Rocstar Time Zooming and Rocket Burnout User/Developer Report

by Mike Campbell

mtcampbe@uiuc.edu

12.10.2007

Abstract

This is a short report on time zooming in ***Rocstar*** and it's use for long running simulations of solid propellant rockets. The focus of this report is on testing, using and implementation of time zooming in the ***Rocstar*** simulation suite and defers the formulation details to other works. Tests, trials, and behaviors of time zooming in ***Rocstar*** will be summarized.

1. Introduction and motivation for time zooming in *Rocstar*

Time zooming is the technology that allows ***Rocstar*** to do high resolution, high fidelity simulations of solid propellant rockets on very long time scales. The formulation of time zooming can be found in the following reference by Haselbacher[1].

Our hope is that we can use the time zooming technology to accelerate ***Rocstar*** simulated time though long, relatively uneventful intervals of rocket operation. We then plan to turn off zooming and bring back full physical detail to study interesting events that occur relatively late in the full operation timescale of the device. Such events may include propellant burnout, critical geometrical changes in the device, fine details in the fluid or structural solutions, or even accident scenarios.

The performance and behavior of time zooming in the ***Rocstar*** simulation is of great interest in determining whether the technology is up to the task for which it is planned. It is hoped that this report will provide a bit of groundwork for testing time zooming, and help in answering some of these performance and behavior questions.

2. Zooming configuration for *Rocstar*

Time zooming is currently supported in only one ***Rocstar*** fluids module, ***Rocflu***. Work is now underway to perform time zooming in the solids domain with the ***Rocsolid*** and ***Rocfrac*** structures solvers. Zooming in fully coupled ***Rocstar*** simulations is also being tested and developed. The state of these efforts will be explained in later sections.

Zooming in ***Rocstar*** is controlled via the `ZoomFactor` keyword in the **RocstarControlFile.txt**. The following table describes the effect of the `ZoomFactor` key value on the ***Rocstar*** simulation.

Propagation Off	No Zooming	Zoom by factor N
0	1	N > 1

1. A. Haselbacher, F.M. Najjar, L. Massa, and R.D. Moser, *Enabling Three-Dimensional Unsteady SRM Burn-Out Computations by Slow-Time Accleration*, AIAA paper 2006-4591, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Sacramento, CA, June 2006

Users would be well advised to note the implications of time zooming upon the ***Rocstar*** system time step and restart checkpoint frequency. When zooming is used, a system step advances simulated time by `ZoomFactor * CurrentTimeStep`, and it is this zoomed time that will be used througout the *interface simulation* in considering other parameters such as `OutputIntervalTime` and `MaximumTime`. These parameters should be adjusted appropriately to account for the zoomed time.

On the other hand, no such time scaling adjustment is currently required for the physics solver modules. Time zooming is implemented in each physics solver separately in such a way that the adjustment of temporal input parameters is not required. Other solver-specific zooming parameters are explained in the solver-specific sections.

3. Zooming *Rocstar* fluid components

Time zooming is currently supported only the ***Rocflu*** fluids module. Work is planned, though not yet underway, to implement zooming in ***Rocflo*** as well. The implementation details of zooming in the fluids modules are deferred to later sections.

3.1.1 Zooming configuration for *Rocflu*

Setting up ***Rocflu*** for zooming requires one to add and/or modify the `TIMEZOOMING` section of the ***Rocflu*** input file. The naming convention and location of this ***Rocstar*** configuration file is:

`Rocflu/Modin/<casename>.inp`

This path is relative to the `RocstarRunDirectory`. Most of the ***Rocflu*** specific time zooming parameters are needed only to describe the geometry of the fluids domain. It is important that we do not apply zooming at or beyond the nozzle inlet. These parameters provide a simple way to describe both simple rocket geometries as well as features such as submerged nozzles.

A sample `TIMEZOOMING` section of the ***Rocflu*** input file and correct syntax follows:

```
# TIMEZOOMING

MAXPLANE 0.85

MINPLANE -1d9

AXIS 1

NOZINLET 0.84

NOZRAD 0.15

#
```

The `AXIS` parameter describes which major axis the rocket lies upon. The default (`AXIS 1`) is the X axis. Other possibilities are the Y axis (`AXIS 2`), and the Z axis (`AXIS 3`). All other parameters specify positions along the specified major rocket axis. Time zooming rocket geometries not lying on major axes is not supported.

The `MINPLANE` and `MAXPLANE` parameters specify the absolute minimum and maximum planes (normal to the axis specified by `AXIS`) between which zooming can be applied. The default is effectively the entire rocket.

Note that if you have a submerged nozzle, the region between the planes will contain the nozzle inlet plane. Thus, the `NOZINLET`, and the `NOZRAD` parameters should specify the nozzle inlet plane and the nozzle throat radius, respectively.

This may all seem rather complicated, but note that if you have a typical rocket geometry and dataset created at `CSAR`, then it most likely lies on the X axis, and probably does not have a submerged nozzle. In this case, the `TIMEZOOMING` section need specify only the `MAXPLANE` parameter such that zooming is not applied beyond the nozzle inlet plane.

Curious users, and those involved in the development effort, will know that there are more parameters in the `TIMEZOOMING` section than those outlined here. All of these other parameters are completely historical and are no longer required or used in ***Rocstar***. They remain for use in further development of time zooming and for use in stand alone application runs which are not the focus of this report.

3.1.2 Zooming configuration for *Rocflo*

Not yet applicable.

3.2 Testing *Rocstar* zooming in the fluids domain

Time zooming was previously tested only in the ***Rocflu*** stand-alone fluids simulation application. The previous tests are summarized by Haselbacher[1]. This report will focus on three dimensional simulations in the context of ***Rocstar*** and it's modules. For our tests, we follow the previous work by Haselbacher, et al, and devise the following test configurations.

3.2.1 Endburner test case

The endburner is the perfect case for the verification of time zooming. After the transients of ignition settle, we expect that the endburner will have very steady and flat pressure behavior. This presents exactly the environment for which time zooming is formulated. This test case can be obtained in the ***Rocstar*** native data archive named `Endburner`.

The head end and aft end geometry of the endburner and it's nominal head end pressure behavior are depicted below in Figures 1, 2, and 3, respectively.

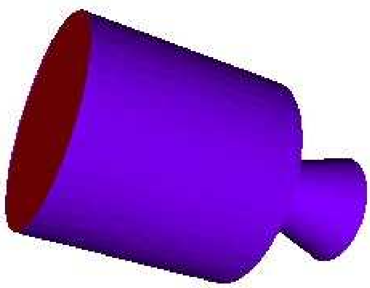

Figure 1.

