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Thermohydraulic Solutions for Thermal Control, Propulsion, Fire Suppression, and Environmental Control Systems

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ABSTRACT

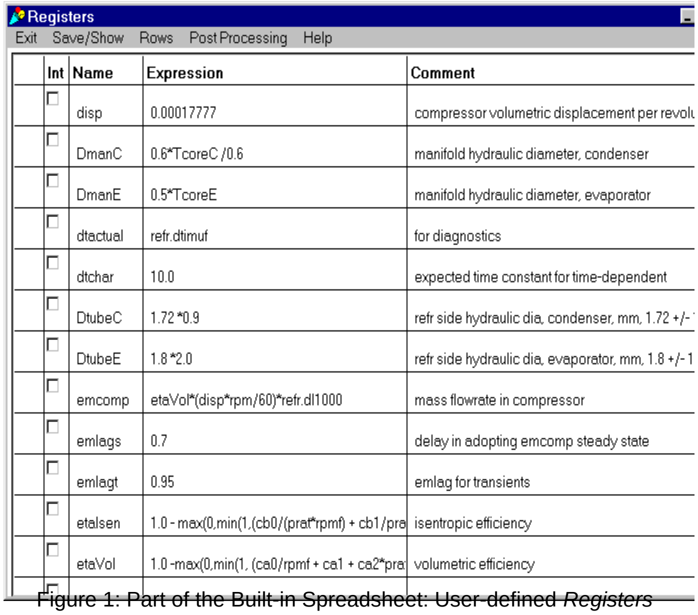
Over the past 15 years, the industry standard tool for thermal analysis, SINDA, has been expanded to include advanced thermodynamic and hydrodynamic solutions (“FLUINT”). With the recent culmination of the unique modeling tools that are described in this paper, and with concurrent expansions described elsewhere (Ref 1), SINDA/FLUINT has arguably become the most complete general-purpose thermohydraulic network analyzer that is available. These advances have enhanced the usage of the code in the areas of liquid propulsion, fire suppression, and environmental control systems (ECLSS), providing for the first time a common framework for analysis and data exchange between engineers in these otherwise distinct specialties.

INTRODUCTION: THERMAL/FLUID NETWORKS

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 the electronics packaging, automotive, refrigeration, and power generation industries.

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, including nonreacting mixtures.

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. A top-level “Solver” module automates design, optimization, and test data correlation tasks, far exceeding the capabilities of traditional steady and transient analyses.



Int	Name	Expression	Comment
☐	disp	0.00017777	compressor volumetric displacement per revolu
☐	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 +/-
☐	DtubeE	1.8 *2.0	refr side hydraulic dia, evaporator, mm, 1.8 +/- 1
☐	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 new geometric (CAD/FEM/FDM) interface that is the first to bring traditional thermal modeling practices into a concurrent engineering environment.

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.

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.

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. Nodes and lumps may be linked using heat transfer *ties*, a network element that can optionally include calculation of convective film coefficients.

Paralleling SINDA while at the same time extending the SINDA design philosophy, FLUINT models can be constructed that employ fully transient thermohydraulic solutions, or that perform pseudo-steady transient solutions (neglecting perhaps inertial effects and other mass and energy storage terms), 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. Figure 2 presents the overall organization of SINDA/FLUINT modeling tools.

SUMMARY OF PRIOR CAPABILITIES

This section briefly summarizes the prior status, which forms the basis for describing recent expansions.

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). 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 predict flow regimes, to model slip flow (unequal liquid and gas velocities), to model nonequilibrium in quasi-stagnant volumes (such as reservoirs and accumulators), and to model nonequilibrium expansions in valves, orifices, and venturis.

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.

DISSOLVED GASES

One of the most significant expansions in recent years is the ability to model dissolution and evolution of noncondensible gases into and out of liquid phases.

Equilibrium solubilities of binary solvent/solute pairs may be defined using a variety of rules (e.g., Henry’s, Raoult’s) and coefficients (e.g., Ostwald, tables of mass or mole fractions). Mixtures of multiple solvents and/or multiple solutes can then be defined. The masses of individual species are tracked through the fluid system, including trace amounts of solutes.

