Regenerator-Displacer Modeling in SINDA/FLUINT

February 20, 2008

Overview

This document has two purposes:

1. To provide guidelines for regenerator modeling using SINDA/FLUINT
2. To demonstrate three completely different methods of creating the same SINDA/FLUINT model (any of which could be used as starting points for a new regenerator model since they have all been created parametrically):
   a. text-based input file
   b. Sinaps® diagram, and
   c. Thermal Desktop®/FloCAD® CAD drawing.

A hybrid regenerator-displacer device used in a single-stage Gifford-McMahon (GM) cryocooler will be modeled, although the results are applicable to stationary regenerators as well.

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The models are available for inspection (www.crtech.com), so the descriptions are not exhaustive.

The organization of this document is as follows:

> First, the concept of a regenerator-displacer (R-D) will be described, along with details of the particular R-D to be modeled.
>
> Second, a summary of the corresponding SINDA/FLUINT model will be presented (the full user's manual is available at www.crtech.com for reference), along with key results.
>
> Next, a summary of the application of each of the modeling environments (text, Sinaps, FloCAD) to this problem will be provided.
>
> Significantly, variations of this model that were explored (but not presented) will be also briefly described. Perhaps this information will help future users avoid dead-ends. However, it is more likely that some of these alternatives might even be needed for other regenerators or for other design scenarios (even different RPM). Therefore, any "conclusions" implied by the presentation of the final model are not firm: they are suggestions only.

Regenerator-Displacers

Stirling cycle and Gifford-McMahon (GM) cycle engines, the *displacer* is the piston on the cold (heat input end) of the device. GM cycles also use *regenerators*, as do many Stirling cycles … at least those intent on achieving the highest possible thermodynamic efficiency. In fact, regenerators are also key features in pulse-tube cryocoolers, a derivative of a Stirling cycle that lacks a displacer

Regenerators are porous bodies, usually cylindrical in shape, through which fluid passes back and forth in a periodic motion. They are often made either of packed (but not sintered) beads, or screens stacked perpendicular to the flow direction. Regenerators are hot on one end, and cold on the other. An ideal regenerator maintains that temperature gradient, heating fluid as it enters one direction, and cooling it when it flows in the other direction.

In one variation of the GM cycle, the displacer is also the regenerator: the “regenerator-displacer” is a cylinder containing a porous material. This porous cylinder is driven back and forth between the cold end (say of a cryocooler, perhaps used in a vacuum pump or sensor cooling application) and the hot end where heat is rejected (by exhausting out the low pressure port).

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In a paper by Kimo Welch (http://www.genvactech.com/Vac_Technologies/Vac_Tech_Article_1.htm), the action of a single-stage R-D is nicely summarized in the figure below:

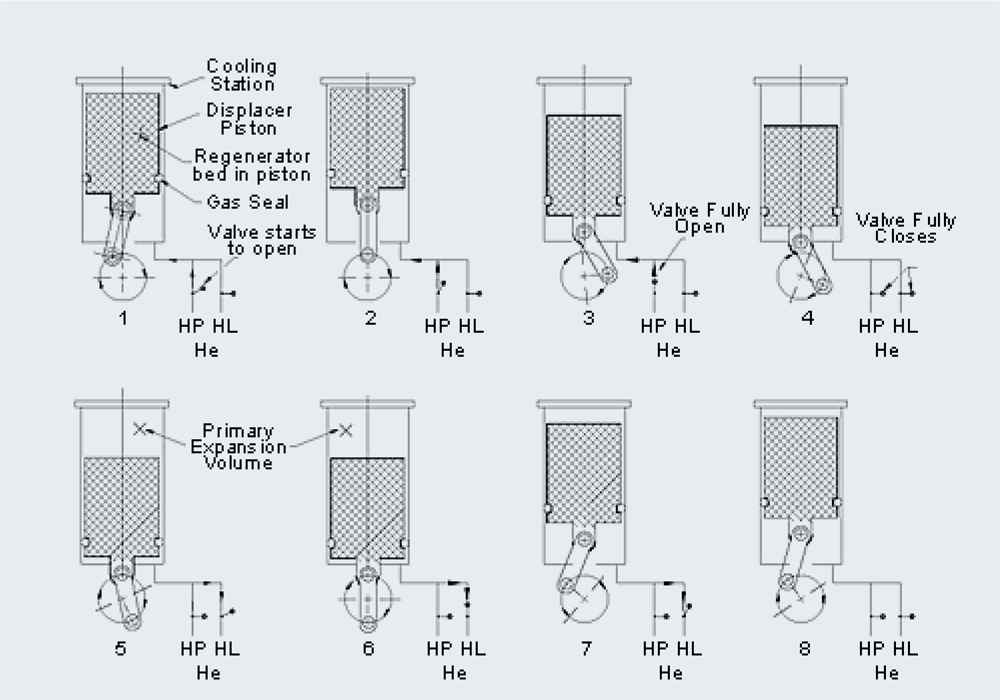

Figure 2. Displacer Operated in Forward Direction Kimo M. Welch

In order to investigate modeling techniques, a SINDA/FLUINT model of the above regenerator-displacer was constructed. In order to demonstrate the various tools with which such a model can be built, executed, and interpreted, three variations of this model are available:

1. An ASCII text file
2. A Sinaps model
3. A Thermal Desktop (FloCAD) model

These models and the associated documentation, which included recommendations for methodology, are available by clicking [URL].

The starting point for the model to be developed is represented by diagram 2 in the above figure, corresponding to a crank angle of zero degrees with the cold volume at its smallest, the warm volume at its largest, and the source (HP) valve just starting to open.

The Regenerator-Displacer to be Modeled

A single-stage helium GM cycle will be investigated, and the R-D consists of lead shot. In this system, the details of the compressor and heat exchanger are neglected by idealizing the inlet and the outlet to be represented by constant temperatures and pressures. The dynamic seal is also assumed to be perfect. The no-load (adiabatic) condition is sought, and parasitic heat leaks through the canister wall are neglected.

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In the following table, appropriate SINDA/FLUINT register names that are used in the subsequently described model are listed. Note that the units in the model may differ from those reported in the table, and this is noted in the Register Name column if so.

Parameter	Value	Units	Register Name
	GM Cycle		
Speed	75	rpm	rpm
Source Pressure	400	psia	Phi (in Pa)
Source Temperature	300	K	Thi
Sink Pressure	200	psia	Plo (in Pa)
	Lead Shot Properties (assumed constant[1] for now)		
Conductivity	34	W/m-k	Klead
Effective conductivity[2]	0.34	W/m-K	KeffLead
Density	11350	kg/m^3	Rlead
Specific heat	130	J/kg-K	CpLead
Bead diameter	1/45	inch	Dbead (in cm)
	Regenerator-Displacer		
Regenerator permeability	2.3e-10	m^2	Plead
Regenerator porosity	40%	-	PorDisp
Displacer diameter	6	cm	Ddisp (in m)
Displacer length	15	cm	Ldisp (in m)
Displacer stroke	2.5	cm	DispDisp (in m)
Gap at zero degrees (hot end)	1.25	cm	GapHot (in m)
Gap at 180 degrees (cold end)	0.2	cm	GapCold (in m)
	Valves		
Valve opening, max	2.5	cm^2	AvMax (in m^2)

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[1] Expanding the model to include temperature-varying and even anisotropic (e.g., stacked screens) properties is trivial but distracting.

[2] This is estimated as 1% of the total, taking into account that the beads contact poorly and at small points with large constriction resistances. Ideally, this value should be measured empirically.

