

Article

Large-Scale CAMUI Type Hybrid Rocket Motor Scaling, Modeling, and Test Results

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Abstract: An understanding of the scalability of hybrid rocket regression models is critical for the enlargement and commercialization of small-scale engines developed within universities and similar research institutions. This paper investigates the fuel regression rates of recent 40 kN thrust-class motor experiments, which were designed based on fuel regression rate correlations of 2.5 kN thrust-class motors from previous research. The results show that fuel regression rates of the 40 kN experiments were within 26% of predictions made using correlations based on 2.5 kN experiments.

Keywords: commercialization; hybrid rocket; CAMUI; modeling



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1. Introduction

In recent years there has been an increase in the development of new rocket systems using hybrid rocket technology [1]. This trend is due to the essentially non-explosive nature of the hybrid propulsion rocket system. Hybrid rockets are inherently safer than their liquid or solid counterparts when the fuel is stored in the solid state, and the oxidizer is stored in the liquid state, as is the case in this research [2]. These separate states remove the possibility of uncontrolled mixing, and consequently, an explosion if any part of the engine ruptures [3]. This robustness against explosion is a strongly desirable trait, especially in the operation of very small, low-cost launchers, be they for suborbital or orbital flights. Once the cost of the launcher hardware is low enough, the ground costs become the main expense, with a substantial part of this being due to risk reduction associated with the explosive nature of conventional solid and liquid bi-propellant rocket engines [3]. Hybrid rockets avoid this cost but have traditionally had too low fuel regression rates and/or too small burning surface areas to produce adequate thrust-to-weight ratios for use as launch rockets or their boosters.

1.1. CAMUI Hybrid Rocket Engine and Simulator

The Cascaded Multi-Stage Impinging Jet (CAMUI)-type hybrid rocket solves the problem of low thrust-to-weight ratio. It is currently being developed as a powerful hybrid rocket engine with the potential of being used for sounding rockets, orbital booster stages, and satellite apogee kick engines. The principle of the CAMUI fuel geometry is shown below in Figure 1. This geometry causes the hot combustion gases to impinge multiple times on the fuel surfaces when exiting each port, thereby significantly increasing heat transfer to the fuel and, consequently, the fuel regression rate. The combination of large fuel regression rates and large burning surface areas results in overall engine thrust-to-weight ratios adequate for launch vehicles and their boosters. Test firings of up to 40 kN class CAMUI engines have been performed successfully.

