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Propulsion Applications of the NASA Standard General Purpose Thermohydraulic Analyzer

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ABSTRACT

The NASA standard tool for thermohydraulic analysis, SINDA/FLUINT, includes thermodynamic and hydrodynamic solutions specifically targeted at the growing demand for design and analysis of liquid propulsion systems.*

Applications in this field have included:

- Helium pressurization system design
- Cryogenic line chill-down transients
- Regenerative nozzle cooling
- Cryogenic turbomachinery chill-down transients
- Hydrazine line filling
- Feedline transients, including pogo suppression
- Feedline anti-geyser design
- Cryogenic tank pressurization and discharge, including thermal stratification, dissolved pressurant, and capillary liquid acquisition devices

Many organizations have previously used separate in-house tools specialized for each of the above applications. However, these organizations typically do not have the resources nor infrastructure to maintain these codes when cognizant engineers are lost, nor to modify and validate them for new vehicles or applications, nor to train new engineers on their use.

The use of a single general-purpose tool to encompass all such analyses offers not only solutions to the above problems, but also enables integrated analyses and the ability to communicate with vendors and customers.

INTRODUCTION: THERMAL/FLUID NETWORKS

SINDA/FLUINT[1] is a network-style analyzer. This means that while it solves large complex sets of simultaneous differential equations, the user does not *directly* define the equations to be solved. Rather, these equation sets are *indirectly* built by the user by instead specifying networks (circuits) of generalized modeling elements, which in turn generate the equations to be solved. These equations vary during the course of the solution (e.g., steady state vs. transient formulations, single-phase vs. two-phase formulations, etc.), but the network does not. Thus, the network becomes a user interface concept: the user need not concern themselves with the math as much as thinking about which building block is needed where.

Complex hardware can be modeled using these generalized building blocks. This approach, plus an extremely flexible and extensible architecture, explains the long term success of SINDA/FLUINT in a wide variety of industries.

OVERVIEW OF THE PROGRAM

SINDA/FLUINT is the NASA-standard heat transfer and fluid flow analyzer for thermal control systems. Because of its general formulation, it is also used in other aerospace specialties such as environmental control (ECLSS) and liquid propulsion, and in terrestrial industries such as electronics packaging, automotive, refrigeration, and power generation.

SINDA/FLUINT is used to design and simulate thermal/fluid systems that can be represented in networks corresponding to finite difference, finite element, and/or lumped parameter equations. In addition to conduction, convection, and radiation heat transfer, the program can model steady or unsteady single- and two-phase flow networks,

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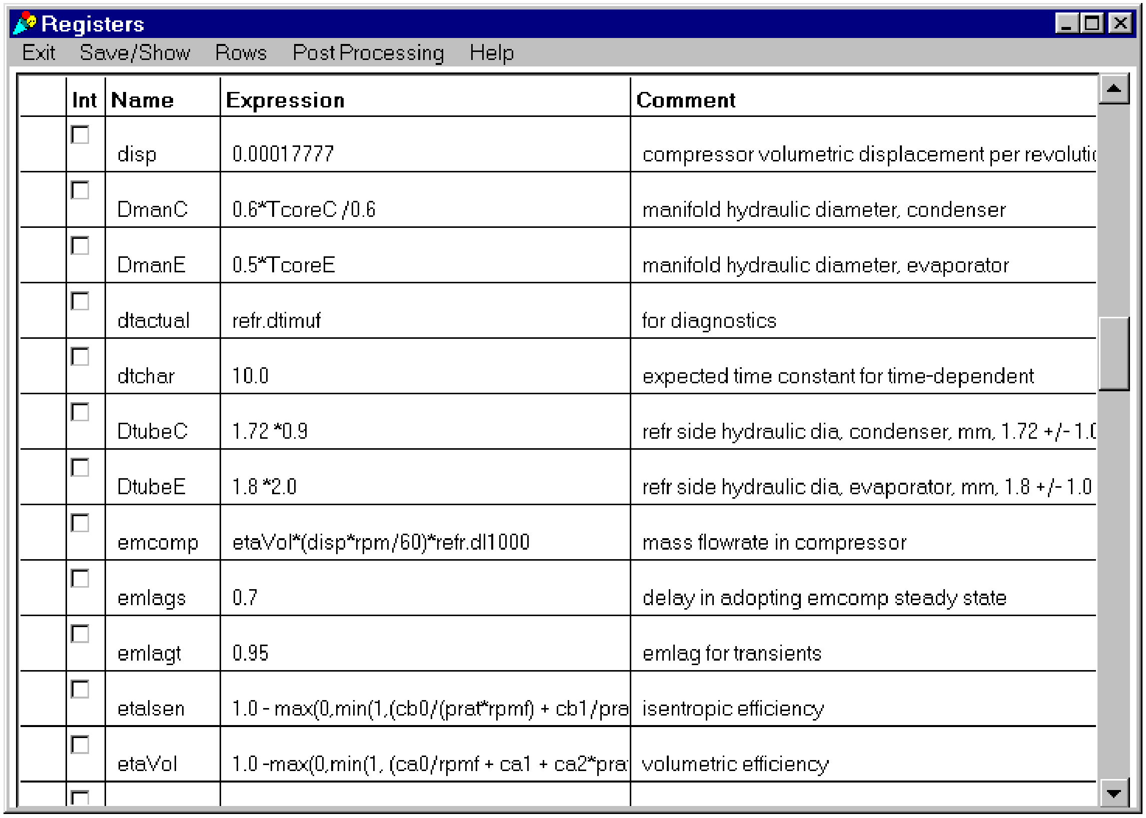
* Applications have also been made to electric propulsion systems and thermal propulsion systems, but discussions of these uses are beyond the scope of this paper.