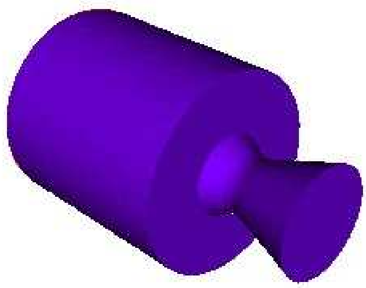

Figure 2.

The head-end view shows the burning surface in red. The rocket is along the X axis, and the burning surface sits at $X = .757276m$. The nozzle inlet sits at $X = .850392m$, and the nozzle outlet is at $X = .900392m$. The corresponding `TIMEZOOMING` section of the ***Rocflu*** input file need specify only one parameter, `MAXPLANE .850392`, to ensure that zooming is not applied in the nozzle region.

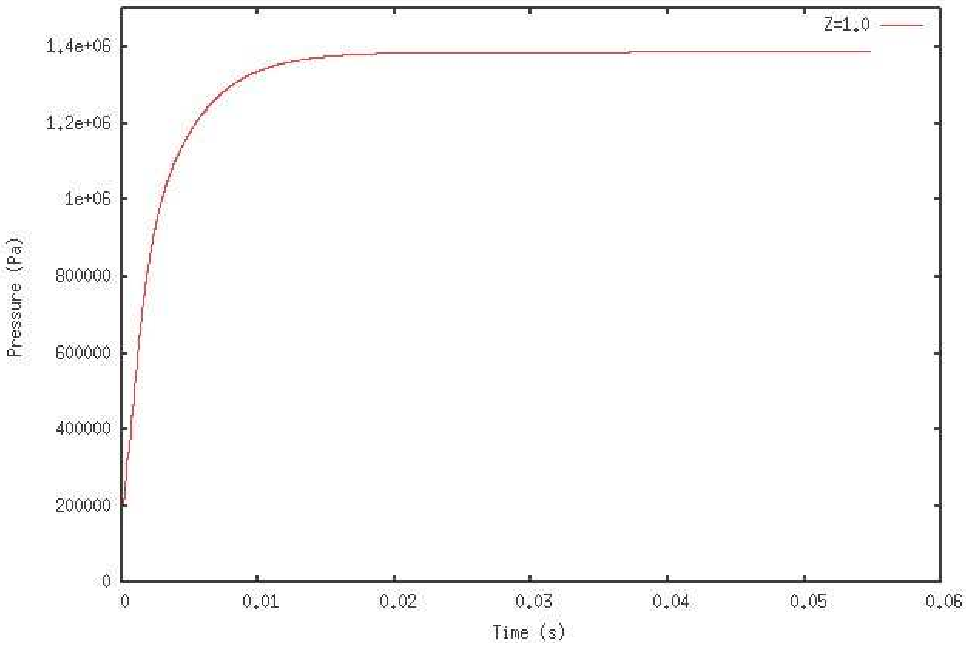

Figure 3. Endburner nominal headend pressure

For the nominal (non-zoomed) Endburner run, the `ZoomFactor = 1.0` parameter is set in the `RocstarControl.txt`. The propellant burn rate properties are set in the `RocburnAPN/RocburnAPNControl.txt` file with `a = 1.30573` and `n = .461`. These are tuned in order to produce a rocket with the head end pressure behavior depicted in Figure 3. This pressure history was generated by a ***Rocstar*** fluids only run with the ***Rocflu*** fluids module.

The zoomed Endburner runs were conducted with `ZoomFactor = 10.0` and `ZoomFactor = 100.0`. Zooming was switched on well after the ignition transients had settled at T = .04s. The results of these runs are shown in Figure 4.

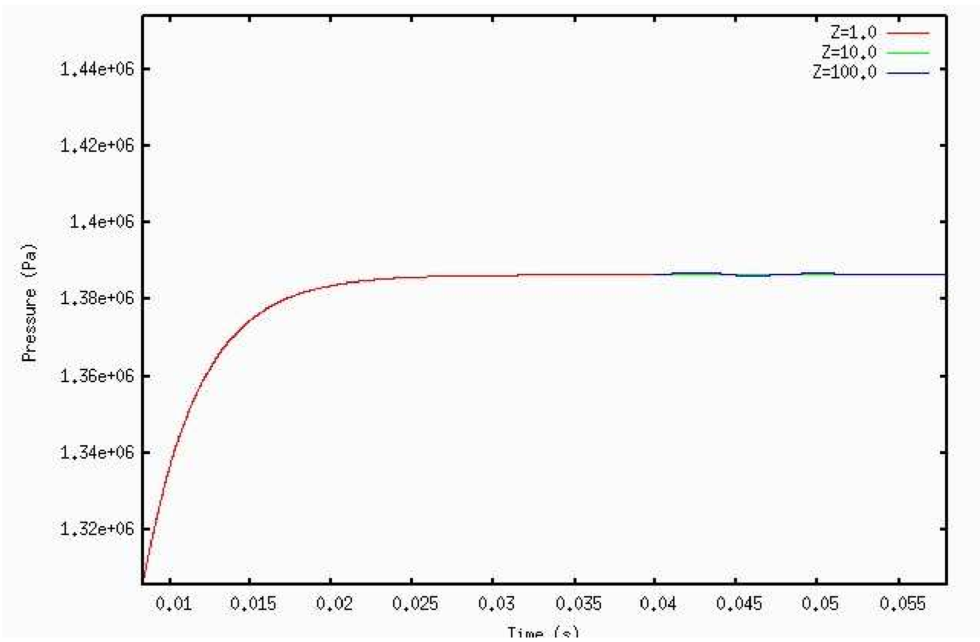

Figure 4. EndBurner head end pressure for Z=10.0 and Z=100.0

Note that there is only a slight oscillation of the Z=100.0 curve, even at this closed in scale on the pressure axis. The nominal (red) curve is hidden by the Z=10.0 curve which lies directly on top of it. Based on this test, it is fairly safe to say that time zooming in ***Rocstar*** is functioning as expected in the regime for which it is designed.

Other tests for which results are not shown consisted of turning zooming on and off to see the effect, if any, on the pressure curve. No such effect was witnessed for the rather featureless pressure behavior of the Endburner.

Further tests and reporting planned for the Endburner include providing quantitative data for the pressure history differences between zoomed and non-zoomed runs. Also planned are zoomed runs from T = 0 for which we will collect data through the ignition transient. Time zooming is known not to capture nominal behavior when $\frac{d^2P}{dt^2} \neq 0$ (this will be apparent in subsequent tests). For the Endburner, we would like to know what effect, if any, zooming through the transient will have on the predicted steady state operating pressure.