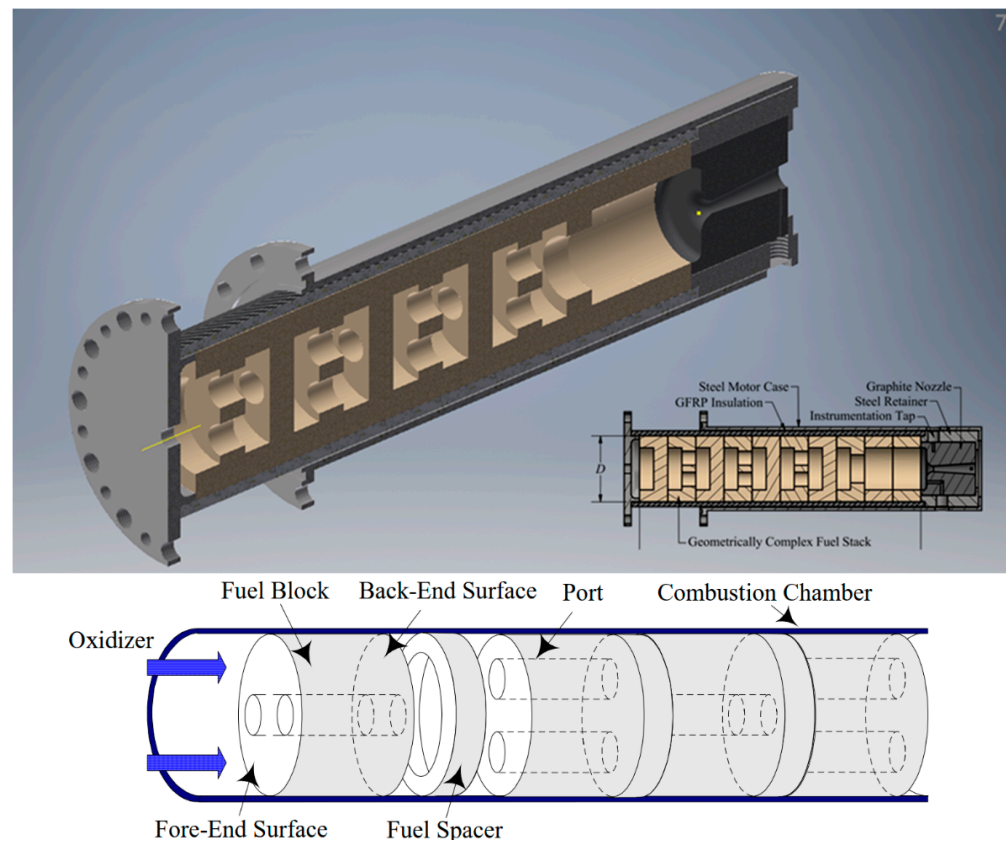


Figure 1. CAMUI fuel geometry concept (top) and burn surfaces (bottom).

1.2. Scaling of Regression Model

Previous work has been done regarding the scaling effect of the solid fuel regression models in CAMUI-type hybrid rocket motors [4,5]. However, this work was focused on the base investigation of the core impinging jet principle. At the start of this research, it remained unclear how well the fuel regression rate correlations of previous research, conducted using <2.5 kN thrust-class motors, would predict the fuel regression rates at larger scales. Accordingly, this work aims to contribute to our understanding of hybrid rocket fuel regression rates in the following ways:

Size: The collaborative work between the Laboratory of Space Systems at Hokkaido University (HULSS) and MJOLNIR Spaceworks (MSW) has allowed for a considerable increase in size, from 2.5 kN (100 mm diameter) to 40 kN (400 mm diameter) motors, and thereby a considerable expansion of the investigation of the scaling effect.

Fuel geometry: This work includes engine designs that have been optimized for performance compared to the previous work that had investigation of working principle as its main design driver. This results in different geometrical proportions compared to previous work.

2. Materials and Methods

The main concept underlying the experimental research of this study is to design a 40 kN-thrust class hybrid rocket fuel grain using empirical correlations derived from 2.5 kN-thrust class and 10 kN thrust class firing tests conducted in previous research and development. This involves three steps. First, the analysis of experimental data from 2.5 kN-thrust class and 10 kN class firing tests to establish fuel regression rate correlations according to boundary-layer combustion theory. Second, an algorithm is constructed for the iterative design and optimization of a 40 kN-thrust class hybrid rocket fuel grain by parameterizing inputs, such as: block dimensions, the number of blocks etc. Lastly, the resulting design is manufactured and hot test fired, allowing for an empirical evaluation of

the prediction performance of the design algorithm based on 2.5 kN-thrust class firing test data and 10 kN-thrust firing data respectively.

2.1. Regression Rate Formulas

For the simulation considered here, the burning of a fuel block is defined to happen differently on the three main burning surfaces: Fore-end surface, port and back-end surface, as shown in Figure 1. The existing model for fuel regression is based on Equations (1)–(3). These are based on the adaptation [4] of Marxman's diffusion-limited model [6], and have been further adapted to include a scaling factor [5] to account for the change in dimensions during burning:

$$\text{Fore – end surface : } r_{fu} = aG_p^{mu} \left(\frac{H}{D_p} \right)^{nu} * \left(\frac{D_p}{D_{pi}} \right)^{mu-1} \quad (1)$$

$$\text{Port : } r_{fp} = aG_p^{mp} * \left(\frac{D_p}{D_{pi}} \right)^{mp-1} \quad (2)$$

$$\text{Back – end surface : } r_{fd} = aG_p^{md} * \left(\frac{H}{H_i} \right)^{nd} * \left(\frac{D_p}{D_{pi}} \right)^{md-1} \quad (3)$$

Although the physical scale and thrust class of the motors used in this research are many times larger than in the experiments used to formulate the regression rate correlations, the mass flux regimes are roughly the same: 200 to 740 kg/m²/s with very few measurements over 600 kg/m²/s.

For this reason, it is reasonable to assume that the assumptions underlying the regression formulations are unchanged. Furthermore, it is worth pointing out that although the impinging jet flow field of CAMUI fuels differs from that of the conventional boundary layer combustion proposed by Marxman et al., previous research on CAMUI fuels has concluded that the underlying assumption of diffusion-limited fuel regression is valid within the above-mentioned flux regime. The only exception is for the fore-end surface of the very first fuel block, and the aft-end face of the very last fuel block, where chemical kinetics and radiation heating are likely to have a non-negligible effect on fuel regression.

