THE UTILIZATION OF THE MAGNUS EFFECT FOR HOT WATER ROCKETS

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ABSTRACT

This paper describes the utilization of the Magnus effect - more commonly know from sports (Tennis, Golf) - to boost hot water propelled rockets. Similar to, and thusly named after, Flettner Rotors for ships, a Flettner Booster consists of a rotating cylinder that, placed in an air-flow, generates a lift force. In contrast to their pendants found on ships, Flettner Boosters do not depend on naturally occurring winds but rather utilize the airflow generated through the ascending rocket. Hot water rockets were chosen as main propulsion system, as they feature an important characteristic: Hot water rockets usually function below Mach 1. The Magnus effect can only be observed for subsonic velocities so that Flettner Boosters can only be applied in this area. Three cases will be presented in the following: A base configuration of the hot water rocket with 100 kg of water at 50 bar pressure as well as two configurations with two respectively three Flettner Boosters. The three configurations will be compared regarding their achievable height without payload and the possible payload weight for the same height. In cooperation with the University of Bremen, a three year lasting project plan for the design and the construction of the described concept was developed. It will be used to apply for the STERN rocket program by the German aerospace agency and is set to start in summer, 2011.

1. INTRODUCTION

The Magnus effect was first described by (and thusly named after) Heinrich Magnus in 1852 [1]. Magnus discovered that a rotating cylinder experiences a force, when held into a streaming fluid. The force is perpendicular to the direction of the streaming fluid and the axis of rotation. The Magnus effect is most commonly know from sports like tennis, where a top-spin generates an additional downward acceleration, or golf, where a supplementary lifting force acts on a back-spin-ed ball. Technical utilizations of the Magnus effect are known as Fletter rotors, named after Anton Flettner. Flettner was the first to mount rotating cylinders on deck of the ship Buckau in 1925. These cylinders functioned as an alternative to sails, propelling the ship when exposed to wind. Five years later, a prototype airplane was developed, after Ludwig Prandtl had discovered that the lift generated through a rotating cylinder could be up to ten times higher compared to a classic wing design [2]. The prototype completely replaced the wings through cylinders, but there is no information available, whether the plane was actually able to lift off. Regardless of this, Flettner continued to use the rotors as a ship propulsion system. The concept was further improved by a team surrounding Jacques-Yves Cousteau which developed the Alcyone (1980) and the most recent implementation 'E-Ship 1', in active service since 2010:

Figure 1. E-Ship 1 with 4 characteristic Flettner rotors on deck, saving up to 40% of fuel Source:Enercon

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While the development on Flettner-propelled airplanes was never continued, the idea was to even go one step further and to investigate whether Flettner rotors and thus the Magnus effect could be used for rocket propulsion. Much like the Flettner rotors on E-Ship 1 are only used to support the main propulsion system, thereby decreasing fuel consumption, the concept was to also just use them as add-on/booster for rockets. As the idea was developed by students, a hot water propelled rocket was chosen as baseline. Hot water rockets, also known as HWRs, represent an ‘easy to fabricate’ class of rockets, rendering them perfect for aerospace-related universities. They are used to teach the fundamentals of rocket science and give students an opportunity for hands on experiences. To increase the number of universities working on HWRs (currently including for example TU Berlin, Braunschweig University and the University of Applied Sciences in Bremen), the German space agency (part of DLR) initiated a program called STERN to support this kind of enterprises. The “Flettner Booster” project was born in this context and planned to be conducted at the University of Bremen.

2. THE MAGNUS EFFECT IN DETAIL

As described before, three elements (compare Figure 2) are important to describe the Magnus effect:

- A rotating cylinder or sphere
- A streaming fluid
- And the resulting force F_{Magnus}

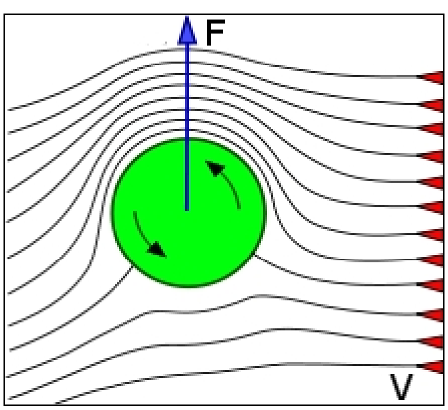


Figure 2. Force F, resulting from Magnus effect, on a rotating cylinder, held into a streaming fluid Source:Wikipedia

The equation combining these three is based on the Kutta-Joukowski theorem:

$$F_{Magnus} = \rho_{fluid} v_{fluid} l_{cylinder} \Gamma$$

Both ‘ρ’ and ‘v’ describe the streaming fluid (its density respectively its velocity) while ‘l’ equals the length of the cylinder. ‘Γ’ characterizes the circulation of cylinder and results from:

$$\Gamma = 4\pi^2 r_{cylinder}^2 \omega,$$

where ‘r’ equals the radius of the cylinder and ‘ω’ the rotational speed.

