Thrust Curves from a Water Rocket Test Stand

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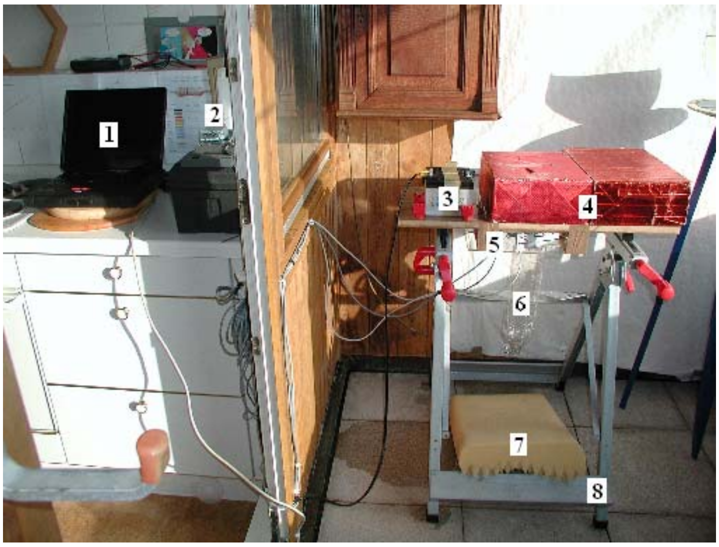
Background and Justification
To measure the thrust of a rocket by a static device - a test stand - is a very common practise[4] even in model rocketry[5]. To our knowledge a description of such a device for water rockets does not yet exist; supposedly due to the very specific characteristics of water rockets. According to Dean R. Wheeler's four-second-tutorial on water rocketry[6], a water rocket is:

soda pop bottle + water + high-pressure air = rocket**.**

Although this sounds very simple and although the principle of the expulsion sequence: water first - excess air second, is clear; it is the combination of the two components: pressurized air and water; that makes the actual process of thrust creation difficult to understand.
The question is: Does the high-pressure air "wait" with its own expulsion until it has expelled the last drop of water? In other words: Is there a clear-cut distiction between the phases of water expulsion (thrust phase I) and excess air exhaust (thrust phase II)? Or is there a smooth transition from pure water to pure air expulsion? The shape of an experimental thrust curve would reveal either a kink - as supposed in theory - or a continous decline over the two thrust phases. It was the purpose of our experiment to find out.

Experimental Setup
Fig. 1 shows the overall setup of our water rocket test stand. The basic idea is to let a vertically mounted PET (**P**oly**E**thanol**T**erephthalat) bottle filled with water and compressed air push upwards against a strain gage unit (Fig. 2) fed independently with 24 V DC by two shortcut motorbike batteries. Responding to minimal deformations, the strain gage units send thrust signals[7] to a laptop PC as a recording unit. For safety reasons, the data producing and recording units are separated by a wooden side with a large window.



1 PC with WINDAQ	**5 Strain gage**
2 Dataq A/D converter	**6 PET bottle**
3 Battery 24 V DC	**7 Cushion**
4 Two bricks	**8 Workbench**

Fig. 1: Water rocket test stand

To respond to the expected thrust in the order of 400 to 450 N, sufficient counterweight is provided by the work bench itself (11 kg), the strain gage units of 3 kg, two bricks of 22 kg , two motorbike batteries (3 kg) and by two steel shackles holding down the workbench and preventing it from jumping up.
The strain gage units "sense" thrust as minimal changes of current intensity, measured as changes in voltage (Fig. 2).