Note that the instantaneous value through time is not available from the test data. Instead, the dimensions used for the scaling factors are initial and average values through the burn. As the regression is non-linear [7,8], this may cause some additional errors that are not addressed in this work.

2.2. Iterative Simulator

A comprehensive CAMUI simulator was developed in Matlab to help analyze the regression characteristics of the CAMUI engine for this research. This simulator uses one set of engine tests to create a regression simulator for the prediction of other engine tests. The principle of the simulator is to import the test data from one series of CAMUI test firings, analyze these data to extract the empirical regression constants, then use these constants with the regression formulas to simulate the regression of any other CAMUI-type engine. This simulator concept is illustrated in Figure 2a,b.

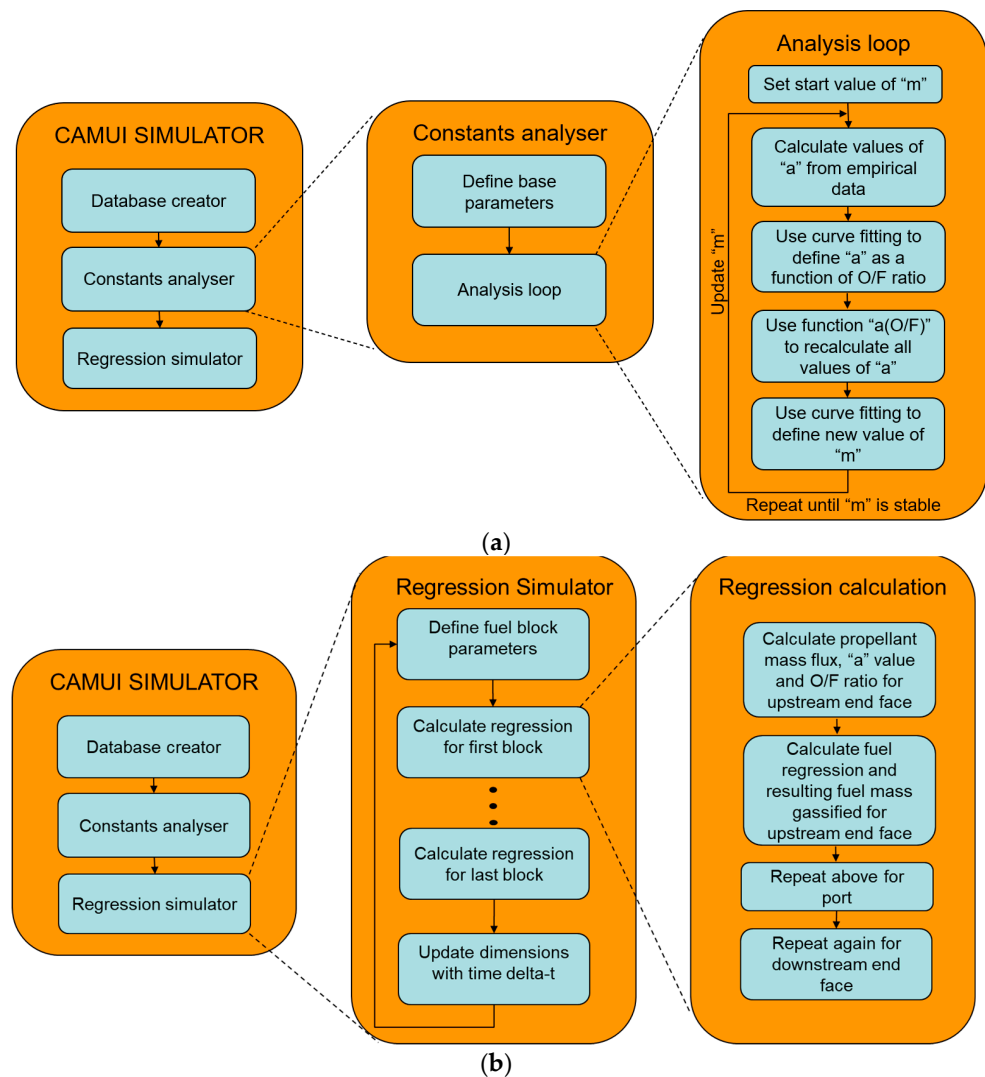


Figure 2. CAMUI simulator concept. (a) Constants analyzer. (b) Regression simulator.