including nonreacting mixtures and nonequilibrium phenomena.

A built-in spreadsheet enables the user to define custom (and perhaps interrelated) variables (Figure 1). The user can also define complex self-resolving interrelationships between inputs, and also between inputs and outputs. This spreadsheet allows rapid and consistent model changes, minimizes the need for user logic, and makes parametric and sensitivity studies trivially easy to perform. Top-level modules automate design, optimization, test data correlation, reliability estimation, and robust design (reliability-based optimization) tasks, far exceeding the capabilities of traditional steady and transient analyses.



	Int	Name	Expression	Comment
	☐	disp	0.00017777	compressor volumetric displacement per revoluti
	☐	DmanC	0.6*TcoreC /0.6	manifold hydraulic diameter, condenser
	☐	DmanE	0.5*TcoreE	manifold hydraulic diameter, evaporator
	☐	dtactual	refr.dtimuf	for diagnostics
	☐	dtchar	10.0	expected time constant for time-dependent
	☐	DtubeC	1.72 *0.9	refr side hydraulic dia, condenser, mm, 1.72 +/- 1.
	☐	DtubeE	1.8 *2.0	refr side hydraulic dia, evaporator, mm, 1.8 +/- 1.0
	☐	emcomp	etaVol*(disp*rpm/60)*refr.dl1000	mass flowrate in compressor
	☐	emlags	0.7	delay in adopting emcomp steady state
	☐	emlagt	0.95	emlag for transients
	☐	etalsen	1.0 - max(0,min(1,(cb0/(prat*rpmf) + cb1/pra	isentropic efficiency
	☐	etaVol	1.0 -max(0,min(1, (ca0/rpmf + ca1 + ca2*pra	volumetric efficiency
	☐			

Figure 1: Part of the Built-in Spreadsheet: User-defined Registers

Concurrent developments have made these features more accessible. C&R's Sinaps*Plus*® is a complete nongeometric (circuit sketchpad) pre- and postprocessor for SINDA/FLUINT. C&R's Thermal Desktop® (with the optional RadCAD® radiation analyzer) is a geometric (CAD/FEM/FDM) interface that brings traditional thermal modeling practices into a concurrent engineering environment. A freely distributed plotting program is also available: EZ-XY™.

SINDA

SINDA uses a thermal network approach, breaking a problem down into points at which energy is conserved (*nodes*), and into the paths (*conductors*) through which these points exchange energy via radiation and conduction. While often applied as a lumped-parameter modeling tool, the program can also be used to solve the finite difference (FDM) or finite element (FEM) equations for conduction in appropriately meshed shells or solids. In Thermal Desktop, for example, one can employ finite difference, finite element, and arbitrary (lumped parameter) nodes all within the same model.