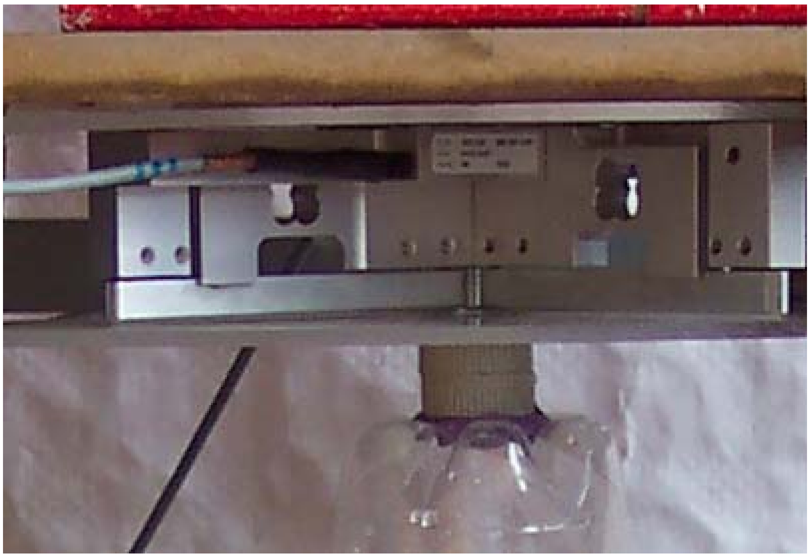


Fig. 2: Strain gage and magnetic fixation of a PET bottle below

Three parallel resistors of 2 times 470Ω plus one 1000Ω, resulting in a total resistance of 190Ω, amplify the voltage of analog signals.
A previous calibration with standard weights has estblished the relationship between Volts and Newtons (Fig. 3)

Fig. 3: Calibration with standard weights (liters of water in the bucket)

A Dataq A/D converter (DI-194RS) converts the signals into digital[8] and tranfers them by interface to a laptop computer (Fig. 4). A specific program (WINDAQ32) records the data at the rate of 240 samples per second, i.e. at time steps of 4.167 milliseconds. These data samples are the basis of subsequent *post factum* data analyses using EXCEL.

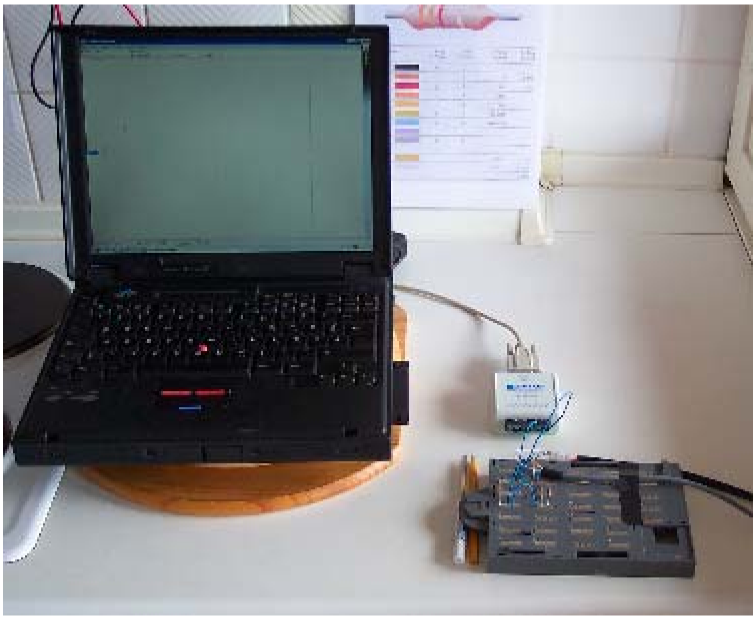


Fig. 4: Laptop PC with WINDAQ Program, DATAQ A/D converter and connection to the strain gage units with independent 24 V DC current supply.

Fig. 5: Air pump with pressure gage and release mechanism with pistol trigger of a Shootinger[9] water rocket. The yellow cushion serves as a damper.

Fig. 5 shows the air filling and release mechanism attached to the bottle. It was taken from a Shootinger launcher set. The cushion serves as a crash protector. After release, this device dashes down at a speed of about 120 km/h.

As a standard, the bottle is filled with 0.6 l red colored water. Air is pumped into the bottle up to a limit of 6.5 bar.