Valve opening, min	0.0025	cm^2	AvMin (in m^2)
Valve cam schedule, inlet	0-90	degrees	(sinusoid assumed)
Valve cam schedule, exhaust	150-300	degrees	(sinusoid assumed)

Thermohydraulic Modeling Challenges

Regenerator modeling presents various challenges to off-the-shelf, general-purpose thermohydraulic solutions such as SINDA/FLUINT. SINDA/FLUINT is capable of solving a wide variety of fluid phenomena with as few or as many simplifying assumptions as the analyst wishes to apply. However, these solutions occur either in the time domain (as transients), or as time-independent steady-state solutions. There is no option for solving in phase space. Therefore, a regenerator poses the following problems:

- A transient solution is intrinsically required: no time-independent state exists which is of any use to the designer. The fact that the diffusivity of the regenerator material is of critical importance to the designer provides a validation of the need to work in the time domain.
- Furthermore, a *cyclically converged solution* is required, meaning that several (at least two or three, but potentially hundreds) of cycles must be analyzed before the N^{th} cycle is the same as the $(N-1)^{st}$ cycle. In other words, any guessed initial conditions must be "washed out" by performing the transient analysis of many crank rotations, with only predictions of the final cycle of interest to the analyst.
- Having to work in the time domain for each cycle means needing to take at least one hundred time steps per cycle, since otherwise important events would be missed during each cycle. Combining this with the above requirement means that from thousands to tens of thousands of time steps might be required to achieve predictions for one design point.
- Large gradients within the regenerator dictate a minimum spatial resolution as well, and this compounds the above computational cost.
- The copious heat transfer area between the material and the fluid must be taken into account. This could actually help simplify the model if it is large enough, but otherwise it can present another numerical challenge: splitting the analytic hairs between the temperature of the local fluid and the co-located regenerator material.

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It might seem adequate to find methods that can achieve answers for one design point in a few hours of computation. However, rarely would such information be of value, since such models *themselves* must be iterated to (1) calibrate them against available test data, (2) test sensitivities and uncertainties, and (3) perform sizing studies. For example, the engineer might want to find the optimum regenerator design (including valve timing), perhaps itself based on a computationally intensive criterion such as cool-down time from room temperature. Speed will always be important.

Because of the above challenges, an investigation was undertaken to discover what were the minimum required[3] modeling techniques that could be applied to a specific problem: a single-stage regenerator-displacer in a simplified GM cycle. To keep the problem tenable, a 1D response (gradients in the axial direction only) was assumed adequate, although implications of extension to a 2D or 3D model are summarized where applicable.

The following section describes the baseline model. A section at the end of this document describes possible variations.

A SINDA/FLUINT Model

Given the above challenges, it is gratifying that a model could be developed which executes fast enough (between about a minute on a PC) that it can itself be exercised repeatedly as necessary for parametric explorations.

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The model is available for inspection, as described later. Therefore, only a summary of important topics will be documented here.

The model uses standard SI units: m, Pa, sec, kg, J, etc. (In FloCAD, the drawing itself can be in different units, but the underlying SINDA/FLUINT model will be generated in either standard SI or US Customary (“English”) units.)

Two submodels were used: a thermal submodel *regen*, and a fluid submodel *helium*.

Thermal Model

The thermal model consists simply of a linear (1D) string of *diffusion nodes*, representing a porous cylindrical section that has been subdivided into 30 axial

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[3] The chosen design is generic to avoid intellectual property concerns. Because test data is therefore unavailable, “minimum required” was defined analytically: any measure that decreased accuracy (including any simplifying assumptions) *and* that significantly affected the results was discarded. Conversely, any simplification that made no significant effect on results was retained. Please keep in mind that these conclusions are very likely to be specific to the specific design investigated, and that some amount of methodology exploration will be needed when these models are applied to *any* new designs (or even to the same design if exposed to a different set of boundary conditions).

sections. 29 axial *linear conductors* between these 30 nodes represent the weak conduction (per *KeffLead*) in the packed shot.

Because the thermal load on the cold head has been neglected, as has the canister itself, no further thermal structure is needed.

The lead thermal properties are approximate, and can be easily replaced (or updated to include temperature dependencies) with more accurate data.

<u>Setting the initial temperatures of this stack of regenerator nodes was critically important in reducing run times.</u> Recall that many transient cycles must be integrated before initial conditions are "washed out" and cyclic convergence is achieved. Normally, thermal initial conditions can be guessed, and isothermal is a frequent choice. Therefore, there are not many software options for setting more complex initial conditions (other than imported them from prior analyses). However, in this case significant computational savings can be achieved by starting from a better guess of the initial temperature profile within the regenerator. As few as 5 cycles can then be integrated (corresponding to just a few seconds of "real time") to achieve the desired result, whereas with more "lazy" initial conditions, as many as a few hundred cycles might be required.

For the regenerator, a simple linear temperature profile suffices as an initial condition. The profile will transition from the hot temperature (*Thi*=300K, based on the temperature of the heat exchanger outlet) to the cold temperature (*Tlo*=50K, guessed then corrected based on earlier runs). A little Fortran-based user logic (placed in OPERATIONS) is the best way to accomplish this. An alternative is to apply results from an earlier run using the various restart options available in SINDA/FLUINT and Thermal Desktop. Even if the earlier run is different, the temperature profile is likely to be close enough to accelerate convergence.[4]

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Regenerator Fluid Model

Real gas helium is used, based on data from NIST's REFPROP program.[5]

The regenerator fluid model consists of an HX (duct) macro (or the equivalent FloCAD or Sinaps "Pipe"). This macro or pipe consists of 30 *tanks* (finite control volumes) and 31 *STUBEs* (zero inertia flow paths). The resolution has been picked to match that of the thermal model: each fluid control volume corresponds to a co-located thermal mass.

The heat transfer between the helium and the lead shot must be estimated, as well as the pressure drop. Built-in correlations were applied to this very low Reynolds number

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[4] This conclusion has good implications for the use of the SINDA/FLUINT Advanced Design Modules when applied to regenerators: incremental changes starting from a prior solution should converge quickly to the new solution.

[5] This FPROP DATA description, f6018NL_helium.inc, is available from C&R, as are many others. Many common fluids are kept updated on www.crtech.com

situation by treating the STUBEs as effective ducts. The flow area (AF) was set to the frontal area times the porosity, then the total bead surface area per axial length was calculated as the cross sectional wetted perimeter (*PWdisp*), setting the hydraulic diameter (DH) value accordingly as 4*AF/*PWdisp*). The actual heat transfer and pressure drop, of course, will be influenced by the Biot number of the lead beads, the tortuosity of the channels and the interruptions of the boundary layers, etc. Such factors should ultimately be calibrated using test data, and SINDA/FLUINT offers many scaling factors (e.g., UAM for tie scaling, FCLM for laminar friction scaling, etc.) and even automated methods for performing such a match between test and predictions. However, the best-guess methodology described above yielded a good match for permeability and pore size data that was available for similarly sized beads (albeit sintered). Therefore, the “equilavent duct” approach was deemed close enough for the purposes of this model.

At the bottom[6] of the regenerator, a single tank (#2) exists to represent the helium at the cold end. The volume of this tank is cycled sinusoidally using a VDOT (rate of change of volume) expression in time (where TIMEN is the current problem time) to represent the motion of the displacer.

