Estimation of the efficiency of two subsystems of the ”Energy Towers”.

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***Abstract*—In order to reduce CO_2 emissions, it is necessary to change over to climate-neutral energies as quickly as possible. To achieve this, the use of climate-neutral technologies must be expanded on the one hand, and on the other hand, the efficiency of existing plants, even those that are not climate-neutral, must be increased.**
In this publication, a new type of plant is investigated, which is designed to enable efficient energy conversion on the basis of Archimedes principle. In this investigation, the conversion efficiencies of two subsystems were calculated. The analytically calculated results provide a first estimate for the efficiencies of the two subsystems and can be further specified when a more detailed model of the plant is available.

***Index Terms*—Energy Conversion, Energy Towers, Archimedes Principle**

I. Introduction

The idea of using the buoyancy force of bodies in a fluid to convert energy is not new, but a profitable realization of the conversion has not yet been achieved. The company ”Energy Towers Holding AG” has the aim to develop a new operating principle to change this. In order to be able to estimate the efficiency and thus, the economic viability of the plant, calculations were carried out for two subsystems of the plant by the ”KIT Campus Transfer GmbH”.
This publication contains the results of the investigations carried out at the end of 2017, using the models and data available at that time.
The paper is structured as follows: In section II, the functional principle of the system and the energy conversions are described. The third and fourth sections describe the simulation of one subsystem each. In section V the results are summarized and in the last section of the paper a short outlook regarding further investigations is given.

II. Principle of Operation

Figure 1 shows a schematic illustration of the plant, which is used in the following to describe its functionality. The plant can be divided into the subsystems ”Primary Energy Conversion”, ”Hydraulic System”, ”Gates”, ”Tower” and ”Electrical Generator”. In Figure 1 only the parts ”Hydraulic System”, ”Gates” and ”Tower” are shown. The ”Communicating Pipe” shown in Figure 1 is assigned to the ”Gates” subsystem and its function will be explained later. In the following, the basic principle of the plant is explained, starting with the processes in the tower.

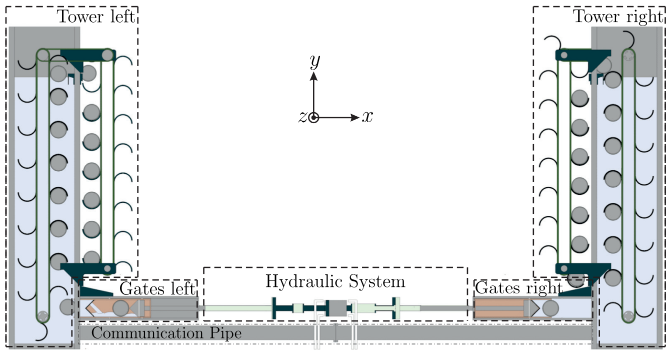

Fig. 1: Schematic illustration of the plant

The round gray objects in Figure 1 represent hollow floating bodies with a cylindrical shape and an average density ρ_{FB} smaller than that of water ρ_{Fluid}. These floating bodies are inserted at the bottom of the water-filled tower and since $\rho_{FB} < \rho_{Fluid}$, according to Archimedes principle, the buoyancy force acting on the bodies is larger than its gravitational force. Consequently, a resulting force acts on the floating bodies in the opposite direction as gravity, which drives the chain drive located in the tower. At the upper end of the tower, the floating bodies are taken out of the water and are transferred to a second chain drive, which is mechanically coupled to the first. The buoyancy force in air is negligibly small and accordingly the gravitational force of the floating bodies now provides a resulting force in the direction of gravity. This force acts as a further driving force of the chain system. Arriving at the lower end of the second chain drive, the floating bodies are transported back into the tower through the gates. To convert the mechanically transmitted power of the chain system into electrical power, the lower pulley of the chain drive located outside the tower is mechanically coupled to an electrical generator. The useful energy of the power plant is the electrical energy fed into the electrical grid by the generator.
In order to run the system stationary, the floating bodies must be transported back down into the tower after passing through the chain drive. The floating bodies must be pushed into the tower against the hydrostatic pressure of the water. This is done by the gates driven by the hydraulic system. The