Explosive phenomena such as the homogeneous nucle-

- Thermal/Fluid Model
    - Registers, Expressions, and 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-varying
                - Time-varying
            - Radiation
                - Temperature-varying
                - Time-varying
        - Sources
            - Temperature-varying
            - 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
        - Ties (heat transfer)
            - user-input conductance
            - program-calculation (convection) conductance
        - Duct macros (subdivided pipelines)
        - Capillary evaporator-pump
        - Ifaces (control volume interfaces), with or without inertia
            - flat (zero pressure difference)
            - offset (finite pressure difference)
            - spring (i.e., bellows, etc.)
            - spherical bubble
            - wick (liquid-vapor interface in 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

Figure 2: SINDA/FLUINT Hierachy of Modeling Options

ation of soluble gases can be modeled. Also, finite-rate dissolution and evolution can be modeled in steady-state solutions and in transient solutions of quasi-steady elements ("junctions").

By default the code will estimate mass transfer coefficients and interfacial surface areas using knowledge of the flow regime and the interfacial heat transfer coefficients. The user can override or augment this default system, or use it to scale the results as needed to quantify uncertainties or to correlate the model to available test data.

CONTROL VOLUME INTERFACES

A new FLUINT network element, the *iface*, has been added to allow subdivision of quasi-stagnant control volumes (e.g., thermally stratified tanks). Ifaces also provide means of modeling liquid/vapor interfaces (including those in porous structures), pistons, bellows, etc. There are many subtypes of ifaces, but all share the option of adding an inertia term to cover modeling of boundaries with significant mass (i.e., a large piston, or the *added* or *virtual* mass of a liquid/vapor interface).

Whereas the previously existing *paths* describe how mass moves from control volume to control volume (as a function of pressure difference and other momentum considerations), *ifaces* describe how the boundary between control volumes moves. For example, a "flat" iface keeps the pressure equal between two adjacent control volumes by adjusting their volumes as needed.

Despite representing a new and perhaps abstract feature that is unparalleled in other fluid network analyzers, ifaces have been readily adopted by users to a wide variety of modeling tasks, and have already proven to be an important tool.

NONEQUILIBRIUM TWO-PHASE FLOW

The ability to model temperature and pressure differences between liquid and gas phases within quasi-stagnant control volumes has always been present in the code, although the robustness of these previous solutions was increased tremendously by the recent addition of ifaces (see above).

In another major expansion, this limited capability has been extended to any part of the code, including pipe flow. Normally, two-phase flow in pipes causes enough mixing to make an assumption of thermal equilibrium between phases a valid one. However, in special cases this is not true, including the propagation of pressure waves through a two-phase line, the effects of strong variations in circumferential wall temperature (especially in cryogenic systems), and the presence of large amounts of noncondensible gases, which can transiently heat or cool due to compression and expansion effects.

SINDA/FLUINT now allows any control volume, whether part of a fluid line or not, to be subdivided into liquid and vapor/gas spaces, invoking fully separate equations for heat transfer, mass transfer, momentum, energy, etc.

In thermohydraulic analysis terms, FLUINT can be used as an HEM (homogeneous equilibrium) code, as a full two-fluid code, or anywhere in between even within the same network. Such flexibility of approach is unique amongst available two-phase thermohydraulic codes, especially when coupled with the intrinsic user extensibility of SINDA/FLUINT.

MISCELLANEOUS IMPROVEMENTS

Various improvements accrue as the code is used in an ever-growing number of applications. These improvements will only be briefly listed here:

- correlations for loss factors for tees, reducers, and expanders
- user-selected flow regimes
- pressure control valves (including backpressure regulators)
- fluid-to-fluid heat transfer tools (*fties*, yet another new FLUINT network element) for modeling conduction within the fluid, important in slow-moving and/or highly conductive fluids
- significant speed improvements for large models, and for models involving complex thermodynamic mixtures
- the ability to refer to *processor variables* (outputs, control parameters, problem time, etc.) within any spreadsheet expression.

The last expansion represents the culmination of years of development in the internal spreadsheet, a database of interrelationships underlying the entire code. Complete with conditional (IF/THEN/ELSE) operators and other tools, spreadsheet expressions are replacing many uses of logic, eliminating the need to learn the rules for translation and the internal calling order. Because interrelationships are self-resolving, spreadsheet expressions exceed what can be done in a traditional logic block. Users find it much more convenient to define how a node, lump, path, etc. operates or changes directly within the definition of that element, rather than defining the element in one place and then modifying it in remote location (i.e., in a logic block).