An important improvement over ancestral versions of SINDA is the inclusion of submodels, which enable analysts to subdivide a large network of nodes and conductors into collections of subnetworks consisting of nodes, conductors, or both. Submodels represent a convenient means of combining separately developed models, each with its own control variables, customization logic, solution method, and perhaps conflicting node and conductor numbering schemes. More often, they are simply used to improve the organization and legibility of the model, or to perform high-level simulation manipulations such as dynamically swapping sets of boundary conditions, evaluating alternate designs or components, or simulating variable configurations.

Solutions may be performed in single- or double-precision without any model or logic changes. Also, either iterative or simultaneous (optimally reordered sparse matrix) solutions may be used in steady-state or transient analyses. SINDA/FLUINT provides a powerful means for creating highly customized solution schemes by permitting the user to vary the underlying methods on a submodel-by-submodel basis.

FLUINT

To answer the need to model two-phase fluid systems and to replace the cumbersome and limited “one-way conductor” methods employed by ancestral versions of SINDA for fluid flow simulation, FLUINT development was initiated by NASA in the 1980’s as a major expansion of SINDA. All major development has been completed, providing unmatched thermohydraulic analysis capability. Thermal and fluid models may be used alone or together to solve conjugate heat transfer problems as typically found in thermal control, propulsion, and energy systems.

FLUINT introduced a new type of submodel composed of network elements*, lumps* and *paths*, which are analogous to traditional thermal nodes and conductors, but which are much more suited to fluid system modeling. Unlike thermal networks, fluid networks are able to simultaneously conserve mass and momentum as well as energy.

Lumps are subdivided into *tanks* (control volumes), *junctions* (volumeless conservation points, instantaneous control volumes), and *plena* (boundary states). Paths are subdivided into *tubes* (inertial ducts), or *connectors* (instantaneous flow passages including short ducts [*STUBE* connectors], valves, etc.).

In addition to lumps and paths, there are three additional fluid network elements: *ties*, *fties*, and *ifaces*. Ties represent heat transfer between the fluid and the wall (i.e., between FLUINT and SINDA). Fties or “fluid ties” represent heat transfer within the fluid itself. Ifaces or “interface elements” represent moving boundaries between adjacent control volumes.

Paralleling SINDA while at the same time extending the SINDA design philosophy, FLUINT models can be constructed that employ fully transient thermohydraulic solutions (using tanks and tubes), or that perform pseudo-steady transient solutions (neglecting perhaps inertial effects and other mass and energy storage terms using junctions and STUBE connectors), or that employ both techniques at once. In other words, the engineer has the ability to approximate or idealize where possible, and to focus computational resources where necessary. Like SINDA, full access is provided in logic and in spreadsheet relationships not only to the basic modeling parameters (dimensions, properties, loss factors, etc.), but also to derived or abstract solution parameters (e.g., the exponent on flow rate of the friction coefficient), and to underlying correlations for heat transfer, pressure drop, etc.

Although the user can build models of custom parts and control systems, prepackaged tools are provided for modeling common components such as pipes, pumps, valves, filters, accumulators, etc. Table 1 presents the overall organization of SINDA/FLUINT modeling tools.

Single- or two-phase flow can be modeled either for pure components (e.g., steam and water), for nonvolatile/noncondensible mixtures (e.g., air and oil), and for condensible/volatile mixtures (e.g., air and oil and steam and water). Gases can dissolve into or evolve from the liquid phases according to saturation relationships and finite rate mass transfer. Up to 26 nonreacting substances can be mixed within each fluid submodel, and up to 25 fluid submodels can be used.

Two-phase flow is by default homogeneous (uniform velocity: equal liquid and gas velocities) and in phasic equilibrium (perfectly mixed: equal temperatures and pressures between phases). However, it is a simple matter to elect the prediction of flow regimes, to model slip flow (unequal liquid and gas velocities), to model phasic nonequilibrium in quasi-stagnant volumes and within duct flows, and to model nonequilibrium expansions in valves, orifices, and venturis.