The volume of the tank (#1) at the top (hot end) of the R-D is similarly cycled, though opposite in phase:

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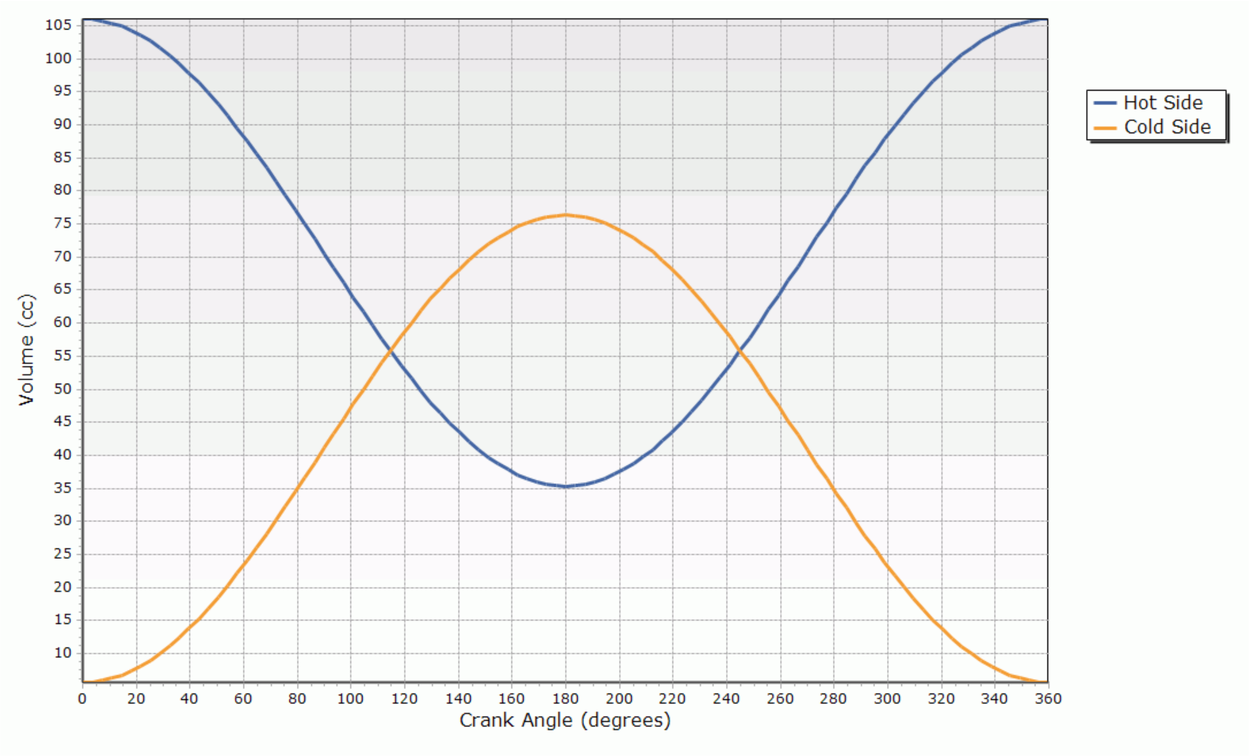
[6] Unfortunately, the depiction in Sinaps and FloCAD is upside down from that of Welch’s Figure 2. Any comments or naming schemes therefore refer to the hot end as the “top” and the cold end as the “bottom.”



Because it must accommodate various mechanical objects, this top (hot side) tank has a larger dead space (smallest volume) than that of cold side, which is as small as feasible. The hot side tank is also connected to the high pressure (HP) source, and low pressure (LP) sink by the valves, as described in the next subsection.

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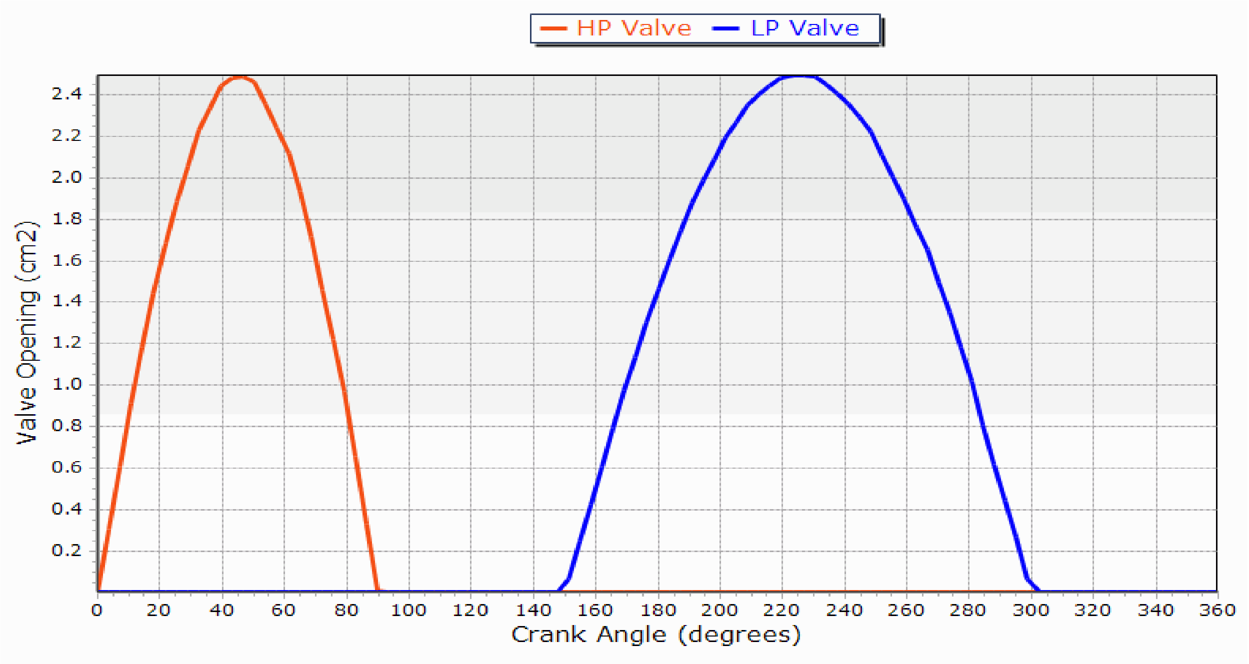
Valve Model

The valves were modeled as orifices, whose opening and closing (AORI value) was controlled as a truncated sinusoid. For example, the HP valve starts to open at zero degrees, reaches full open position at 45 degrees, and closes at 90 degrees. This was modeled as an orifice opening that moves as a sinusoid from 0 to π radians.

A sine-based expression could have been input for the valve throat (AORI values), but instead a “schedule” of valve position versus cycle fraction was specified as an array (ARRAY DATA), with the values cyclically interpolated using the D11CYL utility in FLOGIC 0. This seemingly complex method was chosen such that future analysts using these models as starting points can more easily apply any (arbitrarily complicated) description of valve motion with time.

The resulting profiles are as follows:



To avoid the need to fully close the orifice, a very small opening was allowed instead. The flow through this leak is so small as to not be of any significance to the answer.

As will be discussed later, the valve throat areas chosen were too large, causing pressures to equalize very quickly and a sudden surge to occur in regenerator flow rate each time a valve started to open. It was decided to purposely leave this “mistake” in the model in order to stress the methodology investigations: in order to avoid an overly simplified model that might not be as easily adapted to different designs or conditions.

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Execution and Output Control

To prevent the software from taking a time step greater than 1% of the period (= *1/rps* in seconds, where *rps* is *rpm/60*), the output interval is set to this value: OUTPTF= 0.01/*rps*. However, as will be described shortly, output is later disabled for all but the last cycle.

The register *cycles* contains the number of cycles to run for convergence, even though only the results of the last engine cycle are needed. *Cycles* has been set to 20, which is conservatively high: as few as 5 cycles are often adequate with good initial conditions (see “Thermal Model” above, on Page 6). To test model variations (such as new valve schedules), set *cycles*=1.