3.2.2 Generic center-perforated grain

This test case can be found in the ***Rocstar*** native data archives as the `Sideburner` case. The geometry of the Sideburner is identical to the Endburner, except with the burning surface now the center cylinder.

This geometry presents only a slightly more difficult test for time zooming. In this geometry, the burning surface is cylindrical and has a head end pressure that increases linearly with time, (i.e. $\frac{dP}{dt} \approx$ constant). The initial geometrical configuration and nominal pressure history are presented below in Figures 5, 6, and 7, respectively.

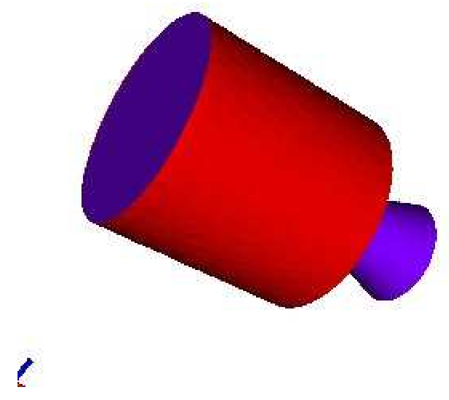

Figure 5.

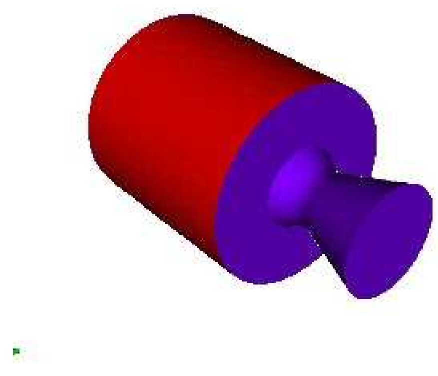

Figure 6.

All time zooming and propellant burn rate parameters are identical to the Endburner case. The nominal pressure history from a ***Rocstar*** fluids only run with the ***Rocflu*** fluids module is shown in Figure 7.

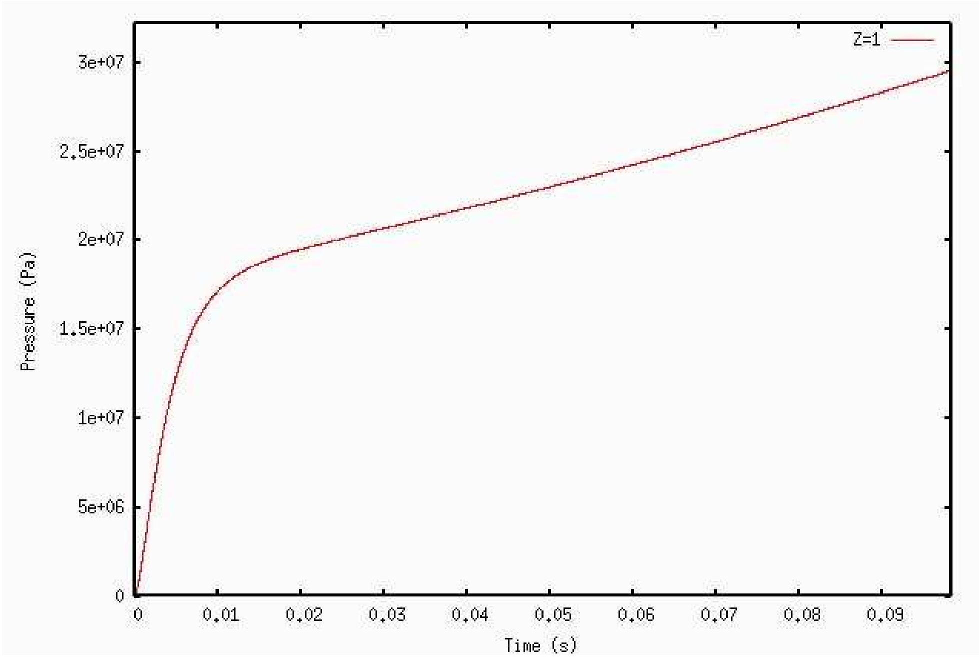

Figure 7. Nominal (Z=1) head end pressure curve for the Sideburner (center perforated grain)

The Z = 1.0 ***Rocstar*** run took several wall clock days to approach 100ms. Figure 8 depicts the geometry at 90ms just before the rocket begins to burn out to the case (case radius = .062m). This case radius was carefully chosen so that the rocket would burn out at around 100ms.

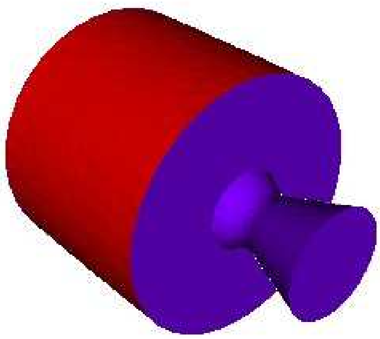

Figure 8. Sideburner geometry after significant burning

In the zooming tests, we find (as expected) that the wall clock runtimes are reduced by a factor equal to the zoom factor. Figure 9 shows the effect on the head end pressure history prediction of running the Sideburner case with the zoom factors of 1, 50, and 100. Smaller zoom factors are not shown due to the high accuracy of these heroic zoom factors.