Table 1: SINDA/FLUINT Hierachy of Modeling Options

- **THERMAL/FLUINT MODELS**
  - **Registers, Expressions, Spreadsheet Relationships**
  - **Concurrently Executed User Logic**
  - **Thermal Submodels**
    - *Nodes*
      - Diffusion (finite capacitance)
        - Temperature-varying
        - Time-varying
      - Arithmetic (massless: instantaneous)
      - Boundary (constant temp.)
      - Heater (constant temp., returns power)
    - *Conductors*
      - Linear (conduction, advection)
        - Temperature- and time-varying
      - Radiation
        - Temperature- and time-varying
    - *Sources*
        - Temperature- and time-varying
  - **Fluid Submodels**
    - *Lumps*
      - Tanks (finite volume)
        - Twinned tanks (nonequilibrium modeling)
      - Junctions (zero volume: instantaneous)
      - Plena (constant temperature, pressure)
    - *Paths*
      - Tubes (finite inertia)
        - twinned tubes (slip flow)
      - Connectors (zero inertia: instantaneous)
        - short tubes (STUBEs)
          - twinned STUBEs (slip flow)
        - valves
          - check valves, control valves
          - pressure regulating valves
        - K-factor losses, bidirectional or not
        - pumps, fixed or variable speed
        - constant mass or volumetric flow rate
        - capillary elements (CAPILs)
    - *Ties* (heat transfer)
      - user-input conductance
      - program-calculated convection conductance
    - *Duct macros* (subdivided pipelines)
    - *Capillary evaporator-pumps* (CAPPMP macros)
    - *Ifaces* (control volume interfaces), w/ or w/o inertia
      - flat (zero pressure difference)
      - offset (finite pressure difference)
      - spring (i.e., bellows, etc.)
      - spherical bubble
      - wick (liquid-vapor within porous structure)
    - *Fties* (fluid-to-fluid ties)
      - axial in a duct
      - user-input conductance
      - constant heat rate
    - *Auxiliary Utilities*
      - choked flow detection and modeling
      - waterhammer and acoustic wave modeling
      - compressors
- **SOLUTIONS**
    - **Steady-state**
    - **Transient**
    - **Goal Seeking**
    - **Design Optimization**
    - **Test Data Correlation**
    - **Reliability Estimation**
    - **Robust Design**

Unique features such as time- and direction-varying body forces and capillary device models are important to the aerospace industry. Because they are unique, such tools have found uses in nonaerospace applications such as modeling rotating machinery.

IMPORTANCE OF IDEALIZATION AND ABSTRACTION

One common pitfall of using SINDA/FLUINT is that it is *too* powerful: it provides the ability to model very complex physics (e.g., nonequilibrium two-phase heat and mass transfer with dissolution). When engineers lack the ability to include some physical phenomenon, they often dismiss it as negligible perhaps adding margins or conservatisms to compensate. However, the opposite is also true: when provided with the ability to avoid making such an assumption, engineers are tempted to include the more detailed physics just in case it matters.

Also, being visual beings, most engineers' attempts to model complex hardware such as pogo suppression chambers and capillary acquisition devices are frustrated by excessive fidelity to the design geometry. Simplifying abstractions often result in much more efficient models that answer the required questions quickly.

Fast executing simplified models are often more valuable than slow executing high-fidelity models. They can be used to explore design sensitivities or uncertainties using parametric analyses or statistical design methods (using the Reliability Engineering module), or to size or select components (using the Solver optimization module), or to automatically correlate uncertainties to test data (using the Solver correlation module).

The ability to make intelligent modeling decisions and to avoid asking the wrong questions (and thereby getting side-tracked by unnecessary detail), requires a knowledge of both the design and SINDA/FLUINT.

Examples of abstractions and idealizations are included below in the discussions of each propulsion application.

FLUID PROPERTIES

Fluids may be assumed to be ideal or real. Perfect gases are sometimes adequate for pressurant gases, and fluids such as hydrazine are often modeled as simple nonvolatile liquids. Otherwise, the capability exists to provide full-range descriptions covering the real gas regime, the supercritical regime, and of course the two-phase regime. This data can be supplied in the form of tables, functions or equations, or even calls to existing property databases.

Often, for the sake of execution speed, preprocessing programs are used (linked to libraries such as MIPROPS, ALLPROPS, GASPROPS, REFPROPS and other NIST databases) to create tabular property descriptions.

Once defined, a fluid can be used alone or in combination with other fluids to create mixtures (e.g., as oils or gases added to a volatile substance).

Data for almost all pressurants and propellants is available, so few engineers will have need to create their own SINDA/FLUINT-compatible fluid descriptions.

PRESSURIZATION SYSTEM DESIGN

The modeling of pressurization systems is relatively straightforward because the flow is single-phase, albeit compressible.

The pressurant (usually helium) can either be assumed to be a perfect gas or a real gas. There no limits to the number of bottles, lines, valves, orifices etc. nor to their layout. Fans and compressors may also be included if applicable.