To verify convergence, a plot of key variables can be made over the last cycle. If the starting point (at zero degrees crank angle) is the same as the ending point (at 360 degrees) for all key variables, then the cycle can be considered converged and the influence of any guessed initial conditions has been eliminated.

To produce binary and text output at only the 20th cycle, and not before, the output operations in OUTPUT CALLS (in submodel *helium*) are bracketed by the conditional phrase "`if(timen .ge. 0.9999*(timend - 1./rps)) then`," where TIMEND is the problem end time, and is equal to *cycles/rps*, with 1/*rps* equal to the cycle period in seconds. The tolerancing (the factor of 0.9999) is used to make sure that both the start and end of the last cycle (0 and 360 degree positions) are captured, since otherwise the start point might be missed due to numerical round-off.

An optional text-based user file (USER1) provides a summary of key temperatures for review. (The column titles were printed in OPERATIONS.)

Results Discussion

A key output is the cycle-averaged temperature of tank helium.2, the helium temperature at the bottom (cold side) of the regenerator. The figure below shows a result of about 55K. (This is optimistic for a single-stage device, but keep in mind that the cold end has been assumed adiabatic and that not even systematic heat leaks through the canister have been included, so 55K is a reasonable result given the assumptions.)

Note that the temperatures of the lead shot are less variable than the helium next to them, as is expected.

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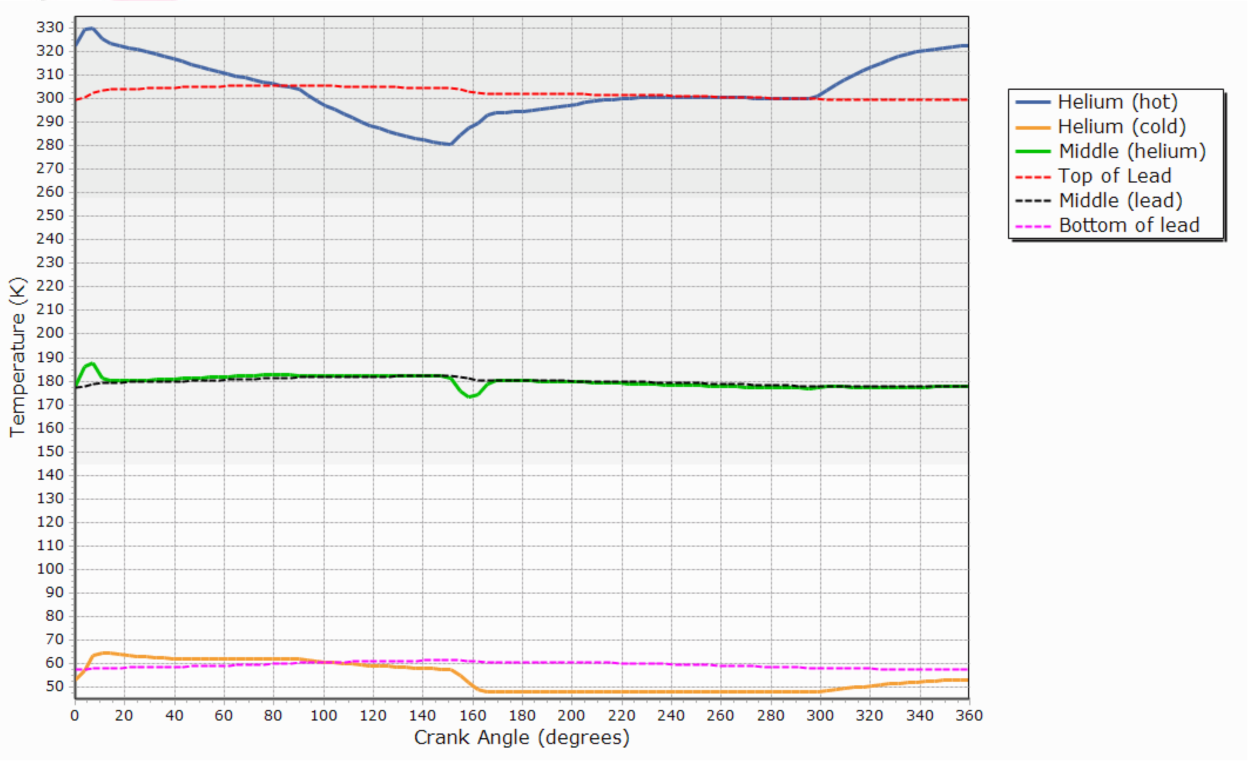
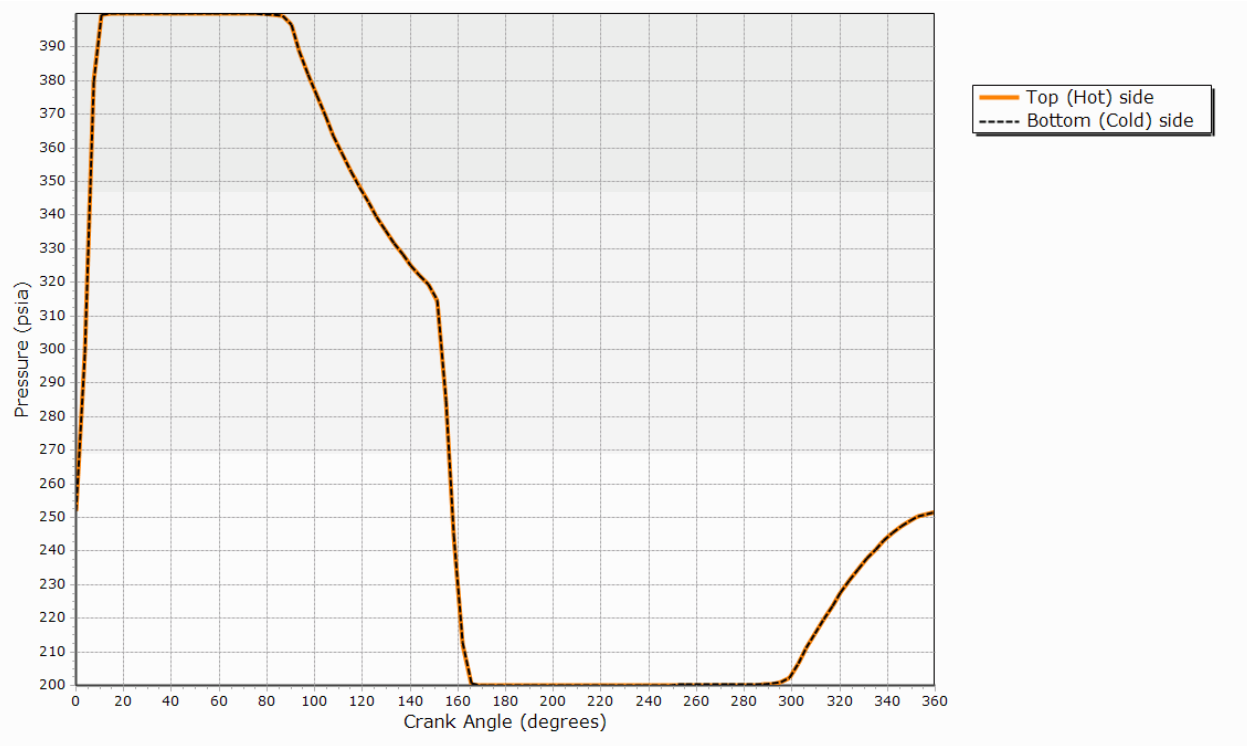


The jumps visible in the green trace above are caused by the opening of each valve, as can be also seen in the pressure plot below. At those times, pressures in the R-D matrix are equalizing with either the supply pressure (from 0 to 10 degrees) or the exhaust pressure (from 150 to 160 degrees).