3. THE BASELINE CONFIGURATION

The Magnus effect has an important constraint that supported the choice of hot water rockets as baseline propulsion system: The Magnus effect can only be observed below Mach 1. Most chemical propulsion systems lead to velocities surpassing the speed of sound soon after launch. HWRs on the other hand usually stay within the subsonic area throughout their flight.

A detailed analysis of different HWR configurations has already been conducted and published in context of the Aquarius project, a hot water rocket developed at the TU Berlin [3]. The configuration of the baseline HWR for this project was chosen with respect to this work. The single stage setup includes the following key values and elements:

- 100 kg of water at a pressure of 50 bar
- 31.7 kg for structure, tank, nozzle and all other non-propellant components
- 4.035 m height
- 0.269 m maximum diameter
- 40 s of thrust

To emulate the decrease in thrust resulting from the drop of tank pressure during flight, the thrust was calculated based on the following equation:

$$F_{thrust} = \dot{m}\sqrt{c_{exit}^2 \Delta t / t_{end}} \ ,$$

where the mass flow ‘ṁ’ was kept constant at 2.5 kg/s while the exit velocity ‘c_{exit}‘ was varied through use of the root function and the time-dependent factor ‘$\Delta t/t_{end}$‘ (t_{end} = 40 s).

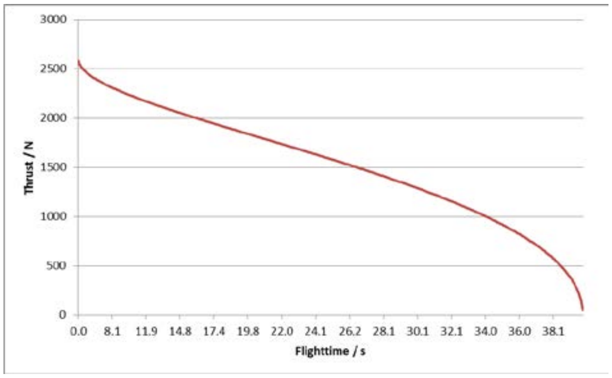


Figure 3. Simulation of thrust decrease over time

The equation was formed to resemble the real hot water thrust behavior, measured by the team of TU Berlin [3]. The average thrust of 1.53 kN is hereby equivalent to a mean exit velocity of 239.6 m/s.

4. THE FLETTNER BOOSTERS

As the force generated through the Magnus effect is perpendicular to both the direction of the streaming fluid and the axis of rotation, the position of the cylinder had to be chosen accordingly. It was decided to place the axis of rotation in the horizontal plane while the streaming fluid would cross at an angle of incidence of 30° (to be still facing downwards). In contrast to their ship-bound counterparts, the streaming fluid is not attained from natural occurring winds but rather from the ascent of the rocket through air. This calls for a deflation of the, in flight direction, streaming air of 60° (concept depicted in Figure 4). For subsonic velocities, this can be realized without losses. To compensate for the remaining 30° of difference between the flight direction and F_{Magnus}, a configuration with at least two boosters is required (thereby canceling the force components in the horizontal plane).

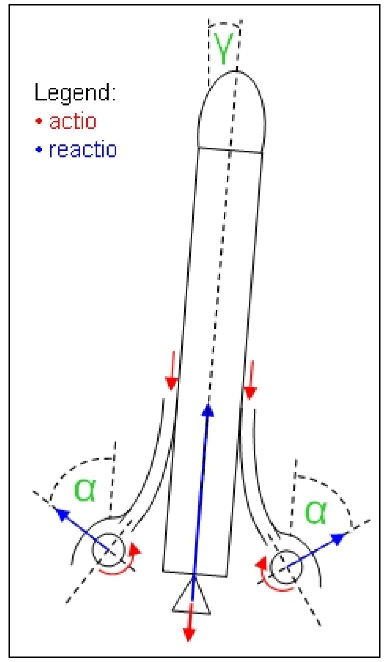


Figure 4. Basic concept of Flettner boosters. Flight angle γ equals ‘0’ for all calculations

The obvious disadvantage of mounting boosters on a rocket is the resulting increase in aerodynamically acting cross section area respectively drag. During the course of this analysis, we studied two configurations: Two boosters for minimal additional drag and three boosters (as shown in Figure 5) to also be able to use them to stabilize and control the rocket during its ascent.

