AN ANALYSIS OF THE BEM THRUST DIAGRAMS

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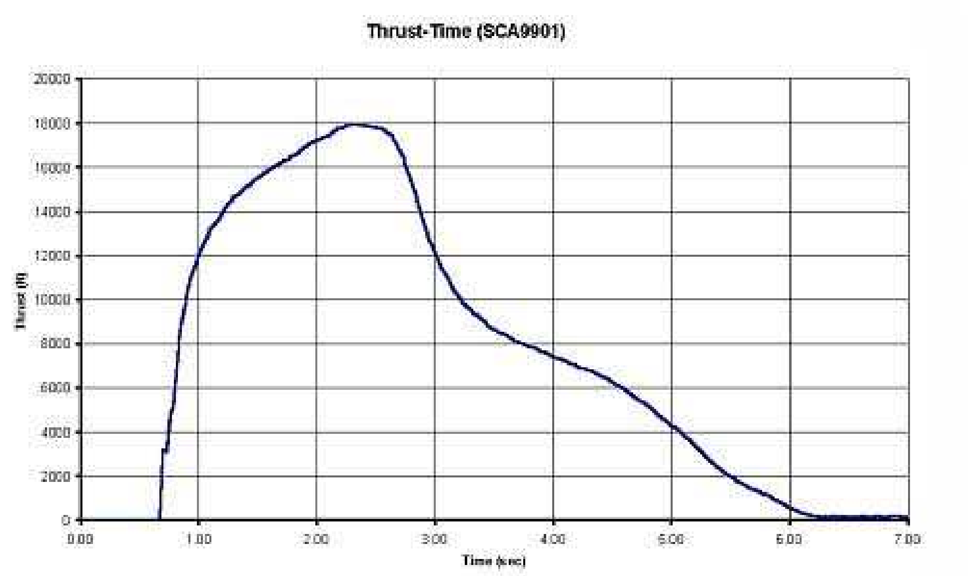
31/08/2006

Let us first of all look at a number of features which already gives some information about the test.

1. the total burning time of the motor is compatible with the stand burning measures, indicating that:
    a. the propellant (or at least one segment) had a normal burning rate
    b. at least one segment, or part of it, burned at the right rate from the inside to the outside
2. the pressure and thrust built up during the first phase of the curve is somewhat slower, essentially as from about 800 N (160 pounds) than in the BEM 1 test, indicating a smaller burning area in the beginning
3. the top of the curve is situated almost exactly in the middle of the total burning time, indicating the possibility that:
    a. or some segments burned from the outside to the inside (tubular? Hence they needed only half the time).
    b. or part of the propellant was consumed much faster (at a rate twice as normal)
4. the lack of a plateau shaped curve in the second part of the thrust curve: even if one or several propellant segments are affected by cracks, erosive burning or tubular burning, after these segments have been consumed, the normal base burning segments should be left over and burn at least for a while in a more or less normal way. The absence of such a plateau indicates that almost all segments were affected by abnormal burning. A good example of such a plateau (between 3.5s and 4.5s) is the following curve of the first static test of the Norwegian NEAR SCAA9901 (www.near.no) (Also see case 2).



5. The BEM 1 thrust curve shows a long tail-off (more than 0.5s) which is most probably not caused by fragmentation of the remaining propellant, but which may rather be a sign for erosion.

A number of different cases have been calculated with a computer model and will be discussed in order to find out in how far they match the registered curves.

Case1: normal burning

The simulation of a normal burning BEM motor is represented in figure 1.