working piston, which is centrally located in the hydraulic system, performs a cyclic linear movement and generates an oil volume flow. This volume flow then generates the desired movement of the gates. To reduce the force required to push the floating bodies into the tower, both towers are connected by the " Communicating Pipe". Thus, when a floating body is pushed into the tower, the water level of the tower does not have to be raised according to the displaced volume, instead a part of the water flows through the "Communicating Pipe" into the other tower where the gate is retracting at that time. A more detailed description of the plant can be found in the patent [1].

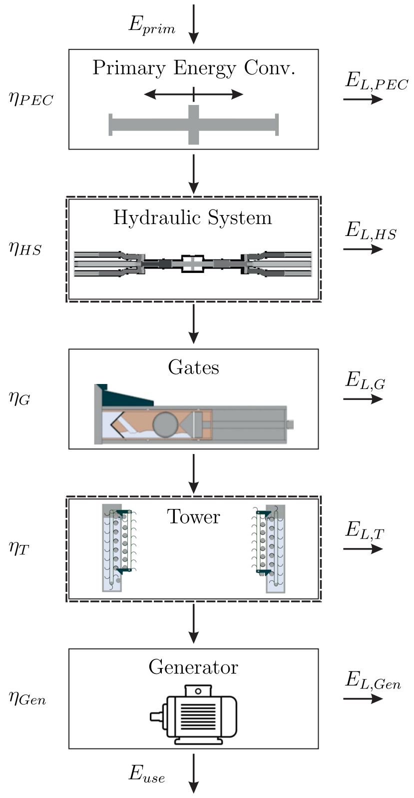

Fig. 2: Illustration of the energy conversions in the plant

It is important to understand that the system uses the buoyancy force only for energy conversion. Accordingly, a primary energy source is needed to drive the system. This primary energy is used to move the working piston of the hydraulic system and represents the energy expenditure of the plant. In Figure 2 the subsystems and energy flows of the plant are shown schematically. It can be clearly seen that several energy conversions are executed in the plant. The total efficiency can be calculated according to Figure 2 as follows

$$\eta_{tot} = \frac{E_{use}}{E_{prim}} = \eta_{PEC} \cdot \eta_{HS} \cdot \eta_G \cdot \eta_T \cdot \eta_{Gen}. \tag{1}$$

In this investigation, only the subsystems "Hydraulic System" (η_{HS}) and "Tower" (η_T) are examined. The efficiency of the other subsystems could not be calculated due to the lack of design details at the time of the investigation.

III. Simulation of the Hydraulic System

This section describes the calculation for estimating the efficiency of the hydraulic system. In order to make the paper not too lengthy, the calculation is not explained in detail, but the basic concept of the calculation is presented. Figure 3 shows the section through the x-z plane (see Figure 1) of the right half of the hydraulic system. In Figure 3 the installed hydraulic cylinders are numbered consecutively. The cylinders perform various tasks, for example cylinder 1 corresponds to the working cylinder and generates the required oil volume flow. The exact function of the individual cylinders will not be discussed here. Instead, Figure 3 should make clear that several hydraulic cylinders are installed in the system.

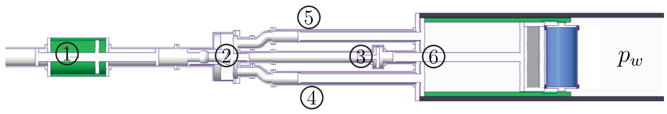

Fig. 3: Hydraulic System

The idea for calculating the efficiency of the hydraulic system was to determine the efficiency of the individual hydraulic cylinders and thus calculate the overall efficiency of the hydraulic system. Flow losses due to valves and pipes were not taken into account. To determine the efficiency of the hydraulic cylinders, a rod and piston efficiency was defined. For each frictional contact of a piston rod with the cylinder, the friction losses considered using the corresponding rod efficiency η_{rod}. Equivalently, the friction losses at the contact points of the piston with the cylinder wall were taken into account by the piston efficiency η_{piston}. For example, the working piston has two rod frictional contacts μ_{rod} and three piston frictional contacts μ_{piston} (see Figure 4), so the efficiency of the working cylinder can be calculated as follows

$$\eta_{WP} = \eta_{piston} \cdot \eta_{rod} \cdot \eta_{piston} \cdot \eta_{rod} \cdot \eta_{piston}. \tag{2}$$