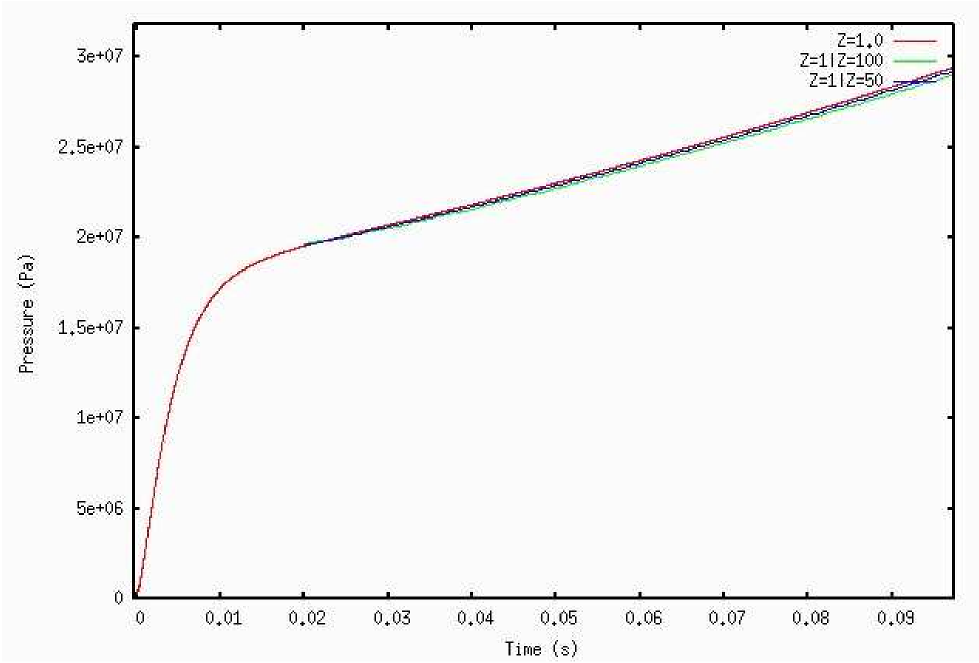

Figure 9. Sideburner head end pressure with Z=1, Z=50, and Z=100

In each test shown in Figure 9, zooming was turned on after the ignition transient had died out at around .02s. The nominal curve is reproduced within a fraction of a percent for each zoom factor (about .8% absolute difference for Z=100).

Tests were also conducted to evaluate the effect of time zooming on the ignition transient. The results of running ***Rocstar*** from T = 0 and through the ignition portion of the pressure curve with various zoom factors is shown in Figure 10.

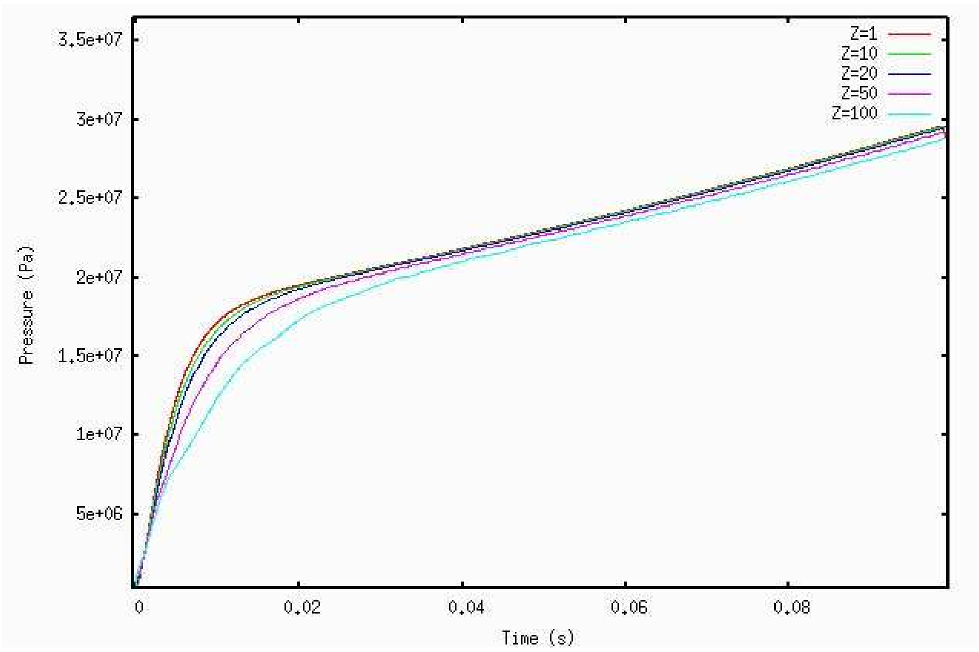

Figure 10. Sideburner head end pressure with zooming through ignition transient

There are a couple of noteworthy features of the solutions shown in Figure 10. It is interesting that despite the curvature of the ignition feature, time zooming succeeds in capturing the behavior quite well at modest values of the zoom factor. Also, there is a rather dramatic effect on the predicted final operating pressure when one uses zooming through the ignition sequence. The predicted quasi-steady operating pressure is off by nearly 4% for the Z=100 curve.

Also of interest is the behavior of our head end pressure solution when time zooming is used for some time, and then switched off. Figure 11 shows some results of testing this capability for zoom factors of 50 and 100 in the center perforated grain test. In this test, zooming was switched on in the quasi-steady regime, and allowed to become steady before being switched off. (Figures currently only show the result for a zoom factor of 50 - these figures will soon be replaced by the one showing both zoom factors). Note that the scale of Figure 11 is magnified in order to closely examine the effect on the head end pressure when zooming is switched off.

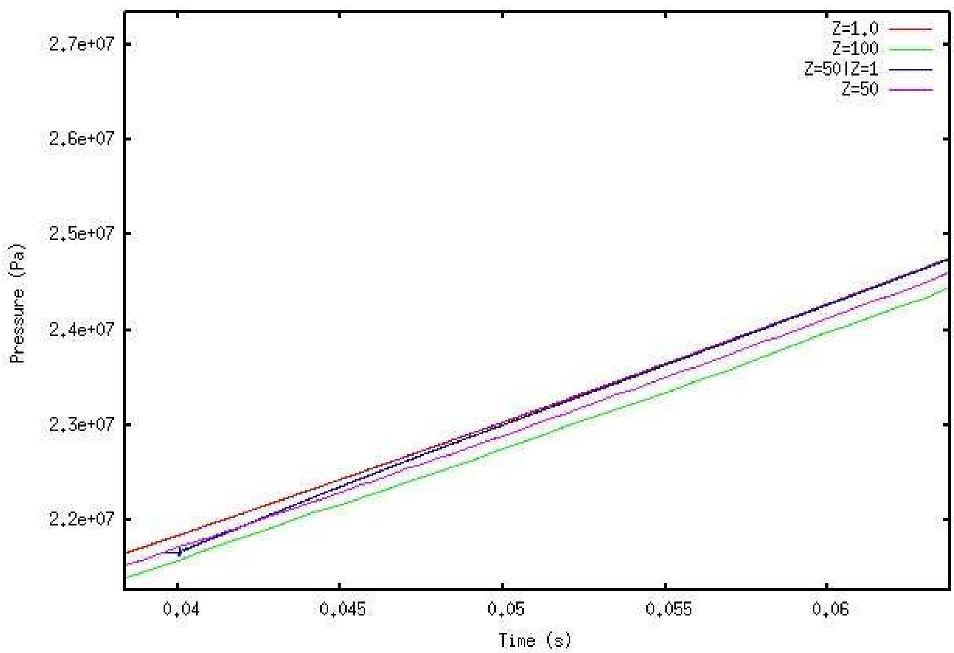

Figure 11. Turning zooming off to recover non-zoomed solution

Further testing is planned for determining the effect of ramping zoom factors, and possibly automatically adjusting the zoom factor based on $\frac{d^2P}{dt^2}$.