2.3. Test Setup

All tests were performed with similar test setups like the one shown below in Figure 3. The LOX tank is filled while the valve V01 is closed and pressurized to a fixed pressure level through the He regulator R01. A chemical igniter, based on a heating wire encased in an epoxy/gunpowder mixture, is then lit inside the engine after which the main valve V01 is opened, allowing LOX to flow into the engine and combustion to occur. After the set burn time, V01 is then closed, cutting off the LOX flow to the engine and ending the burn. The LOX flow is measured using the pressure sensors upstream (P02) and downstream (P03) of the orifice, which has previously been characterized.

2.4. Motors Included

The firing test series used in this analysis are shown below in Table 1. Three engine series are used in this study. They have been named after the diameter of the fuel blocks used. The first two are D230 and D400. The D230 was the engine series used as the baseline upon which the D400 motor was developed. For the sake of investigating the scaling performance of the model used over a larger scaling range, the smaller D100 engine is also included. The burn times noted are the actual measured burn times of the firings. For the D400 the design nominal burn time is 21 s, but due to ground support equipment (tanks) limitations, the firing was limited to 7 s.

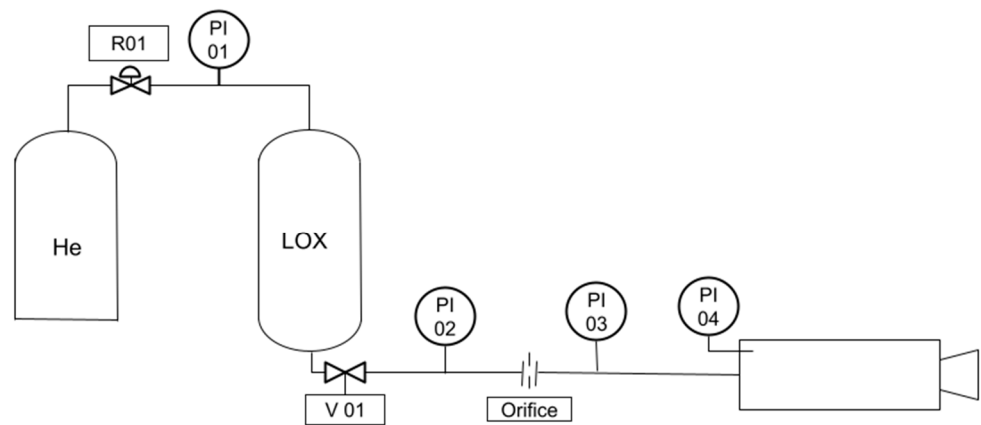


Figure 3. Test Setup.

Table 1. Motors used in this research.

Engine Name	Nr. of Fuel Blocks pr. Engine	Fuel Diameter (mm)	Nominal Thrust Level (kN)	Propellant Flux (kg/m ² /s)	Burn Times (s)
D100	10	100	2.5	200–570	2–5
D230	10	230	10	290–740	5–10
D400	16	400	40	230–420	7

2.5. Fuel Measurement Method

To measure the regression on the upstream end faces and the downstream end faces of the D100 and D230 fuel blocks, the surfaces were measured with a laser distance measurer. The measurements were performed along three lines as shown below in Figure 4 (left). The averaged values of the measurement points were then compared to the original shape to acquire the averaged regression of the given surface. This method will include a systematic error as the measurement points further from the center have a lower weight/area when averaging compared to the points closer to the center. For example, the center point itself is measured three times. To evaluate the accuracy of the method, a 3D scan of one of the fuel blocks was performed and the digital model was compared to the original fuel design. This is shown above in Figure 4 (right). This showed the averaged regression values from the two methods to be within 10% of one another.