Thrust Sequence


Fig. 6: Release

In Fig. 6 red colored water splashes against the rim of the releaser on its way down to the cushion. The surface of red water and the horizontal bar of the workbench are still visible.

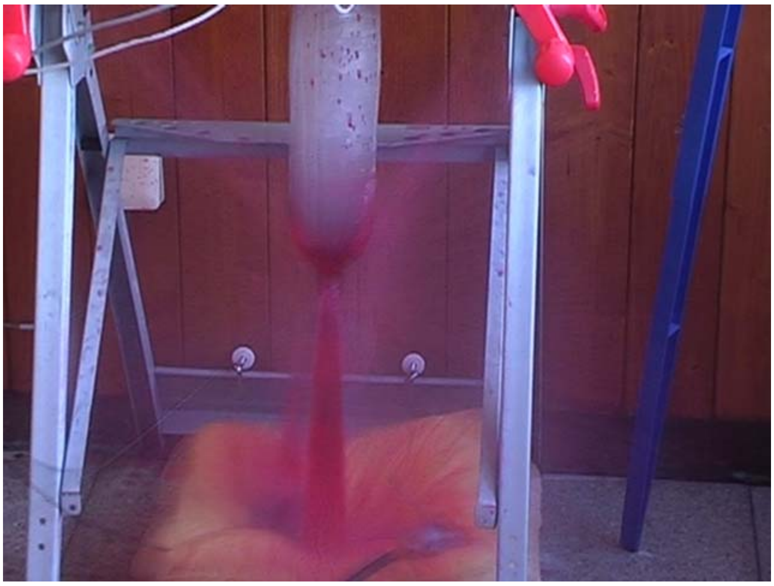


Fig. 7: Water expulsion at t = 0.01s

In Fig. 7 a downward directed cone of red water appears inside the bottle. The red color of the nozzle and the red water jet signify the expulsion of pure water. The releaser is plastered down by the water jet. Fog makes the bottle opaque.

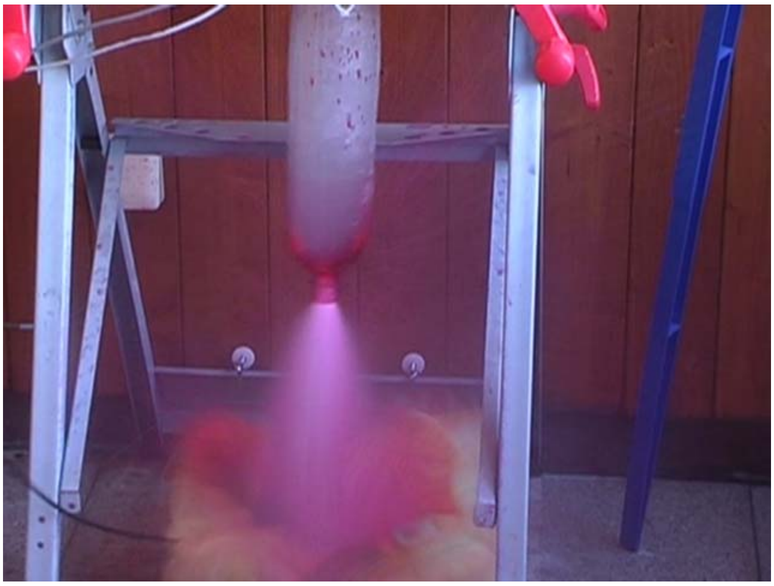


Fig. 8: Air-water expulsion at t = 0.02s

In Fig. 8, the intense opacity of the bottle suggests a 100 per cent relative air humidity. Air has broken through the water cone causing the pink color of the nozzle and the whitish color of the air-water jet.