This rapid equalization is caused by the aforementioned fact that the valve openings (register *AvMax*) are rather large. A noticeable jump in flow through the regenerator occurs at these points, which is not performance enhancing. The good news is that, if more realistic valve responses were modeled, the resulting model would execute even faster since SINDA/FLUINT would not have to resolve (via automatically chosen time steps) the artificial valve transients that resulted in the baseline model. It is also possible that further simplifications could be made in the model that were not feasible because of the extreme case that this “severe valve transient event” represented. It was for that reason (to err on the side of a cautiously conservative modeling approach) that this unrealistic valve throat area was not reduced.

Text Input File

It is challenging to say anything positive about a text input file, which is based on methods dating back to the 1960s and which has not been in significant use for at least the last decade. After all, text-based files are better read and written by computer programs as a way of communicating with each other, which is how Sinaps and Thermal Desktop both communicate with SINDA/FLUINT (though not exclusively).

Nonetheless, the text file is presented because (1) the entire model can be “read,” at least by those engineers which retain that skill, and because (2) the text file contains some of the variations that have been commented out.

Sinaps Diagram-based Model

Sinaps allows the user to communicate with the SINDA/FLUINT software by diagramming the thermal and fluid network on the screen. This diagram is shown post-processed (colored) below, and zoomed in (with no post-processing).

Sinaps also provides forms for providing and reviewing/editing inputs, including a tree-like (hierarchical) model browser. It also allows material properties to be defined and stored in a database, for various analysis cases to be defined within one model (whereas a text file can contain only one case).

In this model, a Sinaps pipe is used to represent the helium flow within the regenerator, with nodes (representing the lead shot) shown to the right in the figures below. The pressurization sources and valves are shown at the top of the diagrams.

Finally, Sinaps allows plots of results to be launched from within the diagram (as well as from other locations, such as from the Register edit table).

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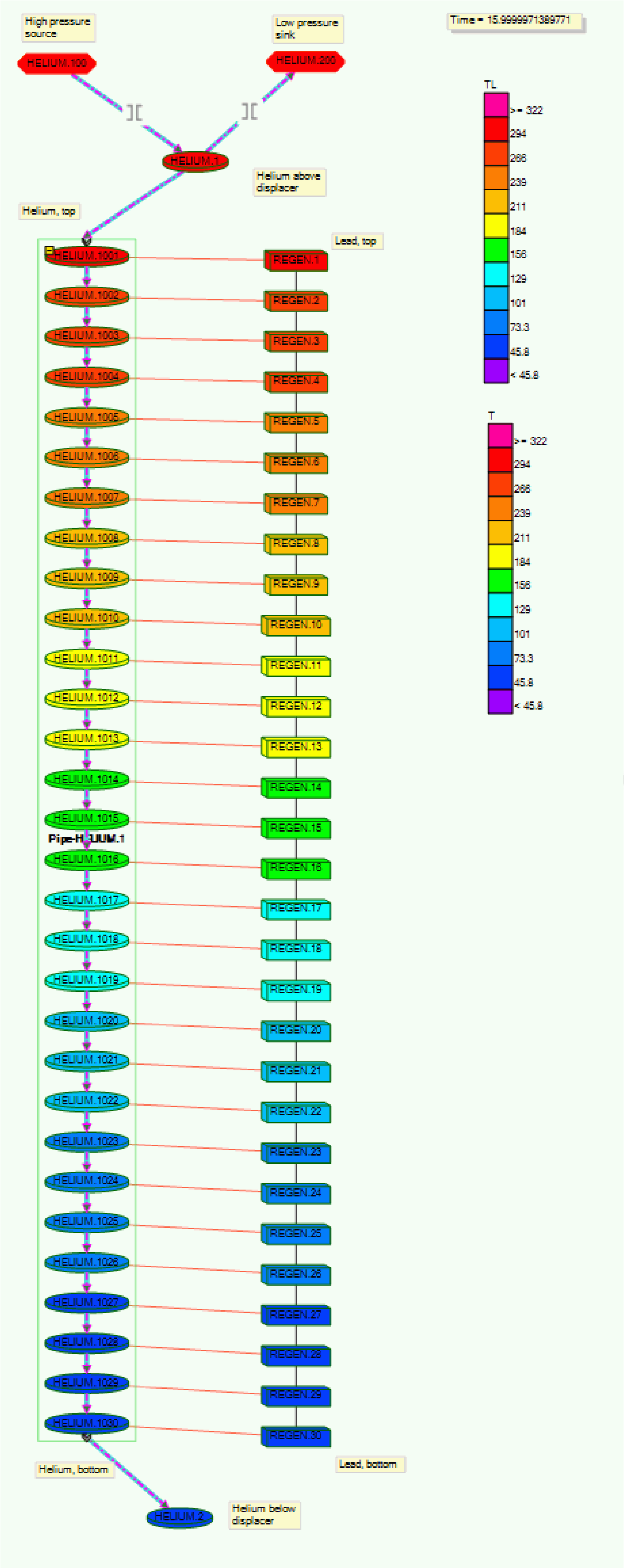
High pressure source
Low pressure sink
Time = 15.9999971389771
HELIUM.100
HELIUM.200
HELIUM.1
Helium above displacer
Helium, top
Lead, top
HELIUM.1001
HELIUM.1002
HELIUM.1003
HELIUM.1004
HELIUM.1005
HELIUM.1006
HELIUM.1007
HELIUM.1008
HELIUM.1009
HELIUM.1010
HELIUM.1011
HELIUM.1012
HELIUM.1013
HELIUM.1014
HELIUM.1015
Pipe-HELIUM.1
HELIUM.1016
HELIUM.1017
HELIUM.1018
HELIUM.1019
HELIUM.1020
HELIUM.1021
HELIUM.1022
HELIUM.1023
HELIUM.1024
HELIUM.1025
HELIUM.1026
HELIUM.1027
HELIUM.1028
HELIUM.1029
HELIUM.1030
REGEN.1
REGEN.2
REGEN.3
REGEN.4
REGEN.5
REGEN.6
REGEN.7
REGEN.8
REGEN.9
REGEN.10
REGEN.11
REGEN.12
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REGEN.16
REGEN.17
REGEN.18
REGEN.19
REGEN.20
REGEN.21
REGEN.22
REGEN.23
REGEN.24
REGEN.25
REGEN.26
REGEN.27
REGEN.28
REGEN.29
REGEN.30
Helium, bottom
Lead, bottom
HELIUM.2
Helium below displacer
TL
>= 322
294
266
239
211
184
156
129
101
73.3
45.8
< 45.8
T
>= 322
294
266
239
211
184
156
129
101
73.3
45.8
< 45.8