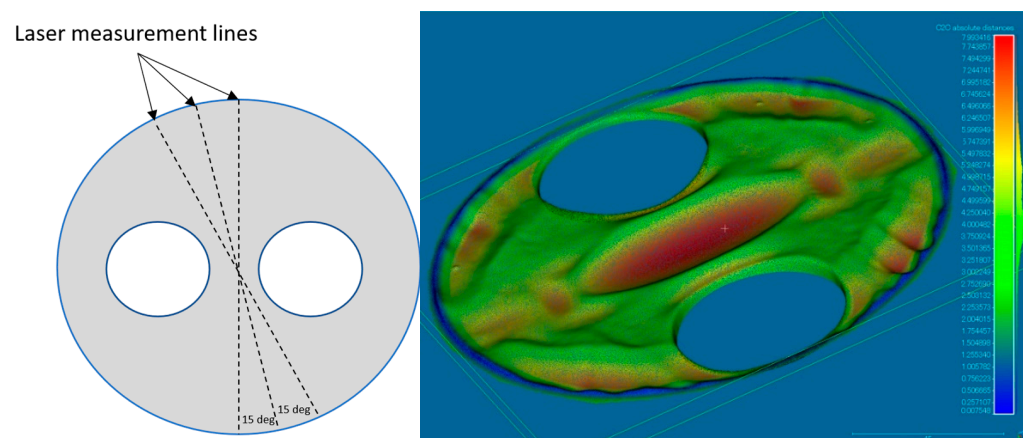


Figure 4. D100 and D230 measurement lines (left) D230 3D scan method (right).

The surface regression of the D400 fuel blocks was measured by hand, before and after the firing. For each surface, 5–10 measurement points were taken across the surface and the averaged values of the measurement points were then compared to the original shape

to acquire the averaged regression of the given surface. Again, to estimate the error of this method, a single surface was mechanically scanned using a mechanical probe mounted to a CNC machine and compared to the hand results. This showed the averaged regression from the two methods to be within 15% of each other.

2.6. Equivalent Burn Time

To account for the difference in both burn time and start-up transient times between the analyzed motors (D100 and D230) and the simulated motors (D400), the burn times were adjusted according to the burn time equivalent principle. This principle is shown in Figure 5, and in short is the time the engine would be firing at its steady-state thrust level to achieve the same total impulse as measured in the test. This is described in detail in [9]. This was only done when simulating D400 motor regression.

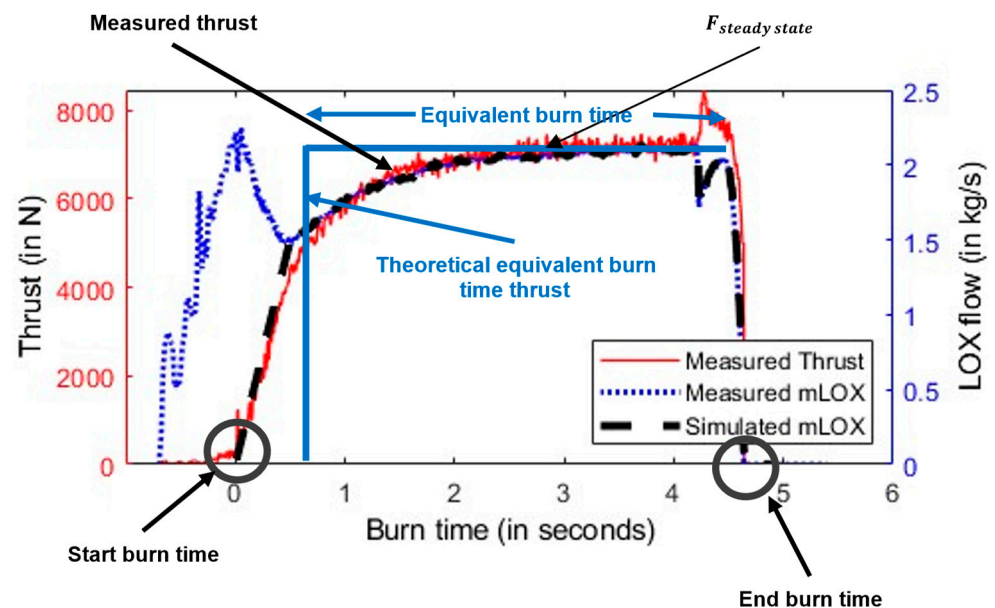


Figure 5. Burn time equivalent principle [9].

2.7. Method of Comparison

For the evaluation of the general performance of the model, the test data from the D100 series is analyzed and used to simulate the regression of the individual motors of the D100 series. Similarly, the D230 test data is analyzed and used to simulate the regression of the individual engines of the D230 series. The simulated regression is then compared with the measured regression. This gives a baseline performance accuracy of the model. To evaluate the performance when used on scaled engines, the test data from the D230 is analyzed and used to simulate the fuel regression of the D400 series. This follows the actual development flow of the D400 motor. Lastly, to investigate the model scaling performance over a larger range, the D100 test data is analyzed and used to simulate the fuel regression of the D400 series. The simulated regression is then compared with the measured regression. This gives the scaling performance of the model.