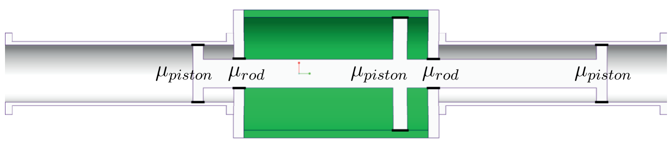

Fig. 4: Friction contacts working cylinder

In this way, the efficiency was calculated for each hydraulic cylinder of the system. The total efficiency is then obtained by combining all cylinder efficiencies. The same efficiency was assumed for each rod contact and each piston contact. However, rod and piston efficiencies are not the same.

Since no concrete design of the hydraulic system was available at the time of the investigation, a high rod efficiency of $\eta_{hm,rod} = 98\,\%$ and a high piston efficiency of

$\eta_{hm,piston} = 99\,\%$ were assumed for the calculations. Depending on the working phase of the system, a different number of hydraulic cylinders are in motion. The number of friction contacts with a relative movement have been analyzed for the different movement phases of the hydraulic drive and range between 19 and 35.
In order to fulfill the function of the hydraulic system, two valves must be installed in the system. The pressure drop of the valves were assumed to be 3 bar for the simulated cycle time of $t_{cycl} = 6$ s.
With the assumed efficiency values and pressure drop a target overall efficiency of the hydraulic system is calculated to be $68\,\%$.

IV. Simulation of the Tower

The basic principle of the tower has already been explained in section II. In this section, the processes in the tower are further detailed and the calculations to determine the efficiency of the tower are explained. The following losses are taken into account when calculating the efficiency:

- Flow losses:
  - Floating bodies in the tower
  - Downward moving mounts
  - Chain elements of the chain drive
- Friction losses:
  - Chain drive
  - Bearing of the rotating pulleys
- Losses during lifting and throwing over of the floating bodies at the upper end of the tower

The quantitative values of the quantities used to compute the losses will not be discussed in detail, they are given at the end of the section in table I.
In the first step the losses of the floating bodies in the tower are calculated, for this purpose a single body in the tower is considered.
As already indicated, the motion of a body in a fluid results from the Archimedes' principle, which states that the buoyant force applied to a body located in a fluid is equal to the gravitational force of the fluid that the body displaces. Accordingly, the buoyancy force can be calculated as follows

$$F_{Buoyancy} = \rho_{Fluid} \cdot V_{FB} \cdot g. \tag{3}$$

From this correlation, three cases can be derived for the motion of a floating body in a fluid:

- $\rho_{Fluid} < \rho_{FB}$: Body sinks
- $\rho_{Fluid} = \rho_{FB}$: Body stands still
- $\rho_{Fluid} > \rho_{FB}$: Body rises

For the functionality of the Energy Towers investigated in this paper (see Figure 1), the floating bodies in the tower must move upwards and thus must have a lower density than water. In this case, stationary operation of the Energy Tower results in the equilibrium of forces shown in Figure 5. In addition to the buoyancy force and the gravitational force, there are two other forces that influence the movement of the floating body. The force $F_{Fluid,FB}$ describes the force acting from the fluid on the body during the movement of the body. It represents the flow losses and depends especially on the ascending speed of the body. The force $F_{Mounting}$ is the force acting on the body from the mount. This force acts with the same magnitude but in the opposite direction from the body on the mount and thus represents the driving force of the chain drive. The force can also be interpreted as a resulting force, which results from the other three forces and drives the chain. The inertial force of the body does not occur in the free punch, since a constant ascending speed is assumed during steady-state operation of the system.