The valves may be pressure regulating valves, or may include arbitrarily complex control logic using formulae or concurrently executed user logic. Choking may be detected and modeled at any valve or orifice in the system, and multiple points can choke simultaneously.

Connections to the thermal environment can be extensive if needed: SINDA, after all, started out as a heat transfer code. Thus, the effect of temperature on the bottles and all components is relatively easily included.

While pressurization system models are often executed in a stand-alone fashion, the capability also exists to incorporate models of the fuel and oxidizer tanks for simultaneous high-level solutions. Cryogenic tank modeling is described below.

CRYOGENIC LINE CHILL-DOWN TRANSIENTS

Because of its ability to simultaneously solve for transient two-phase flow and heat transfer to a wall (which itself may be connected to an arbitrarily complex model of the surroundings), one of the first propulsion applications of SINDA/FLUINT was the prediction of filling an evacuated, warm line with cryogenic fluid. Validations have been made against data for a vacuum-jacketed copper line being filled with liquid hydrogen and nitrogen.

As with pressurization system modeling, this application is easily performed using *duct macros*: axially discretized models of piping segments. These macros automatically include phenomena such as axial variations in density, flow regime, and heat transfer coefficient.

Integration with a supply tank model and an engine model is also possible.

Additional details such as slip flow (the vapor velocity allowed to be faster than the liquid velocity) are easily modeled.

Also, it is easy to include the violent hydrodynamics within the line itself: enabling the flow rate to also vary axially. (This involves the selection of *tanks* instead of *junctions*.) This election is usually only appropriate for determining dynamic loads on the pipe and valves. Otherwise, the computational cost of this election is inappropriate if the design question is simpler: How much cryogen will flow before the exit is 100% liquid?

On the other hand, even more detail may be needed to model large-diameter horizontal cryogenic lines in which the flow stratifies and the top part superheats. In such cases, the pipe wall may need to be circumferentially subdivided and full two-phase nonequilibrium options may needed. Such a model solves the momentum, energy, and mass of each phase separately.

REGENERATIVE NOZZLE COOLING

SINDA/FLUINT may also be applied in models of nozzle cooling systems using the fuel or oxidizer as the coolant, including analyses of distributions and instabilities in parallel lines. Because such applications are very similar to line chill-down analysis, no further details need be provided here.

CRYOGENIC TURBOMACHINERY CHILL-DOWN

A more complicated variation of line chill-down includes a model of a turbopump. Such models tend to be detailed (large number of building-block elements in the networks) both because of the complexity of the solid and fluid passages involved, but also because of the heat transfer coefficients required. The default system for predicting heat transfer coefficients is based on pipe flow (nucleate boiling, in the case of chill-down analyses) and is largely inappropriate for turbomachinery.

Like any parameter in SINDA/FLUINT, the capability exists to augment or replace any heat transfer coefficient by supplying factors, equations, or complete Fortran-coded correlations. The capability also exists to automatically correlate any such unknowns (including factors used in correlations) against test data.

HYDRAZINE LINE FILLING

In addition to freeze protection in hydrazine lines, analysis of adiabatic compression during filling of evacuated lines is a major concern and hence subject to extensive analysis.

While detailed modeling of the two-phase event is possible, a more desirable approach is to make approximations such as:

- neglecting vaporization of the hydrazine (this does not preclude the modeling of the compression of vapor or other gases at the closed end of the line)
- treating the liquid front as one-dimensional

With these approximations, the resulting analysis executes many orders of magnitude faster. In fact, the networks can degenerate into a few trivial elements as shown in Figure 2.