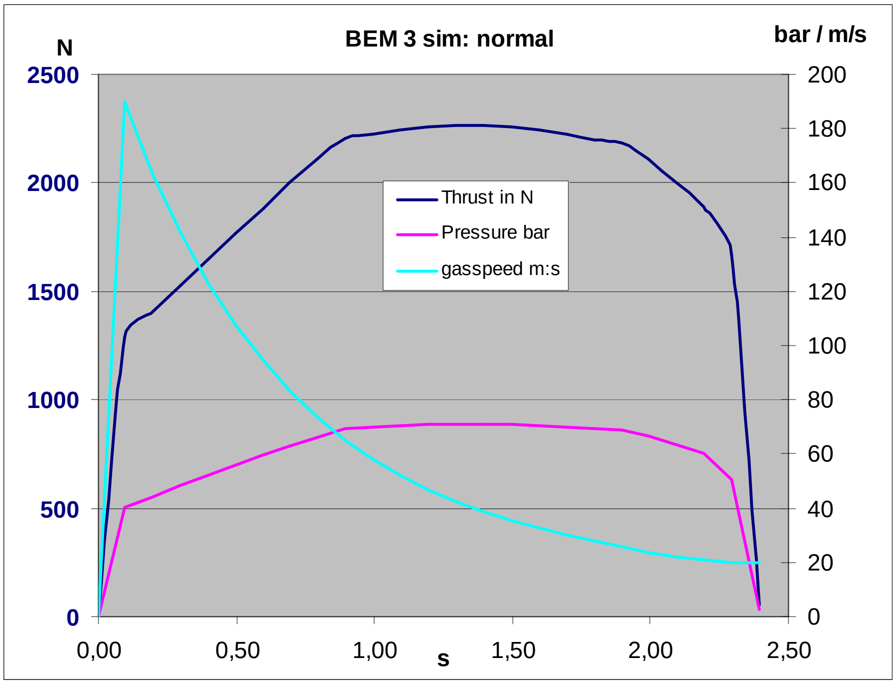


Fig. 1: BEM 3 simulation under normal conditions

Case 2: one or several segments burn from the inside to the outside and from the outside to the inside (tubular).

This may happen when the propellant was separated from the inhibitor. The attractive thing about this is that the burning time of these segments will be about half of the total burning time and that due to the larger burning surface the thrust will, at least for a while (about half of the time) be larger than what is normally expected. On the other hand ones burned out, the thrust will be lower than normal.
In this case we must make a distinction between segments situated near the nozzle and segments situated near the bulkhead.

- when situated near the nozzle end they will only influence the other segments through a higher pressure and hence a higher burning rate.
- When situated well away from the nozzle, they will not only increase the pressure in the motor, but also the mass rate through the subsequent segments

situated closer to the nozzle, thus increasing the velocity in the core of the segments. This may trigger erosion or increase the effect of erosion.

The following figures show what happens in such cases (defaulting segments closer to the bulkhead).