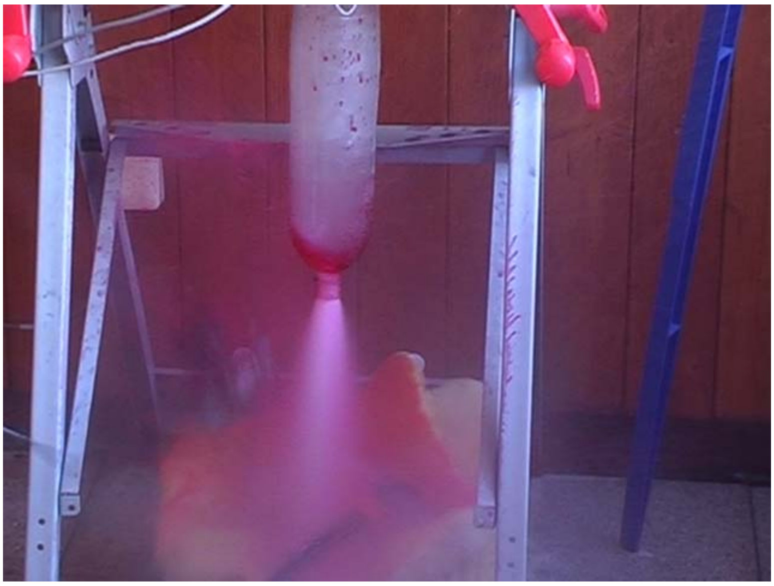


Fig. 9: Air-water expulsion with formation of a clockwise turning water vortex at t = 0.05.

The uneven distribution of red water in the bottle reveals the existence of a water vortex (Fig. 9). The full picture seqence at 0.01s intervals shows that this vortex turns clockwise.

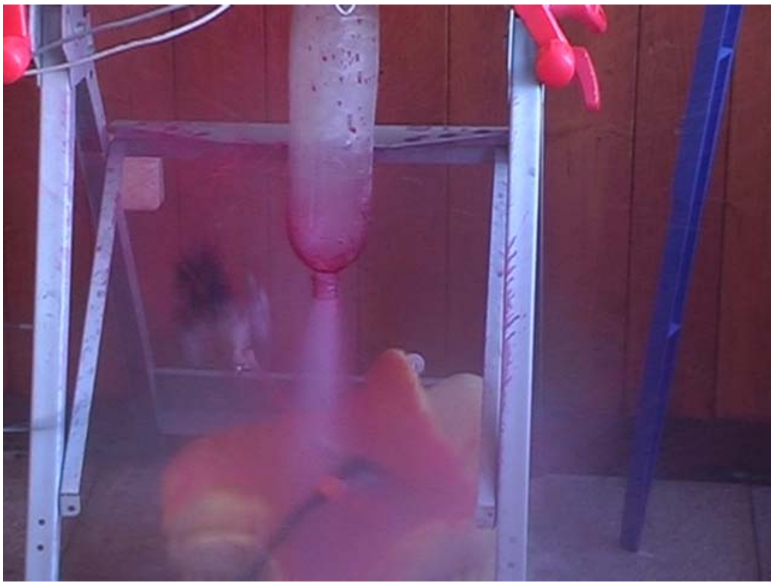


Fig. 9: Vapor exhaust at t = 0.07s

In Fig. 9 little water is left in the bottle covering, as a red film, the surface of the PET material. Opacity is less intense, as the horizontal bar of the work bench is visible again.

Results

Shape of the thrust curve

Fig. 10 shows the thrust curve after converting the measured strain gage samples into EXCEL. The time scale on the bottom abscissa covers the entire measuring period while the scale on top starts counting time at the maximum of thrust. This zero-setting enables us to compare measured thrust data with iterated estimates.