3. Results

Figure 6 shows the general performance of the model, using the D100 for analysis to simulate the same test series. The results are shown below in Figure 6 (left). Similarly, the results from using the D230 for the analysis to simulate the engines of the D230 series are shown in Figure 5 (right).

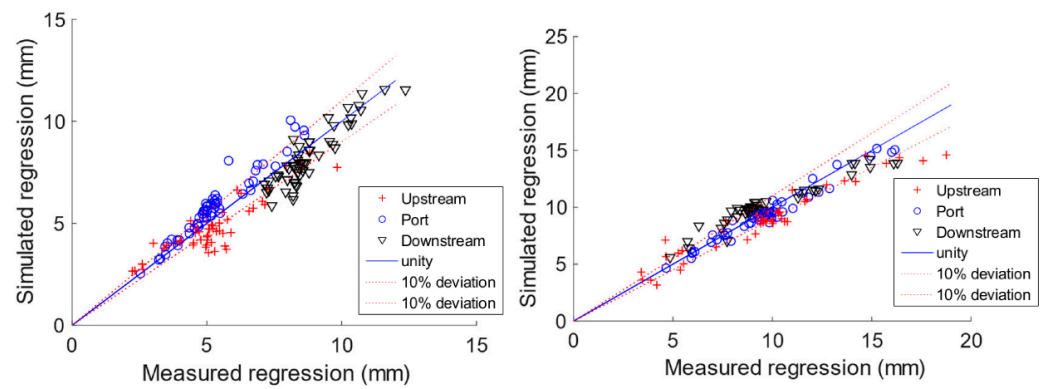


Figure 6. Model baseline performance for D100 (left) and D230 (right).

Calculating the regression error RMS for simulated vs. measured regression from these results is summarized in Table 2:

Table 2. Model regression error RMS.

Motor Series	Error rms (%)
RIE	14.1
TTY	10.8

For the scaling performance of the model, using the D230 for analysis to simulate the fuel regression of the D400 series, the results are shown below in Figure 7 (left). Similarly, the results from using the D100 for the analysis to simulate the fuel regression of the D400 series are shown in Figure 7 (right).

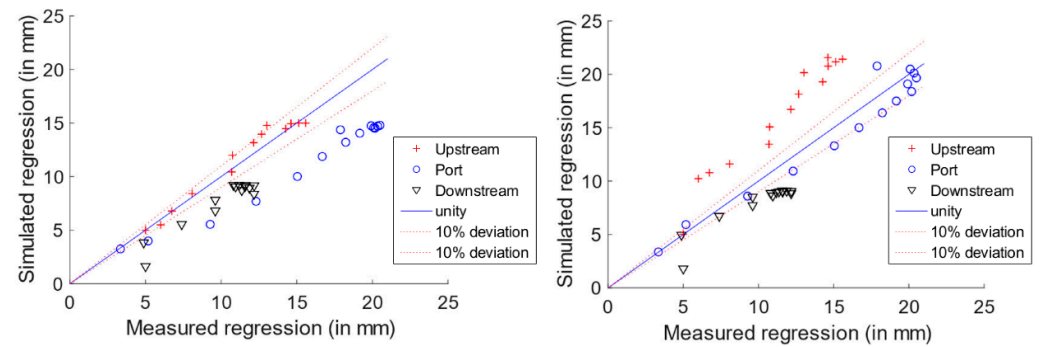


Figure 7. Model scaling performance for D400 based on D230 analysis (left) and D100 analysis (right).

Calculating the regression error RMS for simulated vs. measured regression from these results, the performance is as shown in Table 3:

Table 3. Scaled model regression error RMS.