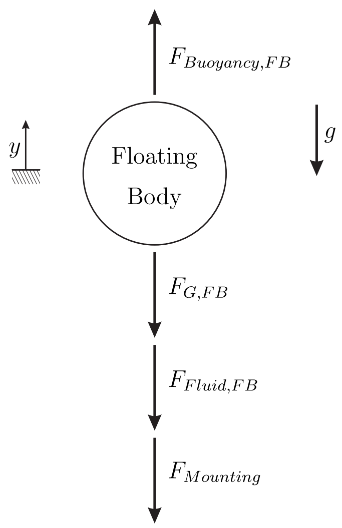

Fig. 5: Free punch floating body

To calculate the driving force $F_{Mounting}$, the forces $F_{Buoyancy,FB}$, $F_{G,FB}$ and $F_{Fluid,FB}$ must be known. $F_{Buoyancy,FB}$ can be calculated using Equation 3 and the calculation of the gravitational force $F_{G,FB}$ is trivial. What remains is the calculation of the force $F_{Fluid,FB}$ which will be explained in the following.
According to [2] and [3], the drag force acting on a body when it moves through a fluid can be calculated with the following formula

$$F_{fluid} = F_{fluid,S} + F_{fluid,F}. \tag{4}$$

The force F_{fluid} is thus composed of a surface and form drag force. The distribution of the two partial drag forces depend on the body geometry. In [3] (Figure 4-114) it is stated that the drag force of a cylinder is composed of $10\,\%$ surface drag force $F_{fluid,S}$ and $90\,\%$ form drag force $F_{fluid,F}$.
The two drag forces can be calculated using the following relationships [3]

$$F_{fluid,S} = \zeta_S \rho_{Fluid} \frac{c_\infty^2}{2} A_0, \tag{5}$$

$$F_{fluid,F} = \zeta_F \rho_{Fluid} \frac{c_\infty^2}{2} A_\perp. \tag{6}$$

In these equations, c_∞ describes the relative velocity between the undisturbed fluid flow and the body. The area A_0 is the area of the body which is surrounded by the fluid, whereas $A_\perp$ is the largest cross-sectional area of the body perpendicular to the flow direction. In the case of the floating body, $A_\perp$ is calculated by multiplying the diameter D_{FB} of the floating body by its length ℓ_{FB}. The parameters ζ_S and ζ_F describe drag coefficients. The coefficient ζ_S depends on the Reynolds number Re as well as on the roughness k of the flowed surface and usually has to be determined experimentally. On the other hand, ζ_F depends on the Reynolds number and the shape of the flowed body. Also, ζ_F usually has to be determined experimentally, but values for standard body shapes are available in the relevant literature. In Figure 6, ζ_F is plotted against the Reynolds number for a cylindrical body. Whereby the Reynolds number of a flowed cylinder can be calculated as follows [3]

$$Re = \frac{c_\infty D}{\nu}. \tag{7}$$

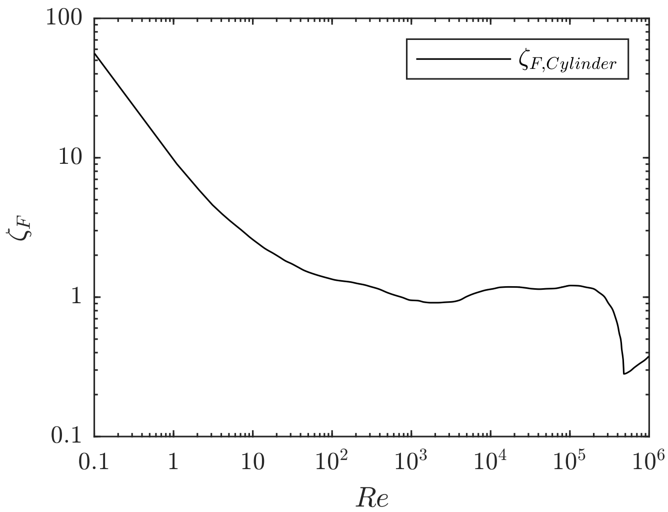

Fig. 6: ζ_F of cylindrical body as a function of Re (see Figure 4-119 in [3])