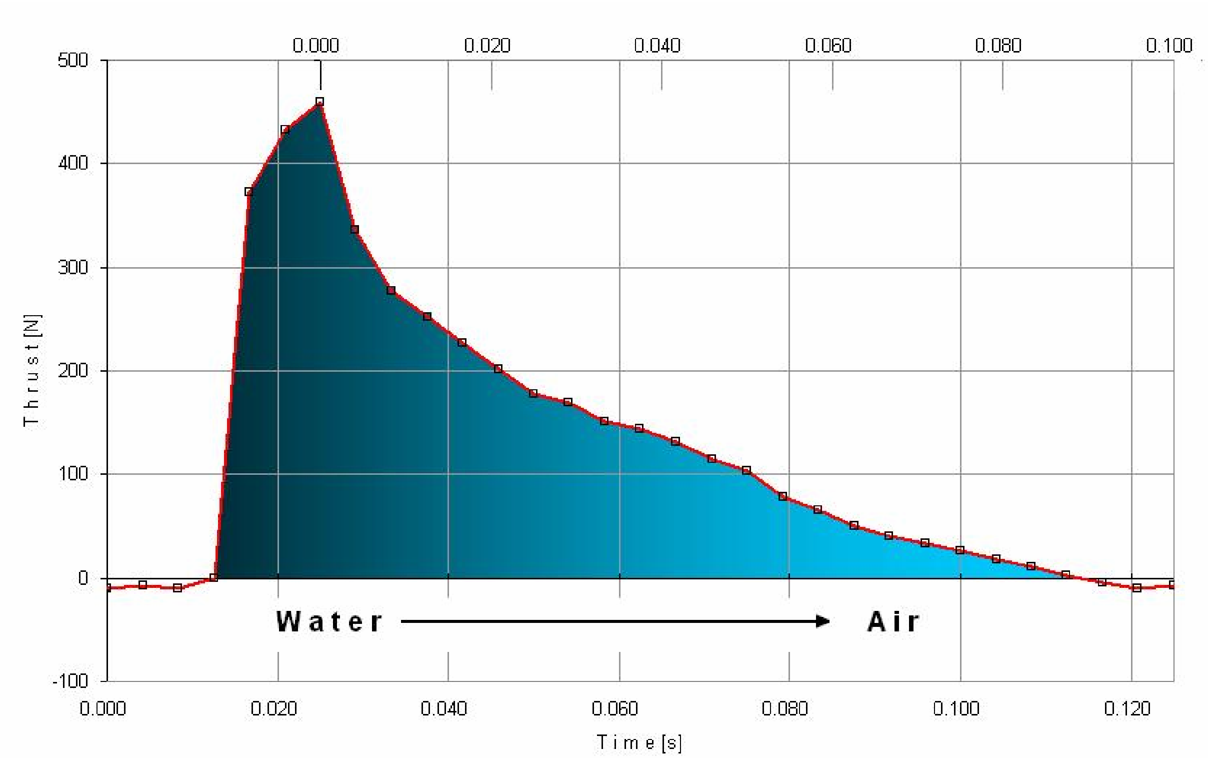


Fig. 10: Thust curve of a water rocket as it appears in the static test stand

From the shape of the thrust curve we conclude that the release mechanism needs about 13 milliseconds to free the nozzle. Accordingly, it takes this time for thrust to attain its full

magnitude of 460 N. Fig. 6 shows that a substantial part of the water load has already gone during this process.
Immediately after maximum, during 8 ms, follows a steep decline of thrust from 460 to 280 N. Then, within the next 17 ms, the decline from 280 to 180 N looks almost linear at a rate of 6 N/ms, followed, up to t = 0.120s, by an even more moderate decrease at an average rate of 3 N/ms. At the endpoint thrust is negative due to the gravity drag of the empty bottle.

Comparison with theoretical predictions
Fig. 11 shows the superposition of the thrust curve as measured in the test stand (red line) and the thrust curve drawn according to iterated values (blue line)[10]. In the iteration model no allowance was given for thrust to build up. Instead, thrust just starts from its maximum at launch. This assumption has turned out to be wrong. Future iteration models should be corrected accordingly.