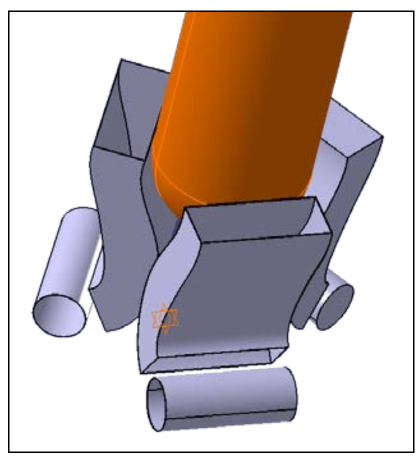


Figure 5. 3D visualization of the three booster configuration with air deflection

The setup for a single booster lists as follows:

- 0.09 m cylinder diameter
- 0.269 / 0.233 m cylinder length (two/three booster configuration)
- 300 rotations per second
- 2 motors model Feigao FG-A-540 (up to 35000 RPM)
- Lithium ion based ultra-capacitors (instead of common batteries)
- 5 kg overall mass (including components, baffle, etc.)

5. CALCULATION

After we assured that there was actually more thrust generated than drag, the three configurations (baseline, two boosters and three boosters) were compared with respect to the following aspects:

- achievable altitude without payload
- maximum payload transfer for a given height

The achievable altitude of the baseline configuration was hereby chosen as the 'given height'. Besides the already mentioned thrust through the hot water propulsion system, the drag acting on the rocket

$$F_{drag} = 0.5\rho_{air}(h)(v_{rocket}(t))^2 (c_D A)_{without/with}$$

and the gravitational force

$$F_{gravity} = m(t)g(h),$$

the thrust through the Flettner boosters was calculated with the following equation:

$$F_{Flettner} = 4\pi^2 z\rho_{air}(h) l_{cylinder} r_{cylinder}^2 (v_{rocket}(t))^2 \cos\alpha$$

Here, 'z' corresponds to the number of boosters and 'α' equals the already discussed 30° (difference between flight direction and thrust through the Flettner booster).

An additional drag, resulting from the cylinder held into the streaming fluid, also had to be considered:

$$F_{cylinder-drag} = 0.5z\rho_{air}(h)(v_{rocket}(t))^2 (c_D A)_{cylinder} \sin\alpha$$

Last, but not least, the dependence between time 't' and the height 'h' had to be established. 'h' was chosen as main variable (to be increased iteratively by a constant value) and 't' therefore calculated through:

$$\Delta t = t_n + t_{n-1} = (h_n - h_{n-1}) / v_{n-1},$$

where v_{n-1}, as the only new unknown, represents the rockets velocity calculated during the previous iteration.

6. RESULTS

With the given parameters and no additional boosters or payload, the baseline hot water propelled rocket reached a final altitude of 6.86 km. In comparison, the two booster configuration reached 8.64 km while the three booster configuration reached 8.76 km. The small difference between the two booster configurations can be related to the high increase in the aerodynamically acting cross section area: While the two booster configuration had an increase of 255% compared to the baseline configuration, the three booster configuration had an even higher increase of 328%. The higher average thrust of the three booster configuration of 2.81 kN could not compensate for this difference in cross section area in comparison to the two booster configuration (with an average thrust of 2.56 kN).

When including a payload, the difference between the two configurations does not change significantly: While the two booster configuration can load an additional payload mass of 27.3 kg, still reaching the set altitude of 6.86 km, the three booster configuration can bring 26.3 kg to the same height. At the same time, the average drag values, which are directly connected to the cross section area, stay, compared to the 'no payload'-configurations, the same (2.64 respectively 2.40 kN). The average thrust of the three booster configuration (2.78 compared to 2.44 kN) cannot compensate for the payload and even results in 1 kg less additional mass. The remaining flight characteristics are depicted in the following in Figure 6 – 8.

Figure 6. Two booster configuration with no additional payload and 5kg per booster (overall mass of 141.7 kg). Reached altitude equals 8.64 km at a maximum velocity of 210.6 m/s and an ascent time of 67.4 s.

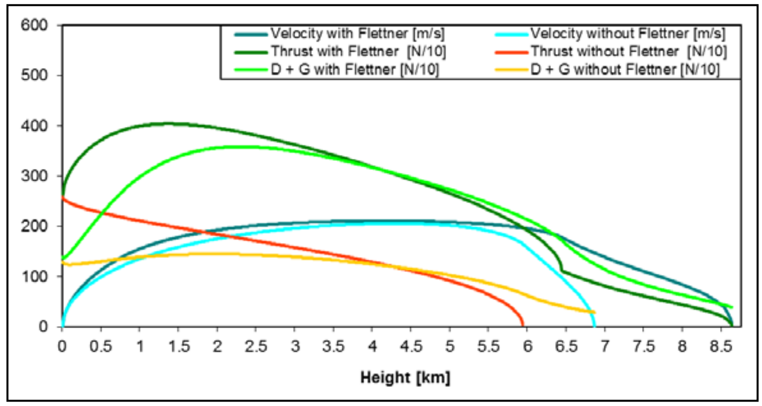
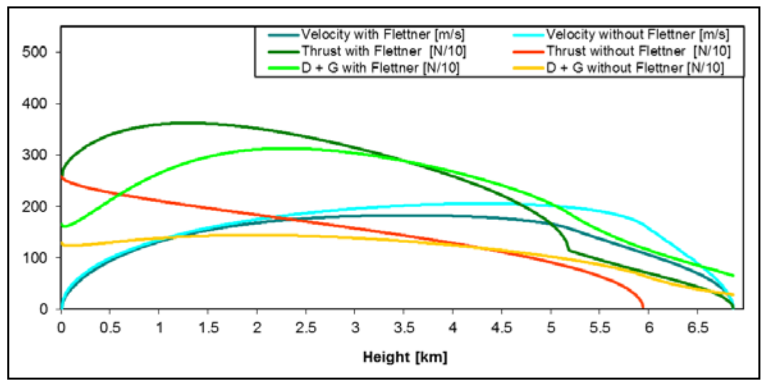


