.7 GPa   10400 ksi	72.0 GPa   10400 ksi

#### Thermal Properties

Property	7075-O	7075-T6, -T651	7075-T73, -T7351
Coefficient of Thermal Expansion @ 20.0 - 100 °C Temp	23.4 μm/m-°C   13.0 μin/in-°F	23.4 μm/m-°C   13.0 μin/in-°F	23.4 μm/m-°C   13.0 μin/in-°F
Thermal Conductivity	173 W/m-K   1200 BTU-in/hr-ft <sup>2</sup> -°F	0.960 J/g-°C   0.229 BTU/lb-°F	155 W/m-K   1080 BTU-in/hr-ft <sup>2</sup> -°F

## 9.3 Stainless steel AISI 316

### Heat treatment and hot forming

Solution heat treatment: 1020-1120 °C  
(cooling by air or water)

Hot forming: 1200-900 °C  
(cooling by air)

### Welding

The material AISI 316 / EN 1.4401 has a medium weldability and can be used with many common processes such as arc or TIG welding. For submerged arc and gas fusion welding this stainless steel grade is only of limited use.

Please note that the material is no longer resistant to intergranular corrosion in the welded state.

If you have further questions about this or any other product, please contact our team at +49 2203-9240-0 or email [agst@agst.de](mailto:agst@agst.de)

**Please note:**  
The information given in this data sheet has been compiled to the best of our knowledge and is based on the current version of the relevant standard.  
It is considered for reference only and we assume no liability for any errors.

The material AISI 316 / EN 1.4401 is an austenitic chrome-nickel-molybdenum steel. The molybdenum content provides high corrosion resistance to non-oxidizing acids and chlorine-containing materials. This stainless steel grade has low precipitation and is suitable for welding, forging and cold forming. Please note, however, that the material AISI 316 / EN 1.4401 does not have any resistance to intergranular corrosion in the welded state.

### Chemical composition (% by mass according to DIN EN 10088-3 for EN 1.4401)

C	Si	Mn	P	S	N	Cr	Co	Mo	Ni	Ti	Other
≤ 0,07	≤ 1,00	≤ 2,00	≤ 0,045	≤ 0,03	≤ 0,10	16,5 – 18,5	-	2,00 – 2,30	10,0 – 13,0	-	-

### Specification

EN-grade: 1.4401  
EN-version name: X5CrNiMo17-12-2  
EN-standard: 10088-3  
AISI: 316  
B.S.: 316S31\*  
JIS: SUS316\*  
Microstructure: austenitic

### Physical properties

Magnetizability: low  
Density (kg/dm<sup>3</sup>): 7,9  
Thermal conductivity (up to 20°C): 15  
Electron resistance at room temperature (in G·mm<sup>2</sup>/m): 0,73

### Possible fields of application

aeronautical industry  
conductor sector  
pressure vessel construction  
chemical industry  
food industry  
petrochemistry  
aircraft intake

### Mechanical properties at room temperature in solution annealed condition (according to EN 10088-3 for EN 1.4401)

Ø in mm	Hardness in HB	Yield strength		Tensile strength		Elongation A <sub>100</sub> in %
		R <sub>p0,2</sub> in Mpa	R <sub>p0,01</sub> in Mpa	R <sub>m</sub> in Mpa	A <sub>100</sub> in %	
≤ 160	≤ 215	≤ 200	≤ 235	500-700	40	-
160 < Ø ≤ 250	≤ 215	≤ 200	≤ 235	500-700	-	-

### Yield strength at elevated temperature in solution annealed condition (according to EN 10088-3 for EN 1.4401)

Temperature in °C	100	150	200	250	300	350	400	450	500	550
R <sub>p0,2</sub> in Mpa	175	166	146	135	127	127	115	112	110	108
R <sub>p0,01</sub> in Mpa	210	190	179	165	155	150	145	141	139	137

(\* in accordance with)



## 9.4 Titanium alloy Ti 6Al-4V



All material we supply has full traceability with inspection certification in accordance with BS EN 10402 3.1. We can supply material with the intent of BS EN 10402 3.2 inspection certification on request.

We have onsite PCN and SNT Level II inspectors who can test material to your requirements.

All information included in this sheet is intended as a guide only and is correct to the best of our knowledge.



### Chemical Analysis

	Al	V	C	Fe	O	N	H	Ti	
Min	5.50	3.50	-	-	-	-	-	-	%
Max	-	4.50	0.08	0.30	0.20	0.05	0.0125	BAL	%

### Mechanical Properties

Typical properties:

Tensile (PSI (MPa))	Yield (0.2% offset), (PSI (MPa) Min)	Elongation in 2" or 4D min%	Reduction of Area Min %	Hardness HRC Typical
130,000 (897)	120,000 (827)	10	25	36

### Physical Properties

Typical properties at room temperature:

Density	4.43 g/cc (0.16 lb/in <sup>3</sup> )
Poissons Ratio	0.33
Shear Modulus	44GPA (6380 ksi)
Modulus of Elasticity	114 GPa (16500 ksi)
Specific Heat	0.5263 Joules/g°C (0.126 BTU/lb-°F)
Mean Coefficient of thermal expansion, 20-100°C (K-1)	8.6 µm/m °C (4.78 µm/in-°F)
Melting point	1604-1660 °C (2920-3020°F)
Thermal Conductivity	6.7 W/m-K (46.5 BTU-in/hr-ft <sup>2</sup> -°F)
Magnetic Permeability	1.00005



### Quick Facts

- High strength to weight ratio
- Known as Titanium Grade 5
- Good weldability and machinability
- Fire and shock resistant
- Favourable cryogenic properties
- Biocompatibility

Titanium is extensively used in the aerospace industry and increasingly used in general engineering applications, especially where high strength/weight ratio and corrosion resistance are major considerations.

Titanium 6AL-4V is a high-strength, alpha-beta alloy which is fully heat treatable and is the most versatile of the titanium alloys.

### Typical Applications

Pumps and valves, turbines and airframes, fasteners, automotive components including valves, springs and connecting rods, orthopaedic implants and surgical instruments, oilfield equipment, stress joints, risers and casings.

### Stock Range

We stock a comprehensive range of round bar sizes between 8mm and 160mm diameter. We can also supply flat bar, rings, blocks and slabs.

Primarily manufactured in US and China

### Industry Specifications

- AMS 4928
- UNS R56400

Material may also be supplied to Customer specifications, subject to enquiry