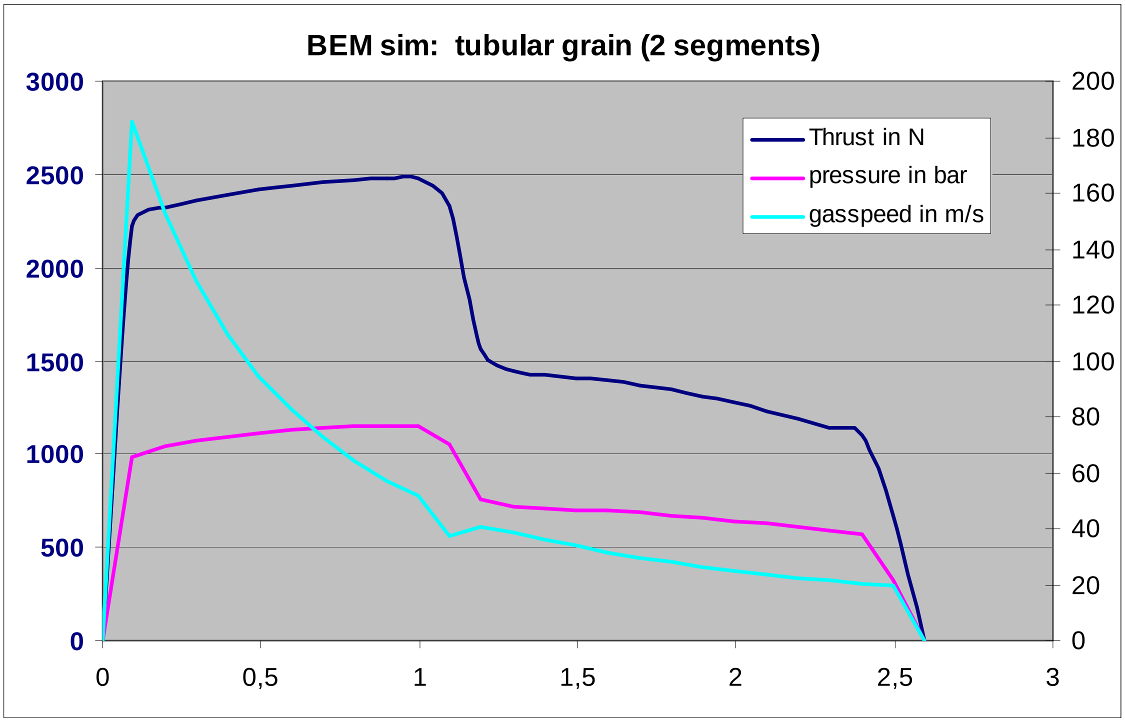


Fig. 2: BEM 3 simulation with 2 segments burning at all sites

One can observe a decrease of the thrust after about half the burning time, but as we are now in a position where there is one segment less the motor will continue to burn relatively stable during the subsequent half of the burning time. So we see two plateaus, one when segments burn at both sides and one with lower thrust, after burnout of these segments.

Case 3: cracks

Occurrence of straight cracks along the axis of the motor can relatively easily be calculated. In the following figure one crack is simulated in 4 of the 6 segments. The influence of one crack in one segment is not very significant given the small increase in burning surface. In general cracks will contribute to a faster thrust increase at the start.