Thus, the form drag force $F_{fluid,F,FB}$ of the floating body can be calculated. However, to calculate the total drag force $F_{Fluid,FB}$ the parameter $\zeta_{S,FB}$ of the floating body must still be determined. For exact values, $\zeta_{S,FB}$ must be determined experimentally. Since this was not possible at the time of the investigation, it was assumed instead, according to [3], that $F_{Fluid,FB}$ is composed of 10 % surface and 90 % form drag force. It follows that $F_{Fluid,FB}$ can be calculated by

$$\begin{aligned} F_{Fluid,FB} &= \frac{10}{9} F_{Fluid,F,FB} \\ &= \zeta_{F,FB} \frac{10 \rho_{Fluid} c_\infty^2}{18} A_{\perp,FB}. \end{aligned} \tag{8}$$

Thus, the driving force $F_{Mounting}$ is given according to the free punch from Figure 5 by the equation

$$\begin{aligned} F_{Mounting} &= F_{Buoyancy,FB} - F_{G,FB} - F_{Fluid,FB} \\ &= V_{FB} g (\rho_{Fluid} - \rho_{FB}) \\ &\quad - \zeta_{F,FB} \frac{10 \rho_{Fluid} c_\infty^2}{18} A_{\perp,FB}. \end{aligned} \tag{9}$$

In the next step, the flow losses of the downward moving mounts are considered. These are calculated in a similar way as those of the floating bodies. However, the mounts are not modeled as cylinders but as rectangular plates, which have a different flow resistance. The flow resistance of a rectangular plate consists according to [3] to 100 % of the form resistance. For a rectangular plate with a length-width ratio of 10:1 (assumed length-width ratio of the mounts), a ζ_F value of 1.29 is given in [3]. This value is valid for a strongly supercritical flow where the Reynolds number has no more influence on ζ_F. Thus, the drag force of a mount can be calculated to

$$F_{Fluid,M} = 1.29 \rho_{Fluid} \frac{c_\infty^2}{2} A_{\perp,M}. \tag{10}$$

For the total drag force of the mounts, the force must be multiplied by the number of mounts n_M in the water. Thereby only those mounts are considered in which there is no floating body, since the mounts carrying floating bodies do not generate additional resistance.

The last flow losses considered are those of the chain elements. Only the cylindrical rollers are considered, but not the connectors of the individual rollers. Since the rollers are cylindrical, the flow drag is calculated identically to that of the floating bodies. This results in the following equation for the drag force

$$F_{Fluid,C} = \zeta_{F,C} \frac{10 \rho_{Fluid} c_\infty^2}{18} A_{\perp,C}. \tag{11}$$

The number of rollers in the water n_C can be calculated using the chain spacing p_C and the chain length located in the water $\ell_{C,W}$ [4]

$$n_C = 2 \left(\frac{\ell_{C,W}}{p_C} + 1 \right). \tag{12}$$

With the introduced equations, the drag forces and thus the flow losses can be calculated. In order to calculate the losses of the chain and in the bearings, the driving force of the chain drive must also be known. The chain is driven on the one hand by the resulting force of the rising floating bodies in the tower, and on the other hand by the gravitational force of the floating bodies outside the tower. In order to take into account that one floating body must always be "thrown over" from the inner chain drive to the outer one, the gravitational force of one floating body is subtracted from the drive force of the floating bodies in the tower (throw-over losses). This results in the following drive forces

$$F_{Drive,iW} = n_{FB}F_{Mounting} - n_M F_{Fluid,M} \\ - n_C F_{Fluid,C} - F_{G,FB}, \quad (13)$$

$$F_{Drive,oW} = n_{FB}F_{G,FB}. \quad (14)$$

The output of the chain drive is located on the lower pulley of the chain drive that is located outside the tower. The force $F_{Drive,iW}$ must therefore be transmitted from the chain drive inside the tower via the horizontal chain drive and the chain drive outside the tower to the output (see Figure 1). The gravitational force of the floating bodies outside the tower $F_{Drive,oW}$ must instead only be transmitted via the chain drive outside the tower to the output.