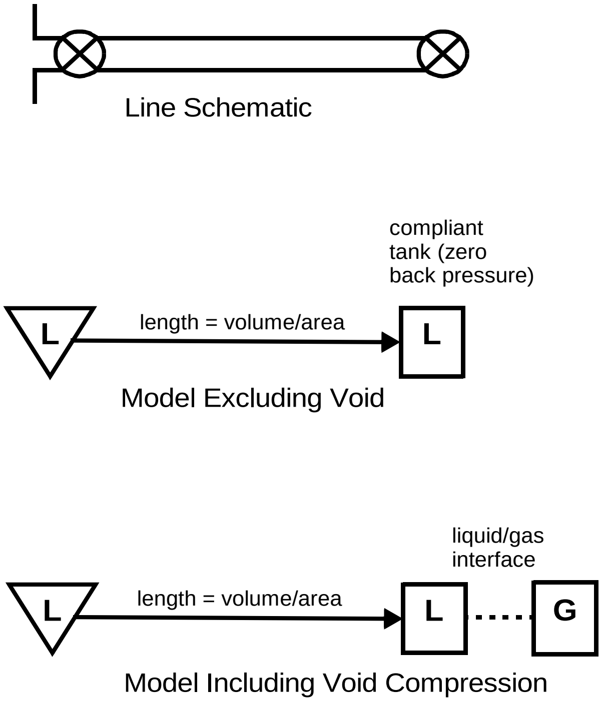


Figure 2: Simplified Hydrazine Line Filling Models

The system at the top of the figure is the line to be modeled: the left valve is opened at time zero, and the right valve remains closed. In the middle of the figure is a simple model depicting the upstream pressure as constant. The downstream pressure is essentially zero, represented by a very compliant (stretched wall) FLUINT *tank*. The volume of this tanks represents the volume of liquid in the line, and starts very small and grows as the line fills. The flow passage (denoted by the arrow) is a FLUINT *tube* represents the length of fluids with in the line. It too starts very small and grows as the line fills. In fact, its length is simply defined to be proportional to the volume of the fluid within the line:

tlen = vol#down / af#this

Although Fortran-style user logic could be used equivalently, the above means “set the length of the tube equal to the volume of the downstream tank divided by the flow area of this tube.”

The analysis adds logic to detect when the line has filled, and then lowers the tank compliance to that of the liquid and container (and any void), perhaps defining the compliance as follows:

comp = (tlen > limit)? CompReal : CompBig

If the void (vaporized hydrazine and any residual gases) is large and/or the temperature of that void is required, it can be modeled separately using a separate FLUINT tank plus a control volume interface ("*iface*") representing the flat front, as show in the bottom of Figure 2. In this case, the compliance of the liquid is zero, or perhaps at least equal to the compliance of the container piping.

FEEDLINE TRANSIENTS AND POGO SUPPRESSION

Fast transient ("waterhammer") analyses can also be performed for engine feedlines. In particular, such analyses are often concerned with transient boiling and with suppression of pressure oscillations.

Models have been built of discretized feed lines using FLUINT *tubes* and *tanks*. While by default liquids are incompressible, the compliance of each tank can be set to the liquid compressibility plus perhaps the compliance of the container piping. Also by default, FLUINT will tend to take a time step that is too large. It must be restricted to resolve acoustic effects using a utility routine. The use of SINDA/FLUINT for such applications has been validated against both analytic solutions and test data that included column separation (flashing).

Pogo suppression chambers and accumulators can also be modeled, including the dynamics of any bellows and/or the thermodynamics of any trapped gas/vapor pocket.

FEEDLINE ANTI-GEYSER DESIGN

A primary concern in engine feedline design is preventing bubbles from entering a turbopump. Also, geysers forming in the feedline can carry enough velocity to cause collapse of the ullage above. One possible solution is shown in Figure 3, in which a small diameter line is placed in parallel with the feedline to establish a circulation. The intent of this circulation is to prevent boiling in the feedline, which also prevents geysers from forming. Helium may be injected at the bottom of the smaller line to assure adequate circulation and to prevent boiling in the smaller line itself.

Like a helium bubbler, the analysis of this system can be quite complicated because of the physical processes involved. Dry helium is injected into a cryogenic liquid. The resulting bubbles evaporatively cool and shrink, perhaps dissolving helium into the cryogen while the bubbles rise upward in the line.