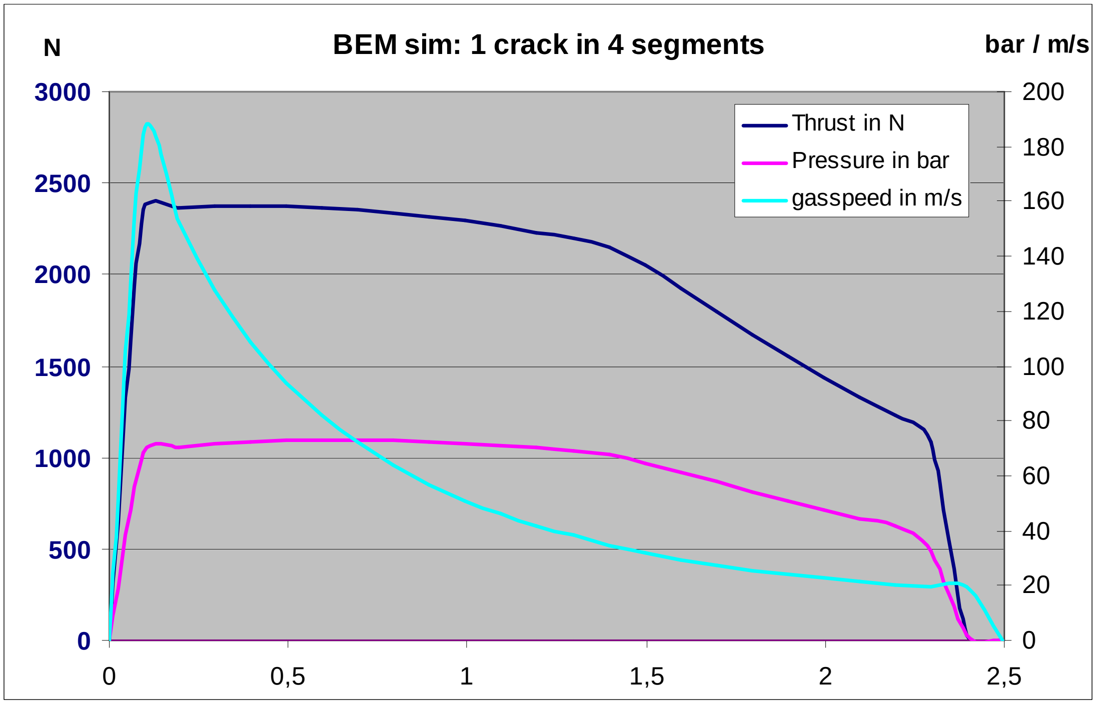


Fig. 3: BEM 3 simulation with one crack over 4 segments

Case 5: what happens if in a number of segments, the bottom and top surfaces do not burn?

In the following figure we have simulated what happens if in 2 segments the bottom and top surfaces do not burn at all. We can see here that the thrust and pressure is taking up

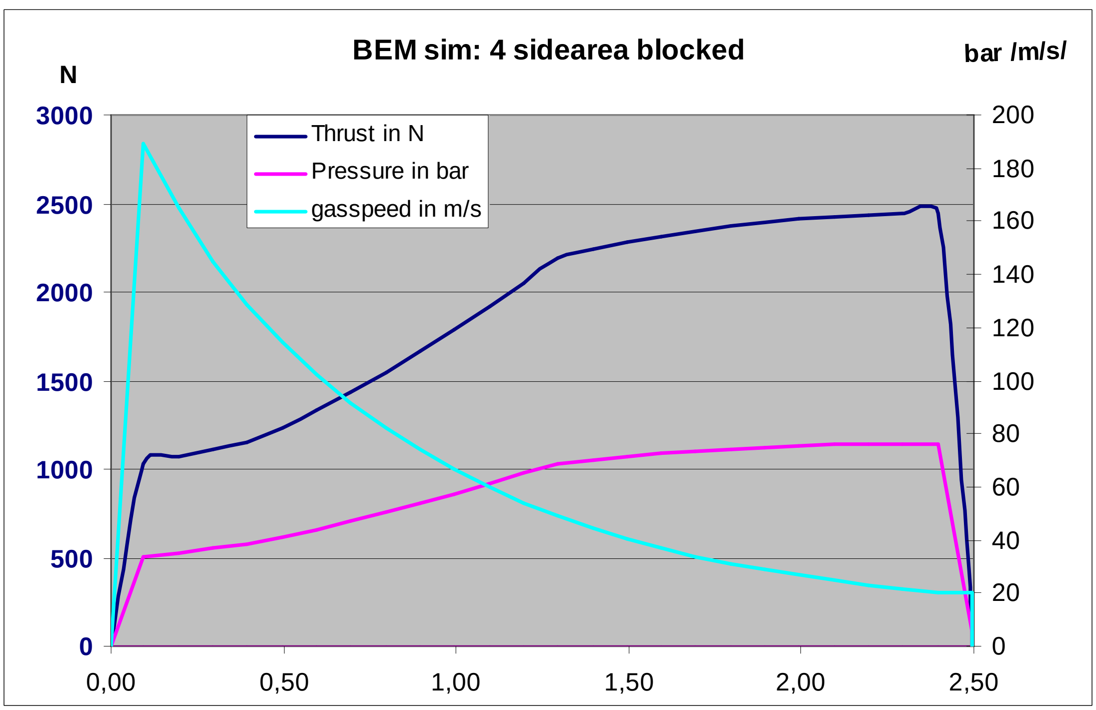


Fig. 4: BEM 3 simulation with 2 bottom and 2 top surfaces not ignited

more slowly and that the maximum thrust and pressure get a bit higher. Although less burning area is available the gas speed is higher due to a lower initial pressure. If more than 2 segments suffer from this problem a slower take up and higher final thrust will be favored.