Burnout of the center perforated grain rocket

The time zooming technology brings full device operating time scales within reach of the ***Rocstar*** simulation. We would like to determine how well ***Rocstar*** can capture pressure curve features induced by the significant geometrical changes to the burning surface at advanced times in the device operation.

The Sideburner case with it's center perforated grain provide a good test case for testing zooming through a simple, yet rather violent propellant burnout event. It's simple because of the simple and smooth cylindrical geometry - which *does not require remeshing to burn out*. The burnout event is violent since the propellant all burns away in a very short interval (it all reaches the case at about the same time) - thus inducing a very sharp feature in the pressure curve followed by a steep depressurization.

Case constraint configuration is needed in order to burn out the propellant to the rocket case. For information on how to do this, please see the brief excursion on setting case constraints at the end of this section.

The small scale of the Sideburner allows simulation of the full rocket burn with a zoom factor of 1.0 in reasonable wall clock time. The results of the unzoomed 4 day run are shown in Figure 12.

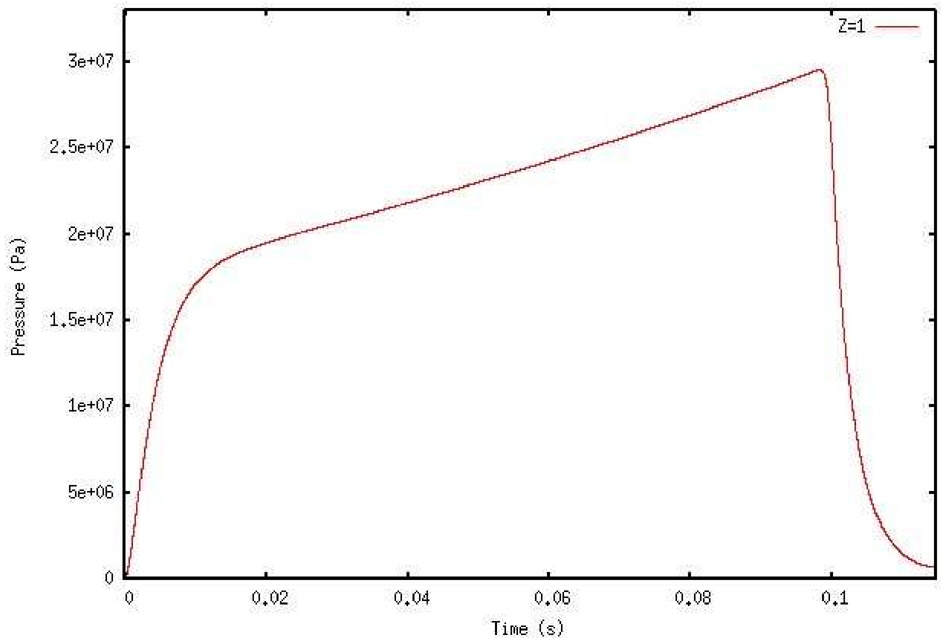

Figure 12. Sideburner burnout with `ZoomFactor 1.0`

We also ran the entire simulation from T=0 to burnout under various zoom factors. The wall-clock runtimes were reduced as expected. The Z=100 case completes a total burn in just over 1 hour. The results of these tests are shown in Figure 13.

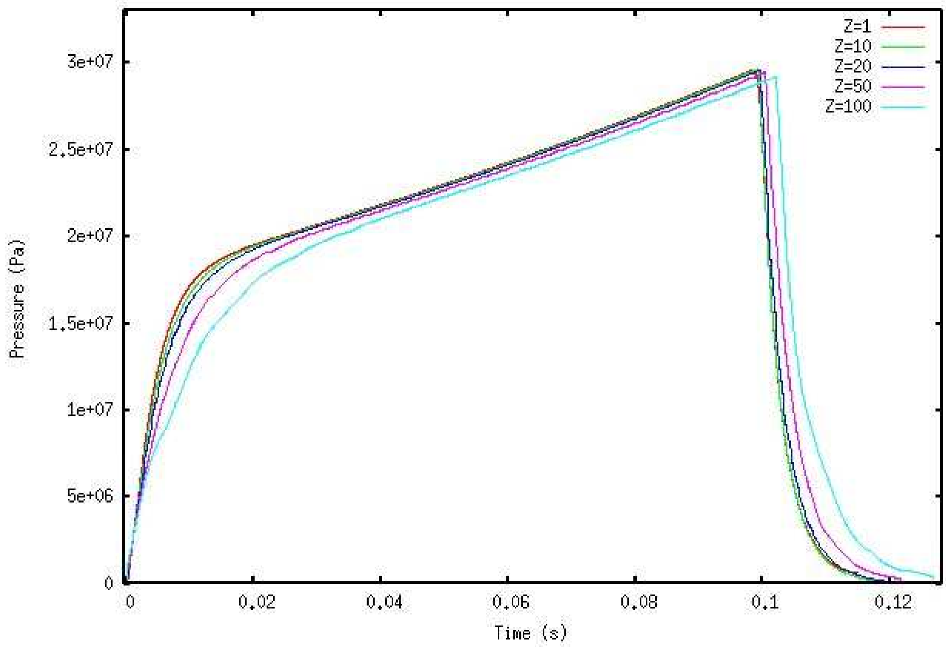

Figure 13. Sideburner burnout at various zoom factors

Since the simulated propellant burn rate has a constant power law dependence on the combustion chamber pressure, the observed shift in the head end pressure curve is expected. Ideally, the total area under the pressure-time curve should be preserved by zooming.

As previously mentioned, our primary use for zooming will be to quickly advance simulated time through relatively uneventful intervals (as shown in Figure 9) to some interesting event (e.g., a burnout event). We must turn zooming off some time before the event of interest to allow the unzoomed solution to be recovered (as in Figure 11) before we attempt to capture any event dynamics. Some results of this type are shown in Figure 14.