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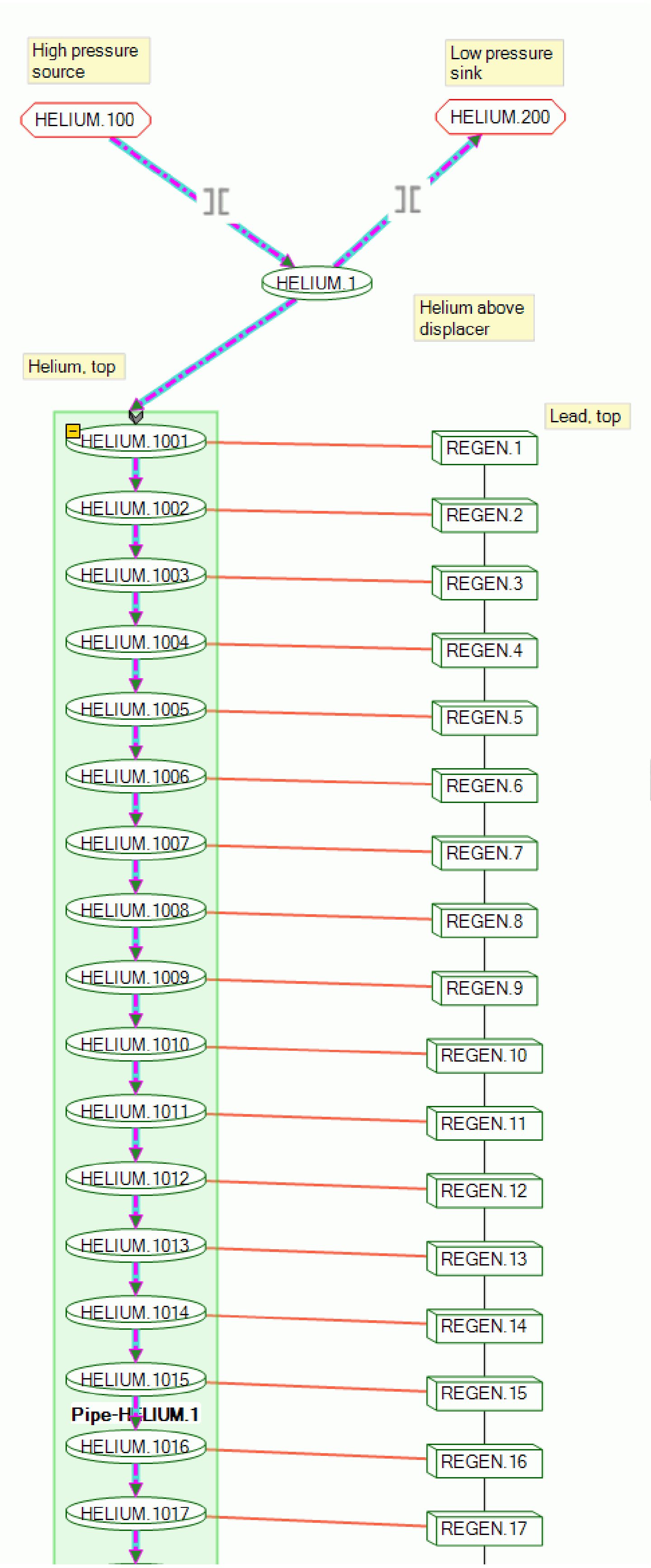
High pressure source
Low pressure sink
HELIUM.100
HELIUM.200
HELIUM.1
Helium above displacer
Helium, top
Lead, top
HELIUM.1001
REGEN.1
HELIUM.1002
REGEN.2
HELIUM.1003
REGEN.3
HELIUM.1004
REGEN.4
HELIUM.1005
REGEN.5
HELIUM.1006
REGEN.6
HELIUM.1007
REGEN.7
HELIUM.1008
REGEN.8
HELIUM.1009
REGEN.9
HELIUM.1010
REGEN.10
HELIUM.1011
REGEN.11
HELIUM.1012
REGEN.12
HELIUM.1013
REGEN.13
HELIUM.1014
REGEN.14
HELIUM.1015
REGEN.15
Pipe-HELIUM.1
HELIUM.1016
REGEN.16
HELIUM.1017
REGEN.17

FloCAD[7] Geometry-based Model

Thermal Desktop (with companion modules RadCAD for radiation, and FloCAD for fluid flow) offers all of the features listed above for Sinaps, but it goes a step further: it provided geometric-based calculations: it can help build the thermal/fluid network and provide network-level inputs based on top-level inputs.

Plain and post-processed 3D drawings of the R-D model in Thermal Desktop/FloCAD shown below make a sharp contrast with the abstract Sinaps diagrams: the cylindrical R-D is in fact constructed as a cylinder on the screen. In other words, the size and shape of the R-D was defined geometrically, so the program was able to generate the nodes and conductors representing the lead shot automatically.

The fluid model was drawn (to the right in the figures) as a FloCAD pipe. The length of this pipe is defined geometrically, and its member tanks and STUBEs are generated according to the current discretization level (axial resolution, which is 30 in this case). The diameter and flow area of this pipe were set manually, whereas in most models they are calculated by FloCAD. In fact, in most models the "wall" represented by the thermal structure is pointed to from the FloCAD pipe, and heat transfer calculations are performed automatically. However, FloCAD lacks provisions for flowing through porous media, so instead a fake (arithmetic or massless) wall of nodes was constructed in the FloCAD pipe. These nodes were then numbered identically with the corresponding nodes in the *regen* submodel. This step was taken such that these massless nodes then disappear (by automatic merging operations), overwhelmed by the mass-containing nodes of the R-D cylinder before the model is launched in SINDA/FLUINT.

Since the pipe (flow passages) and cylinder are defined geometrically, it is relatively easy to change the resolution within Thermal Desktop/FloCAD.