Case 4: resonance

Resonance burning occurs quite easily in long grains with a cylindrical perforation. In the examples I found (double base propellants) this gives rise to irregular thrust curves. This seems not to be the case here, and resonance is consequently not a likely cause. Moreover, the fact that several segments are used and hence the cylindrical perforation is interrupted will reduce the likeliness of resonance.

Case 5: erosion

Erosion can explain the observed thrust curve of BEM 3. Due to the increasing speed of the gas over the total length of the grain, the propellant will burn faster and a conical shaped void will be created inside the motor. Burning rates up to twice the normal rate will cause the burning surface near the nozzle to reach the wall after about half the burning time. From that moment on the thrust will decrease rapidly. Because the segments close to the bulkhead are least affected by gas flow, the total burning time remains more or less the same.

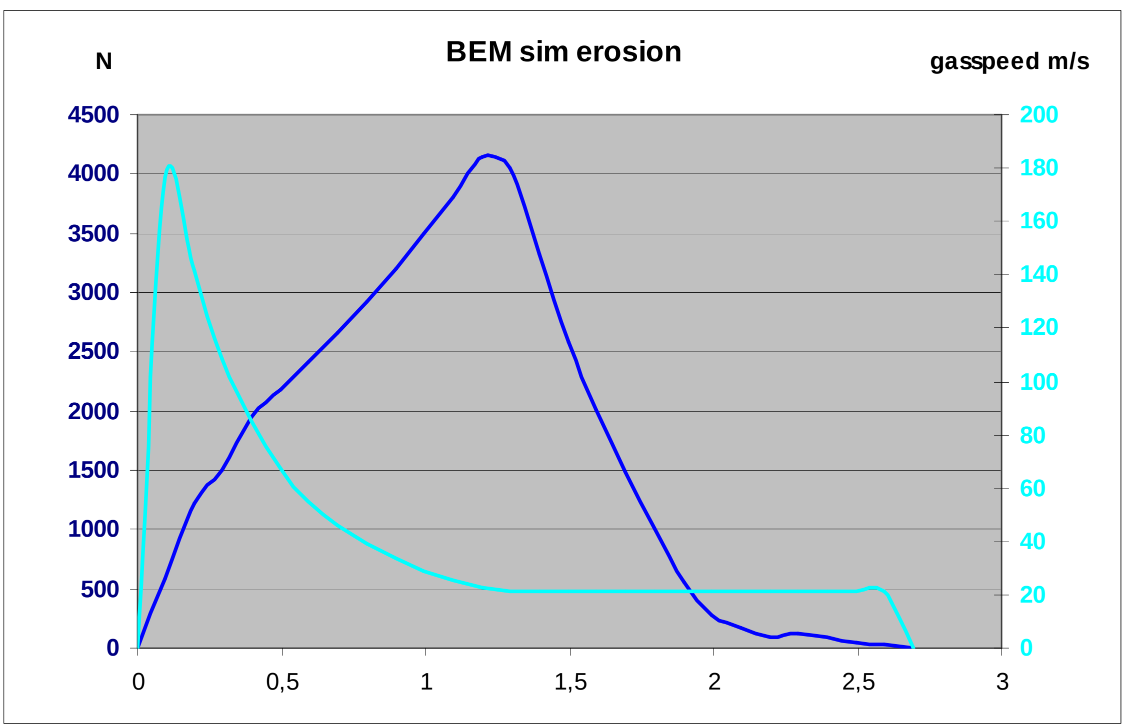


Fig. 5: BEM 3 simulation with erosion

The curve as shown here yields a too high thrust because the actual computer model is only suited for linear (conical) voids generated by linear relationships between burning rate and gas speed or mass rate, while in some relationships used (like in this case) the erosion is even more amplified and hence a curved void (trumpet like) is generated . The fact that erosion in KNSB propellants may not be linear can explain why under mild conditions erosion is rather limited and almost not visible, while under more severe conditions it may suddenly be amplified and in a way get somewhat out of control.