SIMPLIFIED FLUINT MODEL BUILDER

A dedicated GUI, Sinaps*Plus* (Figure 3), has been available for SINDA/FLUINT for the better part of a decade. However, Sinaps*Plus* endeavors not to teach SINDA/FLUINT, but to make it easier to use correctly, and easier to auto-document models and hence to share them with others.

SINDA/FLUINT is intended for the heat transfer and fluid flow professional, and requires a certain investment in training both in code usage and in understanding the physical processes involved. The same wealth of options and capabilities that make it a powerful thermohydraulic analyzer can also make it appear daunting to the novice or casual user.

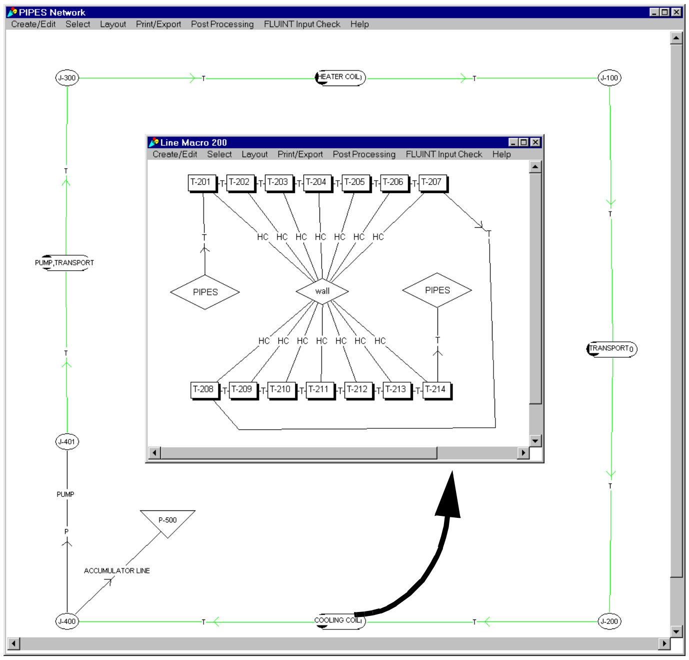


Figure 3: Sinaps*Plus* Diagram of a Fluid Loop (translated from PIPE-FLO)

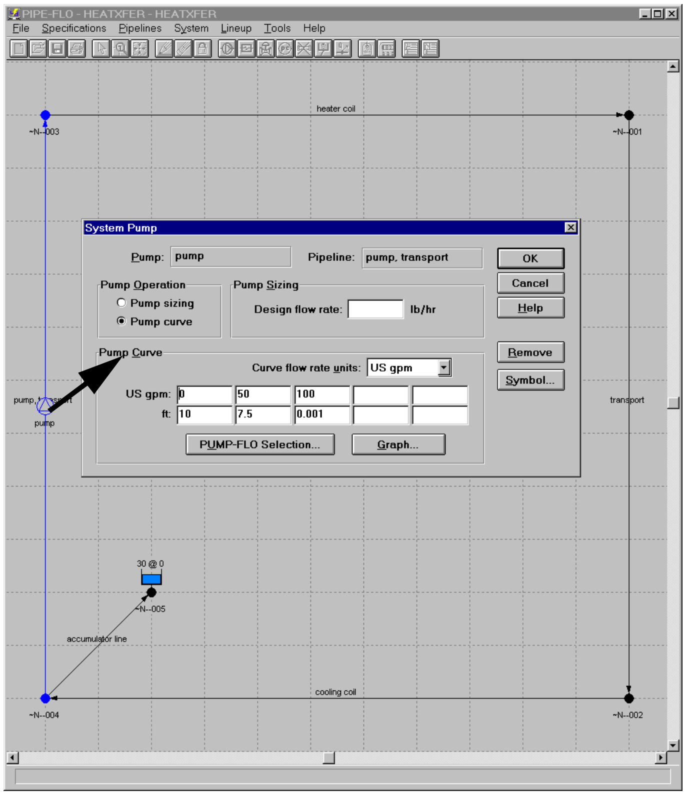
Therefore, an interface to an existing piping network analyzer, PIPE-FLO® (Figure 4), has been created and is now available. PIPE-FLO is a fast and friendly code for analyzing steady, incompressible fluid flow networks. It can be mastered in a matter of hours, and contains built-in libraries of K-factor losses for fittings and valves, as well as complete piping schedules. Supporting tools help design pumps, valves, and orifices, and accept vendor-supplied tables for pumps and other equipment. Networks in PIPE-FLO can be translated into SINDA/FLUINT models, preserving the schematic diagram itself if imported directly into Sinaps*Plus*. Figure 3, for example was created by direct translation of the model shown in Figure 4.