During the transmission of these forces, friction losses occur in the chain and the bearings of the pulleys, which lead to a reduction in the output torque. In [4] and [5], an efficiency of $\eta_{Chain} = 98\ \%$ is given for chain drives. These losses are mainly due to friction losses which occur during the pivoting movement between two neighboring chain elements. The pivoting movements always take place at the transitions between the pulley and the chain, i.e. when a chain element adapts to the contour of the pulley from a stretched position and is then stretched again when it leaves the pulley. It was therefore assumed that the transmitted torque is always reduced due to friction when a loaded chain runs over a pulley. To calculate the bearing losses of the pulleys, a shaft with two rolling bearings is assumed, whose efficiency according to [4] can be assumed to be $\eta_{Bearing} = 99\,\%$.

The force $F_{Drive,iW}$ is transported to the output via three chain drives and thereby a loaded chain runs five times over a pulley. Accordingly, the transmitted torque is reduced five times by the chain losses and four times by the bearing losses. Instead, the force $F_{Drive,oW}$ is transmitted directly from the outer chain drive to the output and accordingly this force is only reduced by losses of one engagement point of the chain and pulley, as well as the losses of one bearing of a pulley.

With the equations and efficiencies introduced, the efficiency of the tower can now be determined. Due to the flow losses, the efficiency of the tower depends in particular on the ascending speed of the floating bodies, which can be calculated using the cycle time t_{cycl} (time required to push a floating body into the tower) as follows

$$c_\infty = \frac{h_W}{n_{FB}t_{cycl}}. \quad (15)$$

Therein, the parameter h_W describes the height of the water head. It should be noted that the cycle time cannot be made infinitely small, since the flow losses also increase with increasing ascending speed. Above a critical ascending speed, the drag force is exactly as large as the ascent force and the floating bodies can no longer ascend faster. At this critical speed, the floating bodies can also no longer provide any driving power.

Below the critical speed, the output power is calculated as follows

$$P_{T,out} = c_\infty(\eta_{CD1}F_{Drive,iW} + \eta_{CD2}F_{Drive,oW}). \quad (16)$$

Wherein η_{CD1} describes the combined efficiency for the transmission of $F_{Drive,iW}$ to the output and η_{CD2} that for the transmission of $F_{Drive,oW}$ to the output. Furthermore, the efficiency of the tower can then be calculated using the following equation

$$\eta_T = \frac{P_{T,out}}{P_{T,in}} = \frac{P_{T,out}}{n_{FB}\rho_{Fluid}V_{FB}g c_\infty}. \quad (17)$$

The power $P_{T,in}$ describes the power which would be usable at the output without any losses.