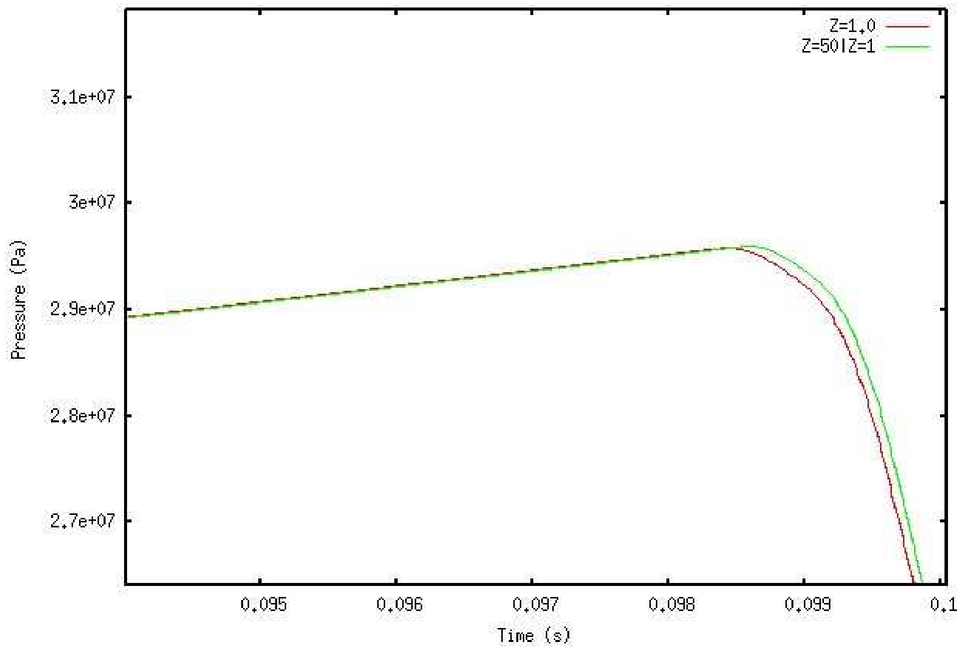

Figure 14. Turning off zooming to capture a burnout event.

Again, Figure 14 shows the unavoidable shift in the pressure curve when zooming has been used at some time in the simulation.

3.2.3 ConeBurner

This case was designed to test the behavior of time zooming under a closely controlled change in burning surface area. In this case, the change in burning surface area, $\frac{dA}{\mathrm{dt}}$, is positive until the propellant burns against the case and then it switches signs until it completely burns out. The ConeBurner geometry is shown at time 0 and after some burning in Figures 15 and 16, respectively.

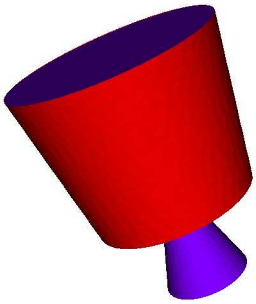

Figure 15. ConeBurner at t = 0

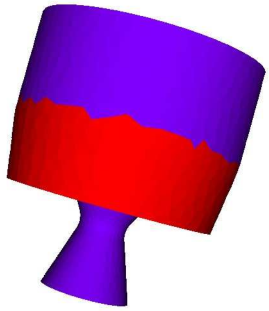

Figure 16. ConeBurner after some burning

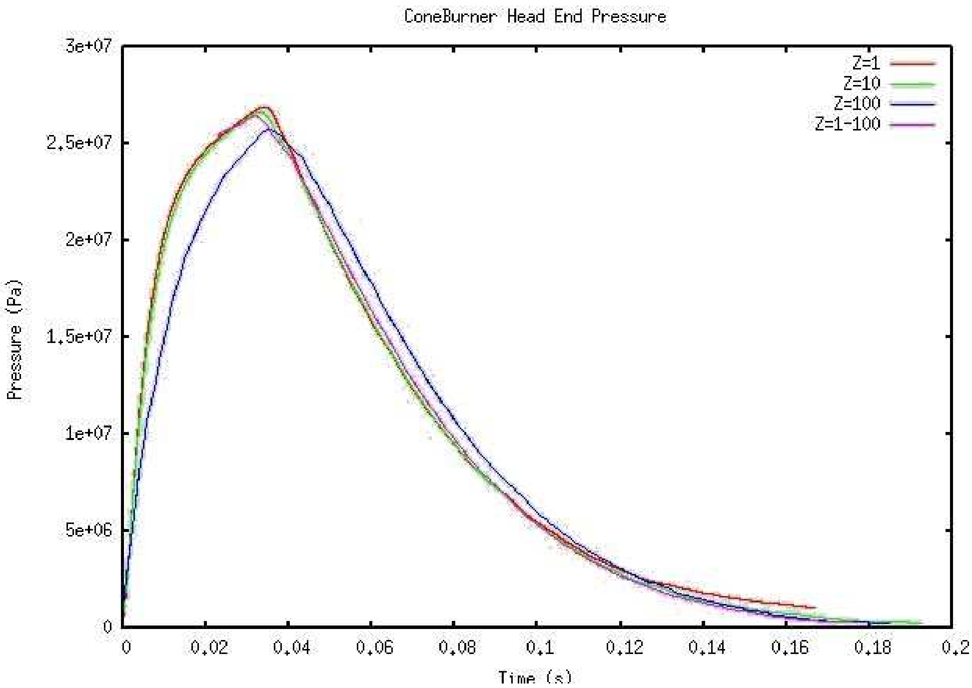

Figure 17.

The ConeBurner never reaches a real quasi-steady state by design, but the zoomed pressure agrees rather well with the predicted pressure of the non-zoomed run. Most of these cases were zoomed from t = 0.

3.2.4 StarBurner

The StarBurner geometry, shown in Figure 18, tests zooming under the condition of rapidly changing burning surface area which is very similar to some of ***CSAR***'s production simulations. This geometry runs very slowly, so the Z=1.0 case has not yet caught up with the Z=50.0 case. The results we have for this geometry so far are shown in Figure 19.

The StarBurner geometry has also been used to test the stability of the time zooming results with respect to the geometrical domain in which zooming is applied. Two tests were conducted in which some portion of the geometry was inappropriately added or taken away using the geometrical zooming parameters. These results are shown in Figure 20.