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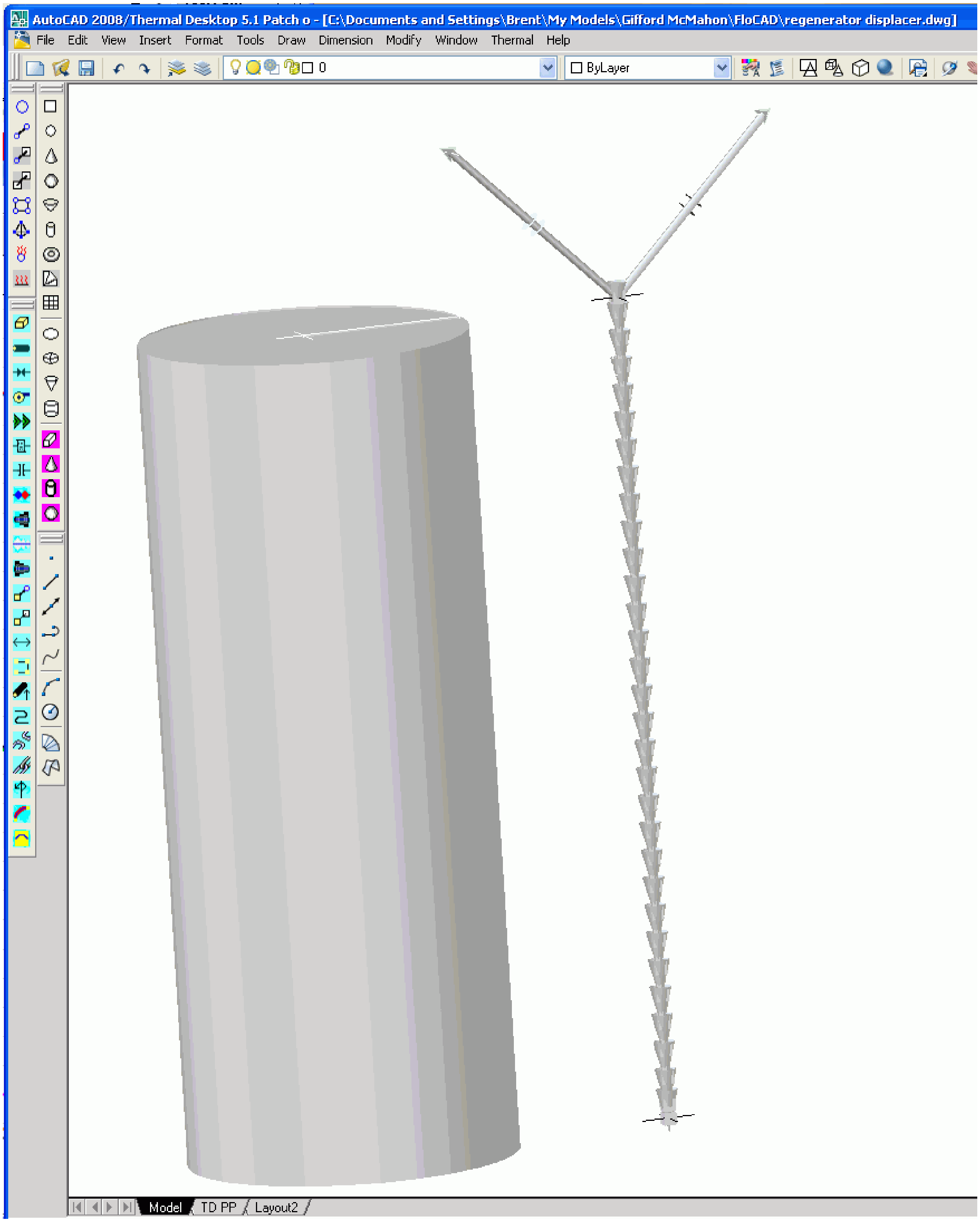
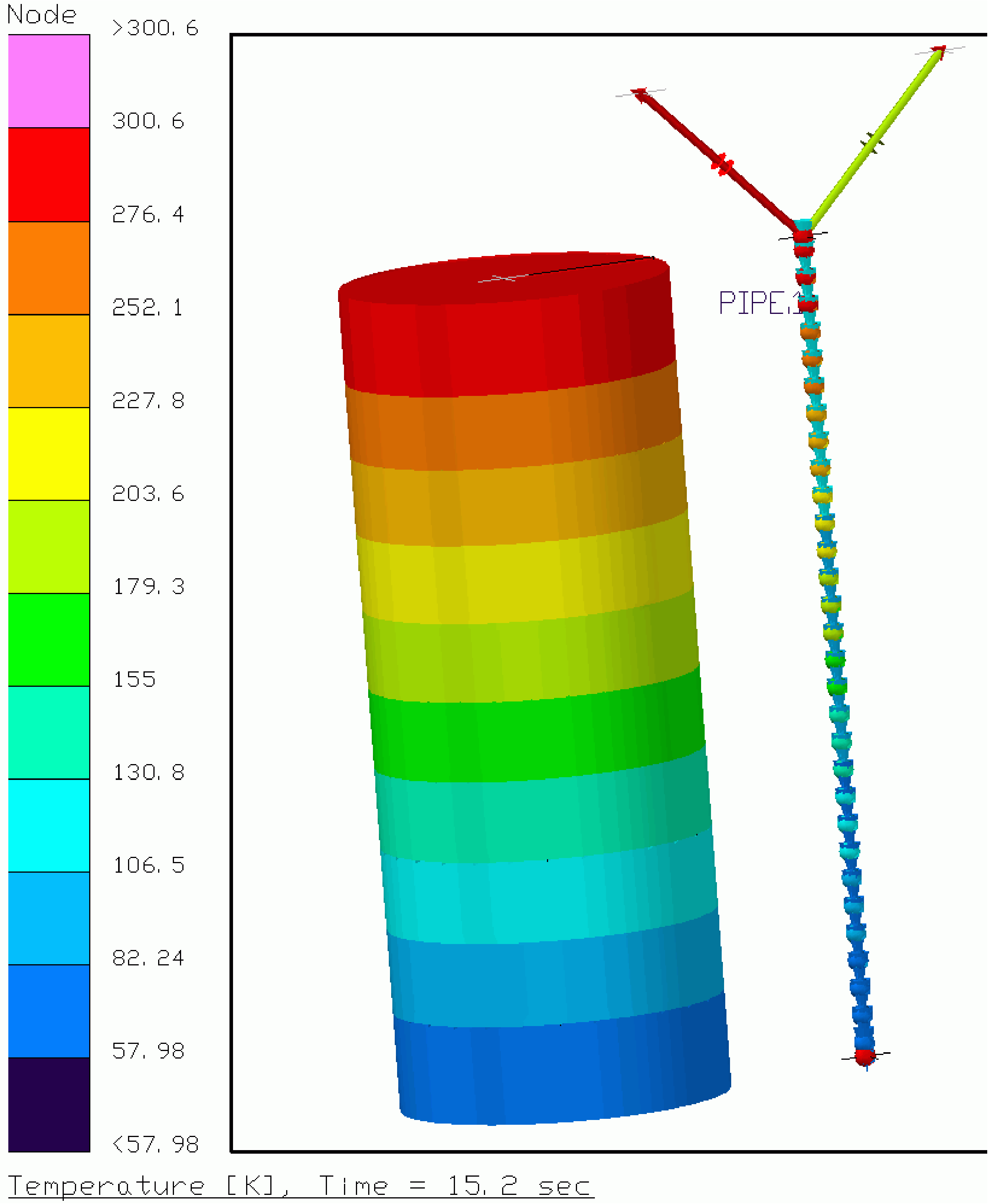
[7] Technically, Thermal Desktop plus FloCAD. RadCAD was not used in this model, although radiation is often important in most realistic cryogenic designs.

AutoCAD 2008/Thermal Desktop 5.1 Patch o - [C:\Documents and Settings\Brent\My Models\Gifford McMahon\FloCAD\regenerator displacer.dwg]
File
Edit
View
Insert
Format
Tools
Draw
Dimension
Modify
Window
Thermal
Help
0
ByLayer
Model
TD PP
Layout2



Summary of Alternatives Investigated: Roads not Taken

The presented thermal/fluid model successfully captures the significant effects of a regenerator-displacer, and does so quickly.

However, it is not the only possible way of modeling such a device, and it is unlikely to represent the best way of modeling significant variations of this device (e.g., different material, pressure levels, rpm, etc.). Therefore, a discussion of alternatives and of the sensitivities of the assumptions applied should be valuable to those engineers using these models as a starting point. In other words, if the available models are applied to new situations, some of the underlying decisions may have to be revisited.

Fluidic Options

Tubes--For helium at the relatively low pressures being considered, the inertia of the fluid is negligible. If this were not true (e.g., a long, thin regenerator using a liquid or other dense fluid), *tubes* might be required instead of STUBE connectors. For this model, tubes only add solution cost, but don't affect the answers.

FTIEs--For similar reasons, axial conduction within the fluid itself is negligible, therefore axial *FTIEs* are not needed. For short, fat regenerators using a liquid or other conductive fluid, this might not be true. For this model, FTIEs only add (relatively minor) solution cost, but don't affect the answers.

Junctions--A significant speed-up can be gained by using volume-less *junctions* instead of *tanks*. If junctions are used to represent the helium with the regenerator, then half that volume should be added to each of the end volumes so the effects of the total volume are not lost.[8] The elimination of volume within the regenerator is a significant assumption, since it not only neglects the mass changes of the helium within the regenerator due to temperature or pressure, it also makes the implicit assumption that the mass flow rate is a constant (in space, but not in time). In other words, if junctions were used, the mass flow rate into the regenerator at the current entrance would exactly equal the mass flow rate at the exit (though the flow rate could vary during the cycle).

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Unfortunately, this assumption was not appropriate for this system. However, the use of junctions instead of tanks might be applicable in other cases, although it is difficult to suggest exactly in which cases this statement might be true. Fortunately, it is trivial to switch between tanks and junctions in the pipe (or HX macro) and, if the results don't change significantly, to take advantage of the speed improvements that result.

One-dimensional response--The validity of the 1D assumption itself can be questioned. For most stationary regenerators, a 1D assumption is very good. In fact, the intent of stacked screens is to make the regenerator respond as a 1D device. For regenerator-displacers, the 1D assumption can be questioned because of the seals: fluid will enter and exit the regenerator at the sides, taking a short cut along the sides of

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[8] Inspection of the expressions used for these volumes will reveal this term (`0.5*PorDisp*Ldisp`), and that it was zeroed out in the final model.

the piston and therefore making the fluid velocities at least a 2D field. While a 2D or even 3D flow field *can* be analyzed in the above approach, the generation of the fluid model is cumbersome, and the solution speeds can be expected to drop significantly (by at *least* an order of magnitude).