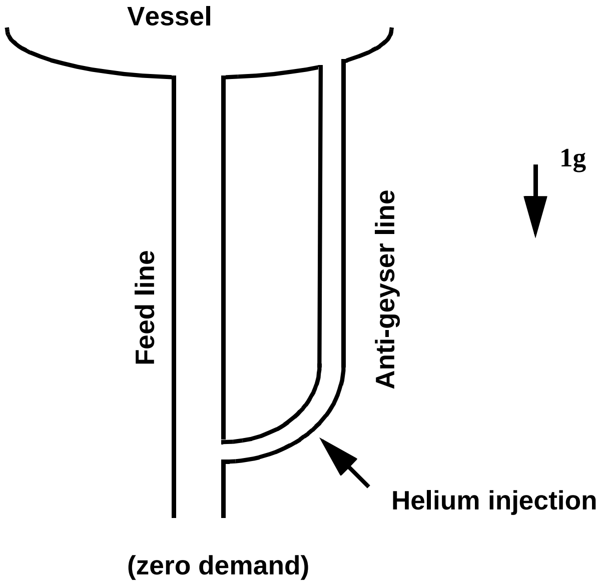


Figure 3: Schematic of Anti-geyser System

The flow rate in the line is proportional to the difference in densities between the two lines, and this may ultimately require the modeling of slip flow distinguishing between bubbly and slug flow. Near the top of the lines, the diminishing hydrostatic pressure may permit boiling to occur.

While FLUINT is fully capable of modeling all of these processes, initial models (especially those used in preliminary design stages) should start with a few simplifying assumptions. For example:

- the dissolution of gas can probably be neglected
- presuming bubbly flow exists, slip flow may be neglected in favor of homogeneous flow
- the volatility of the cryogen itself might be neglected (this does not preclude checks against virtual boiling): the bubbles can be assumed to be 100% helium, neglecting the subcooling generated by evaporative cooling
- all two-phase aspects might be neglected for preliminary sizing of the helium flow: an effective density is all that is needed for such calculations

During steady state runs, the flow rates can oscillate wildly during the course of the solution, and the reverse flow direction may actually result.* One way around this difficulty is to assign a constant mass flow rate device (an "MFRSET") in either of the tubes. Then using either parametric runs or the goal seeking capabilities built into the SINDA/FLUINT Solver module, the value of flow rate that yields zero pressure gradient across the MFRSET is found (in other words, as if the MFRSET had never been needed for stability). Assuming a valid steady state solution has been used as an initial condition for a transient, no such manipulations are needed for transient integrations.

CRYOGENIC TANK MODELING

One of the most important uses of SINDA/FLUINT in liquid propulsion systems is predicting the pressure of cryogenic fuel and oxidizer tanks, including the consumption of pressurant gases needed to maintain adequate pressure.

PRESSURIZATION

Analysis of pressurant storage and delivery systems has been described above. This subsection describes the modeling of the injection of the pressurants into the cryogen itself. For convenience, helium is the assumed pressurant, although of course any gas could be used.

Several liquid-vapor/gas interfaces can exist within a single model of a fuel or oxidizer tank: bubbles within the liquid, droplets or films within the ullage, and of course the main liquid-vapor interface separating the fuel from the ullage.

Injection of gas directly into the liquid phase of a tank via a bubbler can be modeled either as an equilibrium process or a nonequilibrium one. In the equilibrium (equal phasic temperature) case, the analysis can still use finite rate dissolution or evolution. In any case, the fluid is not contained within a pipe and hence the built-in correlations will not be applicable. Therefore, the user will need to supply information regarding the bubble size and velocity in the form of interface surface areas and liquid-side heat transfer coefficients. Because these parameters are uncertain, a default system exists which can be used to scale the unknowns, test the sensitivity of the design to them, and to correlate them to available test data.

Similar options exist to estimate or scale the heat and mass transfer at the main interface and at any interfaces of liquid trapped within the ullage region.

If helium is injected at the top of the tank into the ullage region, then additional effects can be added such as the diffusion of helium through the vapor and vice versa.

Pressurant can exist within the ullage of course, but it can also dissolve into the fuel itself. In this case, the user can model this effect by providing a saturation relationship between the solvent (cryogen) and the solute (helium). Multiple solvents and solutes can exist in a single system. Each saturation relationship can be defined using Henry's coefficients, Raoult's law, Ostwald coefficients, or tables of concentration versus partial pressure and temperature.

A built-in model exists for handling bulk evolution: the homogeneous nucleation of pressurant in response to a sudden drop in pressure. Heterogeneous nucleation can also be modeled, as can evolution of gas within the reduced pressure of the feedline.

CAPILLARY LIQUID ACQUISITION DEVICES

A unique feature of SINDA/FLUINT is its ability to model aspects of capillary structures, such as those that might be used for zero-gravity liquid acquisition devices or baffles. Building block elements exist to model flow in devices like wicks or grooves or holes whose characteristic dimensions are small enough to stop vapor, at least up to their bubble point or capillary limit. Additional elements can model the effects of vaporization across a capillary interface, and can track the movements of the liquid/vapor interface itself.