Together, PIPE-FLO and SINDA/FLUINT provide the rare combination of ease of use coupled with almost unlimited analytic power.

APPLICATIONS

SINDA/FLUINT is widely used for passive and active thermal control system design and analysis, and in recent years has been increasingly applied to propulsion, fire safety, and environmental control. This section briefly lists some of the applications of the *new* features in SINDA/FLUINT to specialized analysis needs within these four fields.

Applications to Thermal Control--The new features in SINDA/FLUINT track noncondensible gases within single- and two-phase fluid loops, both as bubbles and as solutes, and predict the effect of these gases on the loop performance.



Pump: pump
Pipeline: pump, transport
Pump Operation
○ Pump sizing
● Pump curve
Pump Sizing
Design flow rate: lb/hr
Pump Curve
Curve flow rate units: US gpm

US gpm:	0	50	100		
ft:	10	7.5	0.001		

Some of the new network elements, such as ifaces and fties, are particularly useful in the modeling of loop heat pipes (LHPs) and capillary pumped loops (CPLs). The ability to model almost all aspects of these specialized devices has been a strength of SINDA/FLUINT for many years.

Because of its ability to handle compressible flows, real and condensible gases, and complex heat transfer and control systems, SINDA/FLUINT has also been used extensively in recent years for modeling JT (Joule-Thompson) coolers and vapor compression cycles.

Applications to Propulsion--Many of the new features were specifically designed with liquid propulsion design tasks in mind. The new features are useful for two-phase hydrodynamic events (pogo suppression, latch valve waterhammer and line filling). But perhaps the largest range of applications is in the modeling of tank thermodynamics, including equipment and effects such as helium bubblers, liquid acquisition devices, pressurant evolution, thermal stratification, fill and feed line events, and anti-geyser lines.

Applications to Fire Suppression--The processes involved in the explosive depressurization of fire suppressant (e.g., CO_2 or Halon*) tanks, with the subsequent filling and emptying of distribution lines with choking at one or more nozzles, can be modeled by few existing tools, most of which are application- or fluid-specific. In fact, one of the validation cases for the new code came from such applications (Figure 5).

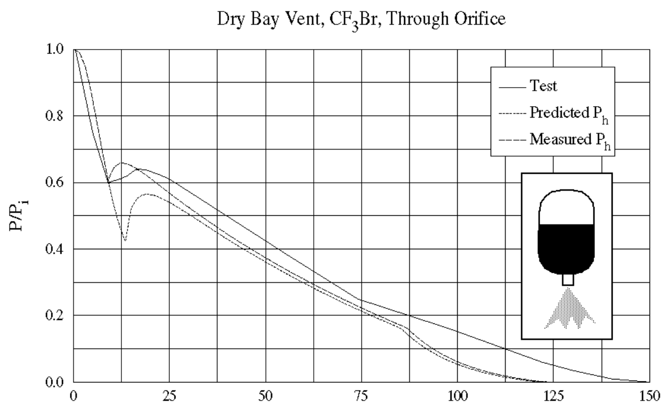


Figure 5: Validation for Modeling Rapid Discharge of Suppressant

Applications to Environmental Control--Tracking of multiple species is important to environmental control system analyses, and in particular the modeling of psychrometrics in cabins and condensing heat exchangers are common concerns. In modeling condensing heat exchangers, SINDA/FLUINT can handle not only thermodynamic (psychrometric) effects, but also diffusion-limited condensation and even dissolution of air into the condensate.

Performing such analyses using the same tools that are used in other related specialties such as thermal control provides a unique opportunity for high-level modeling of complex system interactions, and for top-level design optimization and test data correlation tasks.

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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