Motor Series	Analysis Series Used	Error rms (%)
D400	D230	22
D400	D100	26

4. Discussion

The use of the scaling of the regression model allowed MSW to design and safely fire the D400 engine as shown below in Figure 8. The results investigated in this paper show a good correlation between the simulated regression and the regression measured after firing, both for the baseline and for the scaled modeling results. The results from the baseline performance show that some error is still present. The possible reasons for these errors

are discussed in [10], with the most important ones believed to be the start-up transient effects and the fuel block measurements. Especially the fuel block measurement methods are believed to have a significant impact, and though not quantified yet, the measurement method used for the D100 and D230 fuel blocks includes a systematic error. This error is not seen when simulating the D100 or D230 themselves as the measurement method used in the analysis and for the comparison are the same. As the measurement method used for the D400 is different, the resulting comparison of the simulated vs measured will reflect these systematic measurement errors. Though the fuel blocks from D230 and D100 are no longer available to confirm with 3D scanning, at the time of writing it is believed that the D100 and D230 upstream end face regressions are overestimated by the used measurement method and the ports are underestimated. This would fit well with the systematic error seen in the scaling. Despite these errors the model shows good scalability with an rms error of 22% and 26% when using the scaling from D230 to D400 and when scaling across the wider range of D100 to D400 respectively.

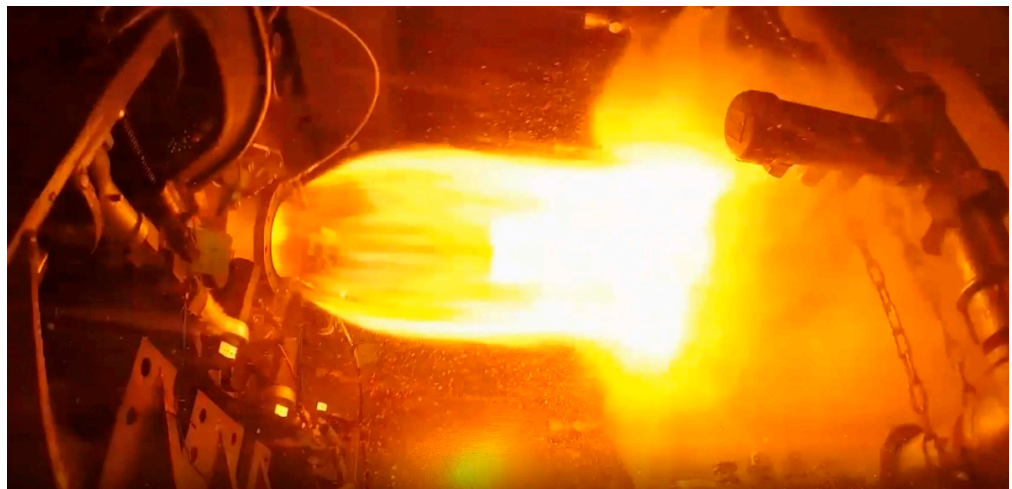


Figure 8. 40 kN motor firing with sound dampening water wall (no nozzle skirt).

5. Conclusions

The goal of this research was to investigate the possibility of using the CAMUI regression model to predict the regression of large commercial sized engines based on the regression data from smaller university project sized engine firings. The research showed good scalability of the model over a large scaling range, in this case up to a factor 16 in thrust class within an rms error of 26%. This has allowed MSW to proceed with the ongoing development of a mass optimized commercial version of the D400 engine based on the regression model, but furthermore shows that, for CAMUI, small scale university engines can be used to correctly predict the regression and thereby the overall performance of much larger commercial sized motors.

Author Contributions: Conceptualization, T.V., L.K., K.Y. and H.I.; methodology, T.V. and L.K.; software, T.V.; formal analysis, T.V. and L.K.; investigation, T.V. and L.K.; resources, T.V., L.K., K.Y. and H.I.; data curation, T.V., L.K. and H.I.; writing—original draft preparation, T.V.; writing—review and editing, L.K., K.Y., H.I. and H.N.; supervision, H.N.; project administration, T.V.; funding acquisition, T.V. and K.Y. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

a	Empirical constant
D_p	Port diameter (m)
D_{pi}	Initial port diameter (m)
G_p	Propellant mass flux (kg/s/m ²)
H	Height (between fore- and back-end surfaces) (m)
H_i	Initial height (m)
md	Empirical constant (back-end surface)
mp	Empirical constant (port)
mu	Empirical constant (fore-end surface)
nd	Empirical constant (back-end surface)
nu	Empirical constant (fore-end surface)
r_{fd}	Regression rate back-end surface (m)
r_{fp}	Regression rate port (m)
r_{fu}	Regression rate fore-end surface (m)
RMS	Root Mean Square
tb	Burn time (seconds)

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