THERMAL STRATIFICATION

Modeling thermal stratification is challenging in a one-dimensional code because the flow is quasi-stagnant. A special network element, the *iface*[2], was introduced in part to help resolve this difficulty,

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* Although nonphysical, this is a perfectly valid answer mathematically. If *can* become a physical solution with the proper initial conditions, but initial conditions are irrelevant in steady state mathematical solutions.

and has proven very successful at the task.

Thus, the liquid and/or vapor within a tank can be vertically subdivided as shown in Figure 4 using ifaces. This model includes heat transfer to wall (via *ties*), and heat transfer and diffusion vertically (via *ties* and species-specific *VFRSET paths*, respectively). Some amount of stirring can also be included, although this parameter must be specified by the user (or used as a correlation parameter). Droplets sprayed into the ullage or bubbles injected into the ullage can also be modeled.

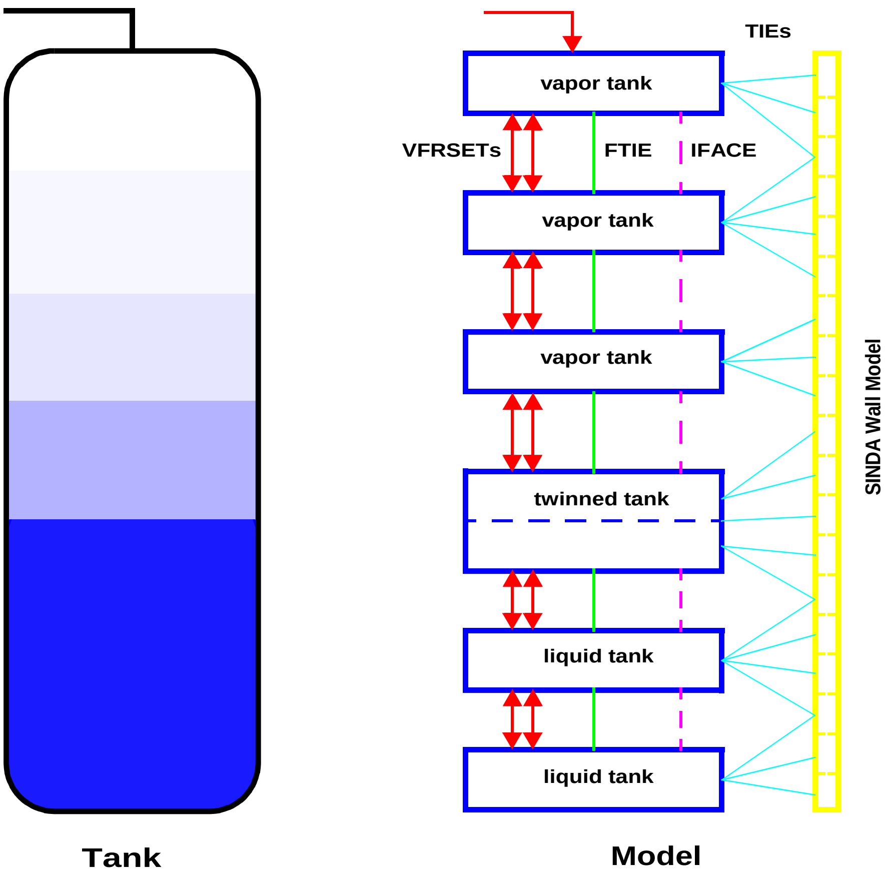

Figure 4: Example Vertically Stratified Tank

Such a model can form a centralized part of a model containing integrated models of the pressurization system, bubblers, and feedline.

CONCLUSIONS

An extensive set of generalized thermal/fluid modeling tools exists that was developed to satisfy the specialized needs of liquid propulsion system design and analysis. These tools can uniquely provide integrated modeling of an entire fuel tank system including pressurization system, feedline, and turbopump. They can also link intimately with thermal models of the structure and environment. Included are high-level design synthesis, statistical design, and model correlation modules. An extensive infrastructure exists of pre- and postprocessing software, training, and user support. While the models made using these tools might be proprietary, the tools themselves are readily available to all organizations, overcoming significant limitations of in-house codes.

ACKNOWLEDGMENTS

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User's manuals, tutorials, and training notes for all software discussed are freely available in PDF format at www.crtech.com

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