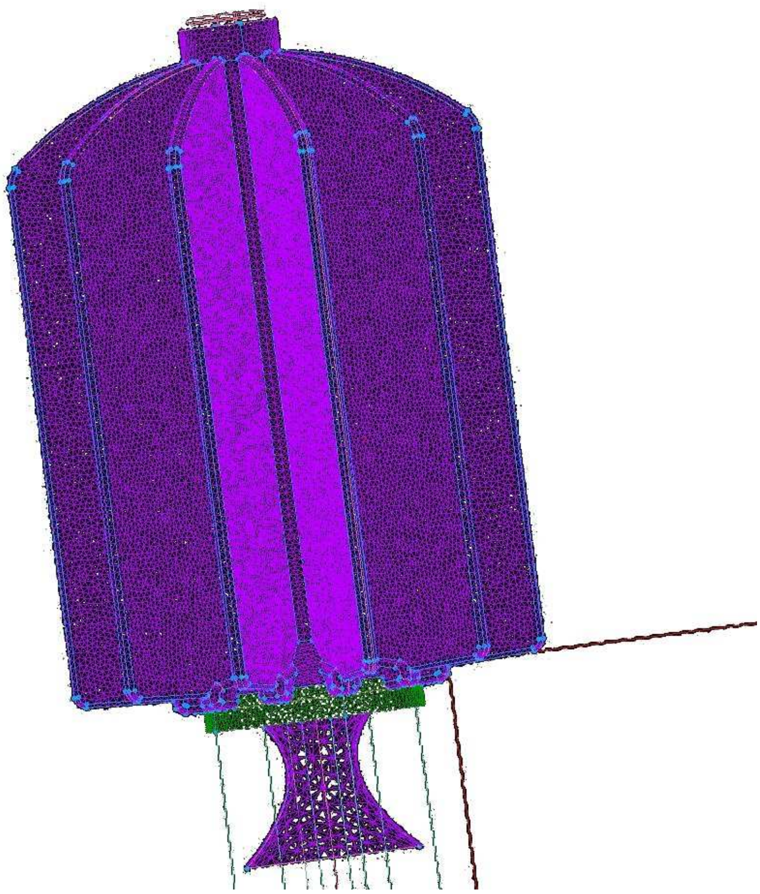

Figure 18. StarMotor geometry

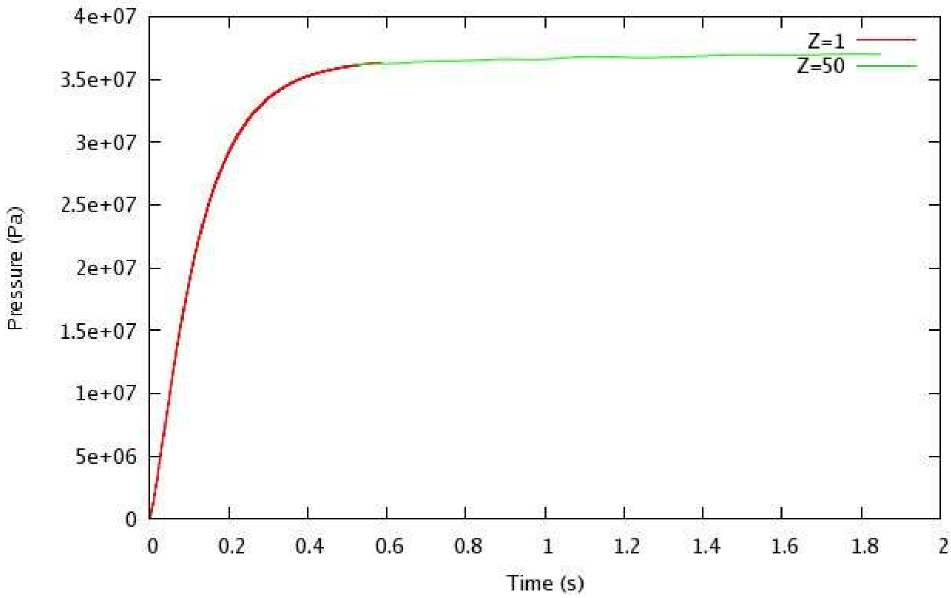

Figure 19. StarMotor Head End Pressure

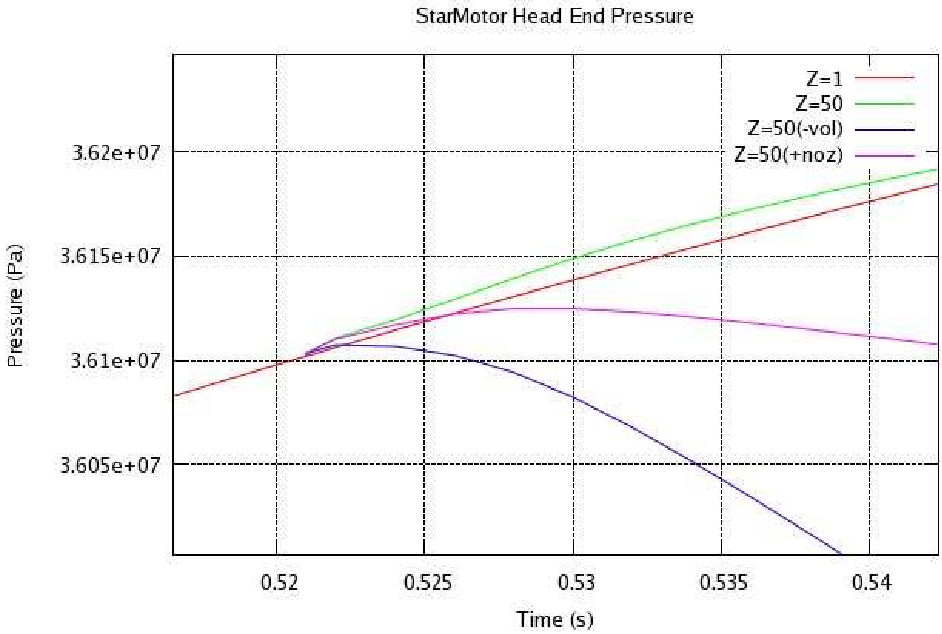

Figure 20. Zoomed HEP under the condition of missing volume, Z=50(-vol), and under the condition of added nozzle (zooming source terms applied in the nozzle region as well as the burning chamber), Z=50(+noz).

Configuration of case constraints in *Rocflu*

To simulate propellant burnout in ***Rocstar*** fluids only runs, the fluids module must be made aware of the case geometry. The fluids module will use this geometry to constrain propellant surface propagation to the rocket case. The `ROCKET` section of the ***Rocflu*** input file is the place to specify these constraints.

The constraint mechanism currently supports spheroidal or planar head ends, spherical or planar aft ends, and cylindrical or square bores. Currently, the limitation exists that the rocket's `AXIS` is assumed to be positively oriented when pointing from the head end to the aft end.