Figure 7. Two booster configuration with 27.3 kg of additional payload and 5 kg per booster (overall mass of 149.7 kg). Reached altitude equals 6.86 km (same as baseline without payload) at a maximum velocity of 183.1 m/s and an ascent time of 64.0 s.



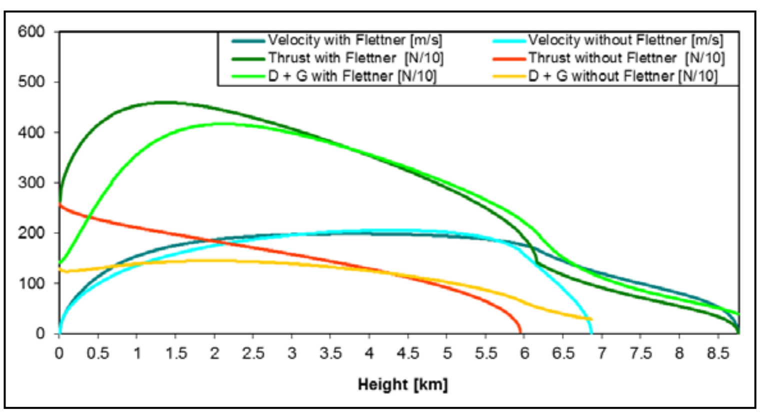


Figure 8. Three booster configuration with no additional payload and 5 kg per booster (overall mass of 146.7 kg). Reached altitude equals 8.76 km at a maximum velocity of 198.5 m/s and an ascent time of 75.8 s.

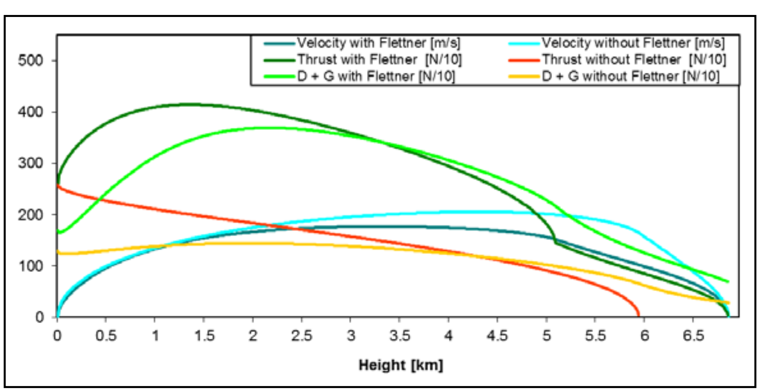


Figure 9. Three booster configuration with 26.3 kg additional payload and 5kg per booster (overall mass of 173 kg). Reached altitude equals 6.86 kg (same as baseline with no payload) at a maximum velocity of 177.2 m/s and an ascent time of 64.9 s.

7. FUTURE STEPS

The team is currently transitioning the Excel-based simulation to Octave, an open-source alternative to MatLab. Once this is completed, it is planned to run calculations with varying rockets as baseline for the Flettner boosters. In addition, a more detailed CAE model is also in the works.

As there was, unfortunately, already another team of the University of Bremen, successfully applying for the STERN program, there is no financial support to be expected from the German space agency. While other financing options are still evaluated, the possibility for a future wind tunnel test is also assessed. One potential candidate is the 'Focke Windkanal', a wind tunnel based in Bremen, Germany, which is available for free for university students.

8. ACKNOWLEDGEMENT

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9. REFERENCES

1. H. Magnus (1852), On the deviation of projectiles; and on a remarkable phenomenon of rotating bodies, Memoirs of the Royal Academy, Berlin

2. L. Prandtl (1952), Essentials of Fluid Dynamics, Hafner Publishing Company, New York

3. AGTWR-Aquarius (1991/96), Procedure Documentation, TU Berlin