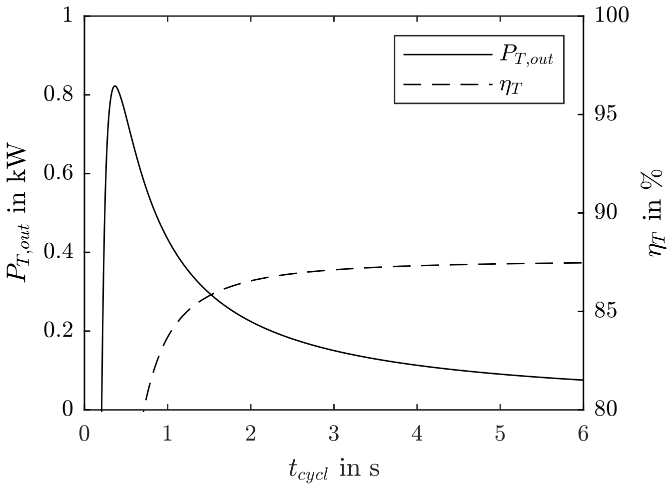

Fig. 7: Tower power and efficiency as a function of cycle time

Figure 7 shows the power and efficiency of the tower as a function of cycle time. It can be clearly seen that the tower does not generate any power for $t_{cycl} < 0.2$ s. This shows that for $t_{cycl} \approx 0.2$ s the critical velocity is reached at which the flow losses are so big that the floating bodies no longer drive the chain . For $t_{cycl} > 0.2$ s, the tower power increases, and reaches its maximum power at $t_{cycl} = 0.37$ s. For larger cycle times, the power decreases again, which is due to the lower throughput of floating bodies.

From the efficiency curve it can be seen that the efficiency increases with increasing cycle time, this was to be expected as the flow losses decrease with decreasing buoyancy speed. For $t_{cycl} > 3$ s the efficiency no longer increases significantly and reaches a value of about $87\,\%$. The remaining power loss of 13 % is thus due to the velocity-independent losses due to the chains, the bearings and the overthrow of the floating bodies.

V. Conclusion and Discussion

In order to gain initial knowledge of the efficiency and thus the economic viability of the "Energy Towers", the efficiencies of two subsystems of the plant were investigated. In addition to the two energy conversions investigated in this paper, three

TABLE I: Parameter table

Parameter	Value	Meaning
ρ_{Fluid}	$997.23\ \frac{\mathrm{kg}}{\mathrm{m}^3}$	density of water
ν	$0.893\ \frac{\mathrm{mm}^2}{\mathrm{s}}$	viscosity of water
g	$9.81\ \frac{\mathrm{m}}{\mathrm{s}^2}$	gravitational constant
D_{FB}	0.15 m	diameter floating body
ℓ_{FB}	0.3 m	length floating body
V_{FB}	$0.0053\ \mathrm{m}^3$	volume floating body
ρ_{FB}	$94.31\ \frac{\mathrm{kg}}{\mathrm{m}^3}$	average density floating body
$A_{\perp,FB}$	$0.045\ \mathrm{m}^2$	perpendicular cross-section floating body
n_{FB}	40	number of floating bodies in water
$A_{\perp,M}$	$0.0026\ \mathrm{m}^2$	perpendicular cross-section mounts
n_M	82	number of mounts in water
$A_{\perp,C}$	$0.0026\ \mathrm{m}^2$	perpendicular cross-section chain rollers
$\ell_{C,W}$	19.5 m	chain length in water
p_C	0.0159 m	chain pitch
h_W	10 m	height water head in the tower

further conversions take place in the plant, whose efficiencies were not taken into account in here.
The investigation of the hydraulic system showed a target overall efficiency of $68\,\%$.
The investigation of the subsystem tower showed that the efficiency of the tower mainly depends on the cycle time. For a cycle time of $t_{cycl} > 3$ s, an efficiency of about $87\,\%$ is achieved. However, the efficiency decreases significantly with decreasing cycle time and for $t_{cycl} < 0.2$ s the tower cannot generate any power at all.
In summary, for the assumed efficiencies in the hydraulic system and a cycle time of $t_{cycl} > 3$ s, both subsystems show promising efficiencies. However, it should be noted that the efficiencies were calculated based on simple analytical models and only the described effects in the respective subsystems were considered. Therefore, the calculations provide a first estimate of the efficiencies of the two subsystems.

VI. Outlook

As pointed out in the previous chapter, this study focuses on the efficiency of two subsystems. Thus, no statement can be made about the performance of the overall system. For this reason, as a next step, the efficiencies of the other subsystems, especially the gates, must also be estimated in order to identify the potential of the plant.
Moreover, the design and the functionality must be further detailed so that even more precise calculations can be carried out. In the end, it should be possible to calculate the efficiency of the entire plant using one simulation. For this purpose, an overall simulation model is in work, in which the individual subsystems are coupled with each other.

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