At some point, such a scientific approach might yield to an engineering approach: take into account the lack of true 1D behavior via test-based correction factors applied to a 1D model. It is even possible to correct the simulations of a 1D model based on a few solutions of a slower (and therefore less frequently exercised) 3D model.

Axial Resolution

For the current design, an axial resolution of 30 is adequate: 40 or 50 subdivisions do not appreciably affect the answers. However, *this number should be revisited with any significant change to either the design or the operating conditions*. All of the models are built to enable easy changes to the resolution to facilitate such investigations, with those variations being easiest to apply within the FloCAD and text file versions.

Infinite Convective Heat Transfer within the Regenerator

The heat transfer area between the fluid and the metal in the regenerator is huge, and the conduction/convection lengths are incredibly short: the convective heat transfer coefficients are enormous despite the laminar flow. Under most circumstances, the temperature difference between the lead shot and the helium next to it is less than a degree: much less than the temperature difference axially.

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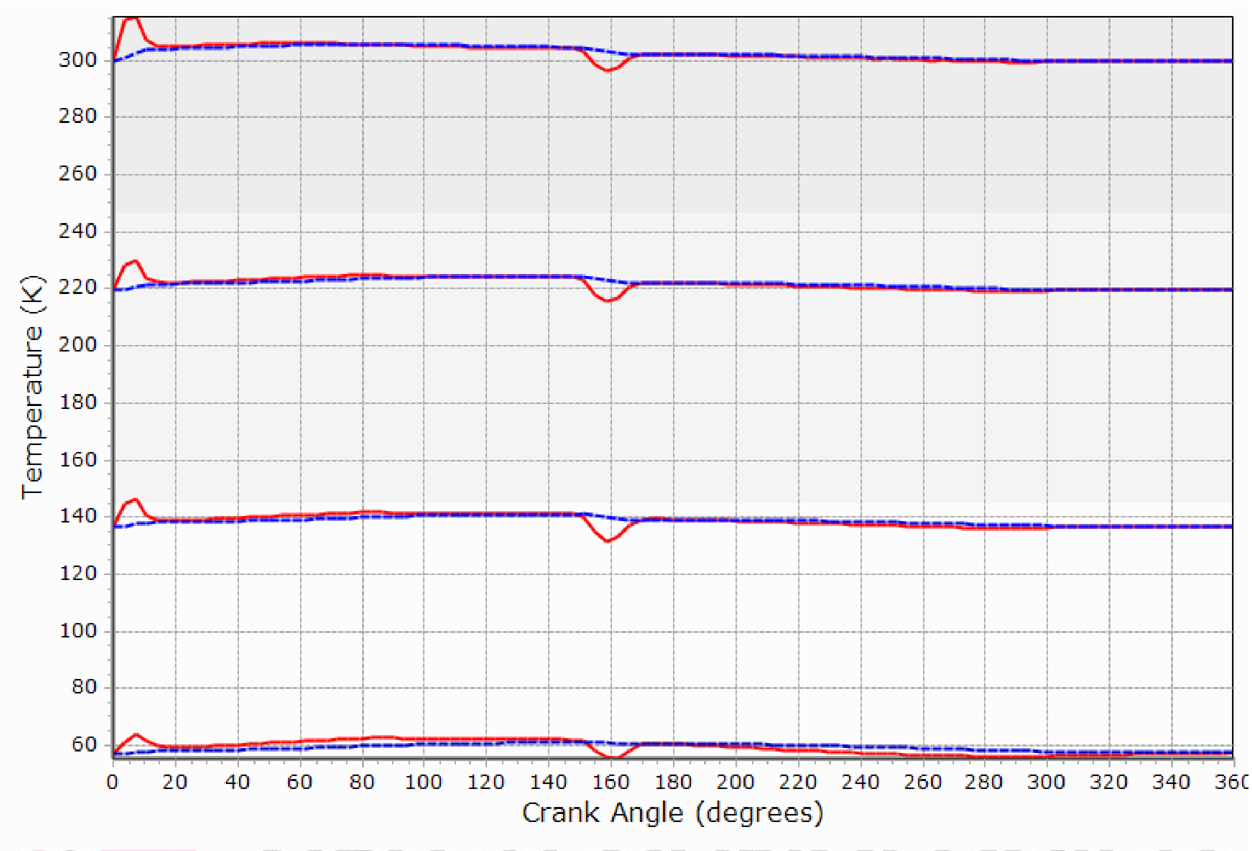
Temperature profiles of helium (solid, red) versus lead (blue, dashed) are presented at 4 locations through the regenerator:



The only exceptions to the above observation (that of fluid and metal temperatures being the same at any location) are (1) when the valves crack open and the flow rate pulses, and (2) within the first millimeter or two of the *current* entrance. The first (temporal) case would be eliminated by a more realistic valve model, but also does not last for very long in any case: it represents a short fraction of the total cycle as can be seen in the above plot. The second (spatial) case for inlet variations only affects a very small portion of regenerator, and again not for the entire cycle.

Why is this observation important? If the flow is truly 1D, and if (like the use of junctions described above) the flow rate can be assumed to be spatially (but not temporally) constant through the regenerator, then a very significant approximation can be made:

> The fluid model can be replaced by a simple superposition of an advection term to the thermal model if the distinction between helium and lead temperatures is negligible (i.e., if the convective heat transfer within the regenerator is infinite).

In other words, the motion of helium through the regenerator can be removed from the *helium* model and relocated to the *regen* thermal model as an advection (“material flow”) term, with the nodes in the thermal model now simultaneously representing both the helium and the lead at the same geometric location.[9]

Specifically, if the flow rate and entrance temperatures can be predicted (using a much-reduced fluid submodel consisting of end tanks[10] and a pair of CAPIL connectors to represent the flow resistance of the regenerator[11]), then those factors can be applied to a superimposed set of one-way SINDA conductors.[12]

The speed-up of the resulting model is tremendous: almost an order of magnitude, even with greatly increased axial resolution. Unfortunately, in the particular case investigated, the “infinite convective heat transfer” assumption was *not* appropriate: a full fluidic solution was required.

However, this conclusion may not be the true for other designs or operating points, and the tremendous speed-up that results is worth the attempt. Perhaps correction factors can be applied to yield the same result as the more complete solution, in the same way a faster 1D model can be corrected based on a few 3D solutions. (As was mentioned above, SINDA is replete with opportunities for applying correction factors, and it features methods for calculating them based on available test data.) Or, this “fast but approximate advection model” might be used to explore a wider design space parametrically, with the more complete solution used to perform final verifications and fine-tuning.

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[9] For the extra careful analyst, the thermal mass of those nodes can be increased slightly to cover the gain of helium mass, whose Cp is significant even if its density is not. This gain would have to assume either a constant or a temperature-dependent mass of helium. It is unlikely to be worth the bother, but this hasn’t been verified.

[10] Enlarged as they are in the junction case (above) as needed to conserve total volume.

[11] Comments in the text file version reveal these CAPILs and the HTRLMP call to the junction in the middle.

[12] Comments in the include (insert) file reveal the one-way conductors used to model advection. In the FloCAD model, use the Advection tab in the R-D cylinder to define the helium flow. However, since that option by default would cause lead to flow instead of helium, a parallel (and again, with identically named nodes to force an automatic merge) “cylinder of helium” would have to be constructed.