Conclusions:

Cracks, resonance, tubular burning, delayed or non burning of some top and bottom surfaces, in itself, don't seem to be able to explain the behavior o the BEM 3 test. So far only erosion, seems to make any chance. Erosion may however be triggered by any of the other possibilities when gas speed or mass rate is exceptionally increased.

The configuration of the BEM motor seems able to lead to significant erosion of the propellant segments. The fact that the BEM 1 test generated a relatively normal thrust diagram is most probably due to the fact that the burning rate was significantly lower than expected. But also in the BEM 1 test erosion probably occurred given the very long tail-off.

Still very little is known about when and how erosion occurs in KNSB motors. Results from AP propellants don't seem to fit well for KNSB. Much more reliable information on motors with progressively higher ratios of Ap/At are necessary to increase our knowledge.

The major point however is whether the SS2S motor will suffer from the same problem. In AP rocket motors is was found that extrapolation from small scale tests to large scale motors is difficult but in general erosion seem to decrease with size. In the following figure the SS2S is simulated under normal conditions with a throat diameter of 7.5 mm.

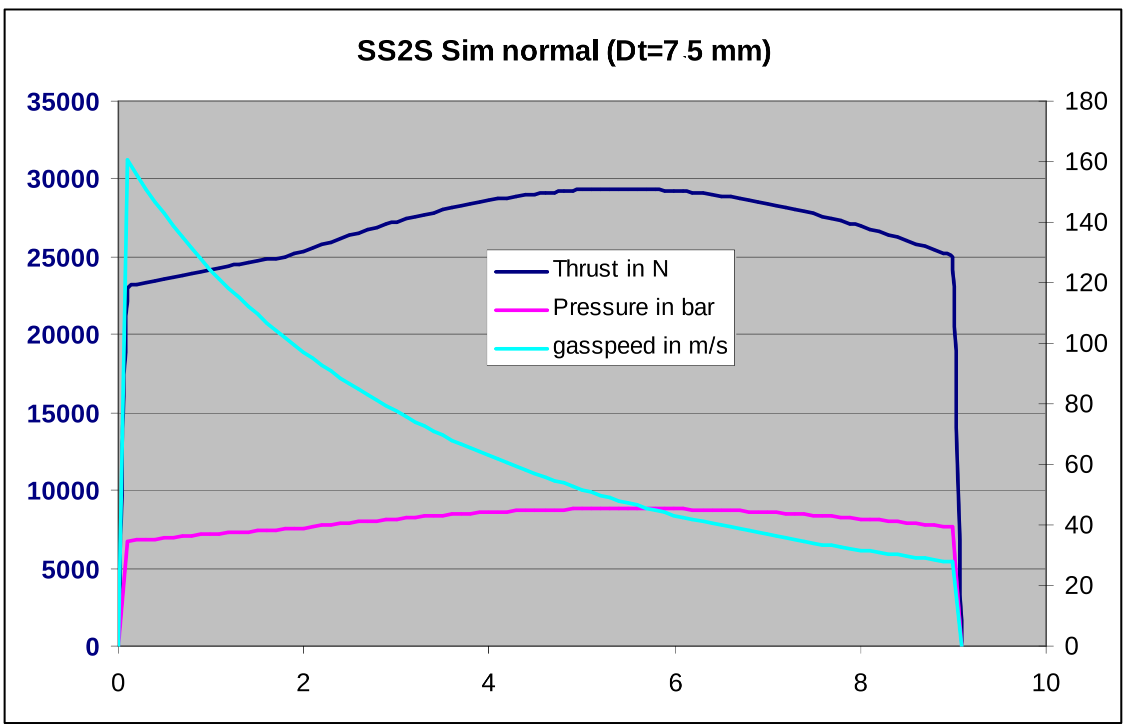


Figure 6: SS2S simulation with a nozzle throat of 75 mm

One can see that the gas speed is limited to about 160 m/s as compared to the BEM where roughly 190 m/s is reached. But also the pressure is low with a maximum of 45 bar as compared to almost 70 bar in a normal burning BEM. Hence these conditions are favorable (if gas speed is the dominating parameter) and erosion may be limited.