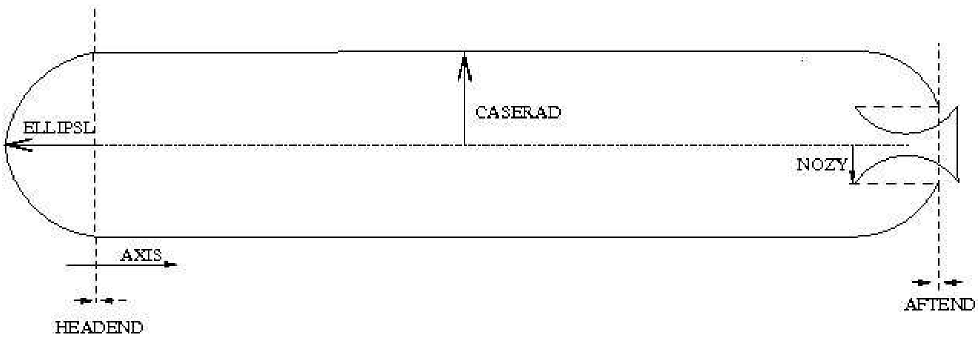

Figure 21. Sketch of typical rocket case with relevant constraint parameters

Only a few constraint parameters can describe a fairly complex geometry. Figure 15 shows a sketch of the most complex case geometry currently supported by the constraint mechanism. For simple cylindrical rockets, one needs only to specify the `CASERAD` parameter.

4. Zooming the solids

We need input here from the structures group. The general attitude (motivated by back of the coctail napkin calculations) is that zooming should work in the solids without any (non-trivial) modification to the structures solvers. We are currently testing this hypothesis.

5. Coupled zooming

Work on coupled zoomed runs is ongoing.

Briefly, the status is that after several minor (but hard to track down) bug fixes and changes - coupled runs with zooming and face-offsetting propagation do not crash. ***Rocfrac*** cannot seem to tolerate significant mesh motion before experiencing element inversion. This makes testing coupled zooming with ***Rocfrac*** unfeasible. ***Rocsolid***, on the other hand, tolerates large deformations and burning robustly - but displays improper surface regression.

We are experiencing what appears to be accelerated propagation with Z=1.0. This is currently being looked into.

6. Implementation of zooming

This section will cover the crucial details of time zooming implementation in ***Rocstar***.

6.1 Time zooming in *Rocman3*

This section is incomplete. It will be filled out properly during the course of testing/perfecting the coupled zooming.

Roughly, the interface module advances the simulated time by $\Delta t = \text{zoomfactor} \times \text{timestep}$. The propellant surface is advanced according to zoomed time. **Important:** *Nominal values for mass flux are passed to fluids!* This little doozy of a detail comes from the way time zooming is implemented inside the fluid code. The requirement on boundary conditions is accounted for in the fluids zooming source terms.

In coupled runs, we calculate the mass flux naturally and geometrically by approximating the volume swept out by the burning surface propagation. The resulting mass flux will need to be scaled by the zoomfactor unless we modify the implementation of time zooming in fluids.

6.2 Time zooming in *Rocflu*

The relevant quantities and routines are outlined.

Relevant quantities:

dt = fluid time step

$\boldsymbol{v}$ = fluid velocity

$\boldsymbol{r}$ = surface regression velocity

$\boldsymbol{n}$ = normal vector

Z = zoom factor

ρ_i = cell density

$\boldsymbol{v}_i$ = cell velocity vector

E_i = cell energy (kinetic + internal)

$(\rho \boldsymbol{v})_i$ = cell momentum density = $\rho_i \cdot \boldsymbol{v}_i$ (no sum)

$(\rho E)_i$ = cell rho E = $\rho_i \cdot E_i$ (no sum)

V_i = cell volume

∂V_i = cell boundary

$V_D = \sum V_i$ = total domain volume

∂V_D = domain boundary

V_i^- = old cell volume

$V_D^- = \sum V_i^-$ = old domain volume

Above sums are over $i=1$ to N, where N = total number of cells.

Rocflu's conserved quantities (CV) are ρ, $\rho \boldsymbol{v}$, and ρE. Each of these quantities are stored in every fluids cell center.

$\frac{\mathrm{dV}_i}{\mathrm{dt}} = \frac{V_i - V_i^-}{\mathrm{dt}}$, for which we will write $\mathrm{d}_t V_i$, for convenience

$\frac{\mathrm{dV}_D}{\mathrm{dt}} = \frac{V_D - V_D^-}{\mathrm{dt}}$, or $d_t V_D$

F = source function

ϕ = one of the conserved quantities

$R_i(\phi)$ = fluid residual = $\oint_{\partial V_i} (\phi \boldsymbol{v} \cdot \boldsymbol{n})\, ds - \int_{V_i} F(\phi) dV$

$\bar{R}(\phi)$ = bulk residual = $\oint_{\partial D} (\phi \boldsymbol{v} \cdot \boldsymbol{n})\, ds - \int_D F(\phi) dV = \sum R_i(\phi)$ (sum over cells)

Arrays and data structures:

Let $CV(1{:}\mathrm{N}) = \{\rho, (\rho \boldsymbol{v}), (\rho E)\}$, for each cell 1-N, so that $CV(i) = \{\rho_i, (\rho \boldsymbol{v})_i, (\rho E)_i\}$

Let $CV_{\mathrm{bulk}}(1{:}5) = \frac{1}{V_D}\{\rho_i V_i,\, (\rho \boldsymbol{v})_i V_i, (\rho E)_i V_i\}$, where repeated indices imply sums over cells

Let $R1(1{:}5, 1{:}N) = d_t\, V_i \frac{(Z-1)}{Z} CV$, this quantity is for each CV and each cell := $R1_i(\phi)$

Let $R2(1{:}5, 1{:}N) = (Z-1)\frac{V_i}{V_D}\bar{R}(\phi)$, one for each CV for each cell := $R2_i(\phi)$

Let $R3(1{:}5, 1{:}N) = \frac{(Z-1)}{Z}\frac{V_i}{V_D} d_t V_D\, CV_{\mathrm{bulk}}$, no sums, one for each CV and cell := $R3_i(\phi)$

***Rocflu* routines:**

RFLU_TimeZoomComputeBulkVars - This straightforwardly computes the CV_{bulk} array. There is an additional array computed in this routine that is not mentioned here because it is not used (yet). Luca may have use for it in future implementations of time zooming. (namely, the TimeZoom%CvdVdtBulk array)

RFLU_TimeZoomSumResiduals - This computes the $\bar{R}(\phi)$ term by $\sum R_i(\phi)$

RFLU_TimeZoomAddSource - The big cheese. This one calculates and applies the source terms, $\overline{R}1, R2,$ and $R3$, to each $R_i(\phi)$, so that each cell's RHS is modified as follows:

$$R_i^{'}(\phi) = R_i(\phi) - R1_i(\phi) + R2_i(\phi) + R3_i(\phi)$$