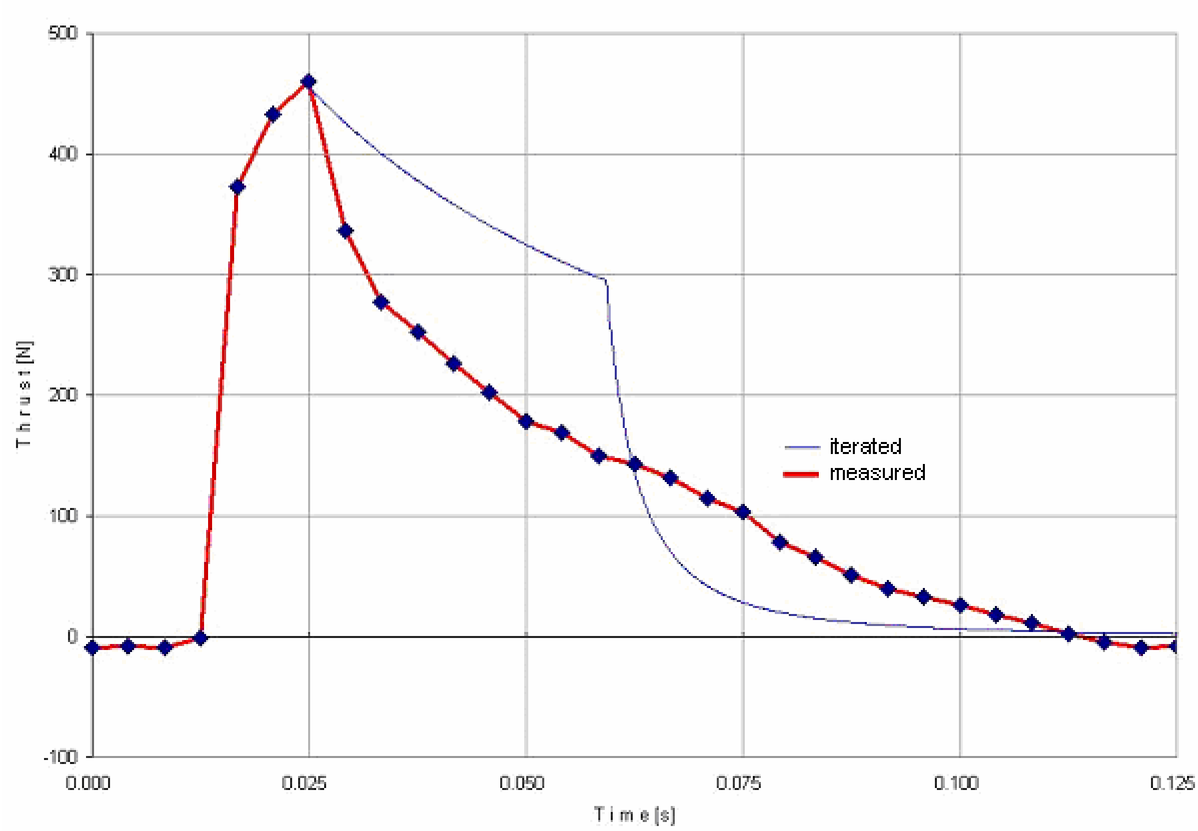


Fig. 11: Superposition of an iterated thrust curve (blue line) characteristically showing a kink at the supposed 'Water Out' event

The kink in the thrust curve, as predicted in the iteration model at the 'Water Out' event, does not occur under test stand conditions. Instead, a smooth transition from pure water to vapor expulsion is confirmed by Figs. 6 to 9. This can be simulated by reducing exponentially the density of water to that of saturated air.

Conclusion
The static test stand can very well predict the maximum magnitude of thrust but not its time-dependent course. There, the predominant role of the exceptionally high acceleration of a water rocket is not taken into account. Therefore, it seems highly improbable that - under the condition of an immense acceleration - water forms a downward directed cone as in Fig. 7. Instead, it may turn out that the water load is flattened and that the kink in the iterated thrust curve is, in fact, justified. Only direct high-speed observations of an accelerating water rocket can reveal how expulsion shifts from water to air.

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