In the next simulation the throat diameter was made smaller (65 mm). Now the maximum pressure goes up to 75 bar. Gas speed is lower because with higher pressure the density of the gas is higher. The mass rate (not given in the figure) is however about 35% higher.

If erosion is rather a function of gas speed then a high initial pressure (strong diaphragm) and high burning pressure (small throat area) must be favored. In general when the pressure is very low gas speed close to 1 Mach may be obtained. This may be the case with a weak diaphragm. If on the other hand mass rate (expressed per unit cross area of the void) is the determinating parameter, the opposite will be true. But also the Reynolds number could be important as turbulence may play an important role.

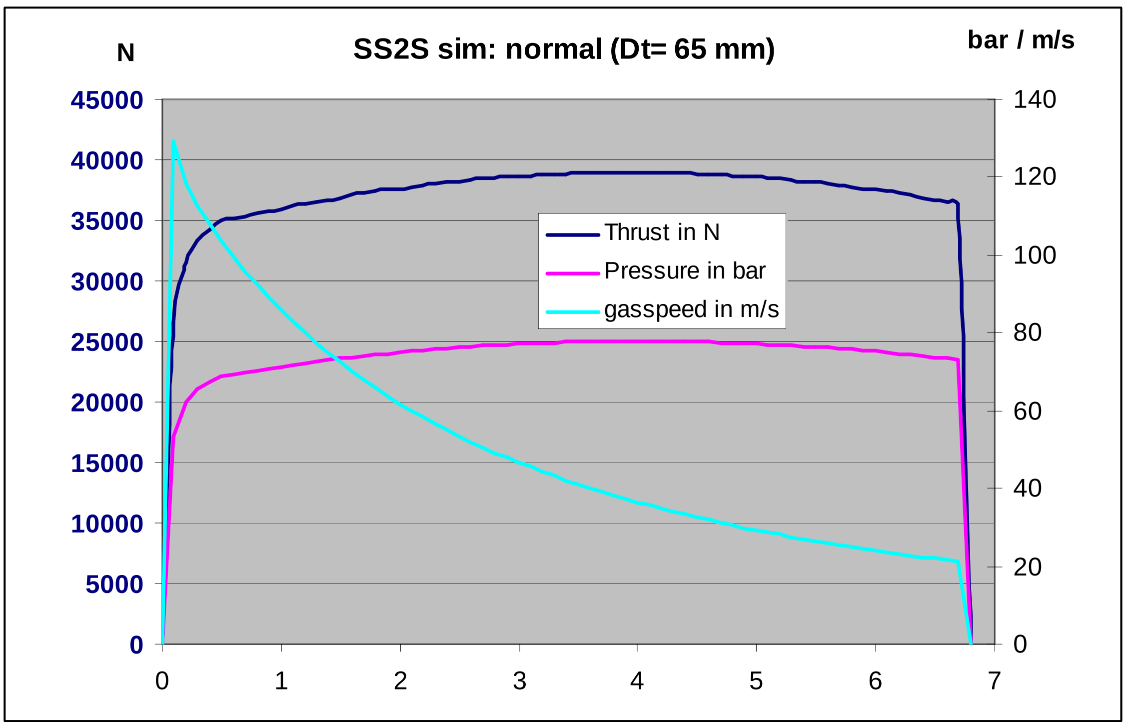


Figure 7: SS2S simulation with a nozzle throat of 65 mm

The fact that the second static test of the NEAR SCAA9901, the largest KNSB motor known, performed very well is however a good sign.