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Vapor Compression Cycle Air Conditioning: Design and Transient Simulation

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ABSTRACT

This paper describes the application of the general purpose SINDA/FLUINT thermohydraulic analyzer to the modeling of vapor compression (VC) cycles such as those commonly used in automotive climate control and building HVAC systems. The software is able to simulate transient operation of vapor compression cycles, predicting pressures, coefficients of performance, and condenser/evaporator liquid positions in a closed two-phase system with a fixed fluid charge. The program can also be used to size components, to estimate the impact of tolerances and other variations, and to help estimate uncertainties given limited test data.

SINDA/FLUINT (Ref 1) has a user base numbering in the thousands. It has several graphical user interfaces, preprocessors, and postprocessors; has strong links to CAD and structural tools; and has built-in optimization, data correlation, parametric analysis, reliability estimation, and robust design tools.

Nonetheless, widespread application to vapor compression cycles is comparatively recent (Ref 2), and is largely due to an increased demand for transient modeling of air conditioning systems. Toward this requirement, SINDA/FLUINT's unique abilities to analyze transient two-phase phenomena have been recognized as being critical to achieving accurate performance predictions.

INTRODUCTION: SINDA/FLUINT

SINDA/FLUINT is the standard in the aerospace industry for heat transfer and fluid flow analysis of 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, including nonreacting mixtures and nonequilibrium phenomena.

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. 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.

FLUINT

To answer the need to model two-phase fluid systems, 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 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.).

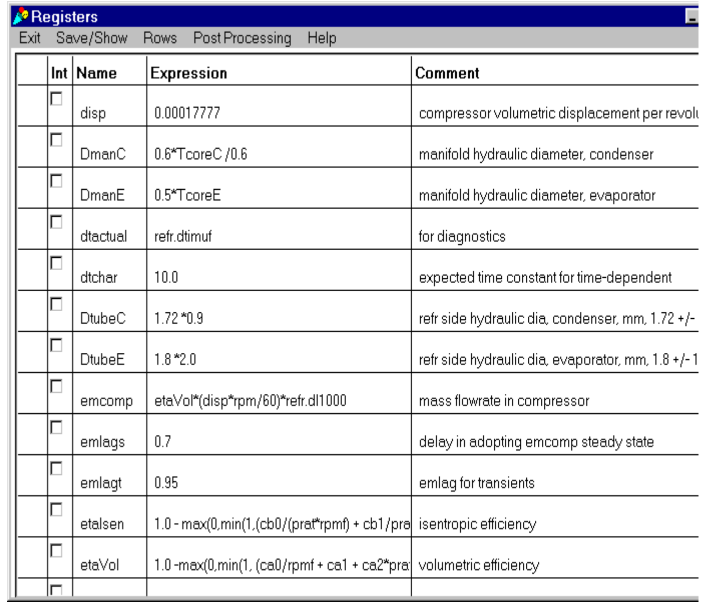
In addition to lumps and paths, there are three additional fluid network elements: *ties*, *fties*, and *ifaces*. Ties represent heat transfer between the fluid and the wall (i.e., between FLUINT and SINDA). Fties or “fluid ties” represent heat transfer within the fluid itself. Ifaces or “interface elements”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


Registers
Exit Save/Show Rows Post Processing Help

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
☐	etaIsen	1.0 - max(0,min(1,(cb0/(prat*rpmf) + cb1/pra	isentropic efficiency
☐	etaVol	1.0 -max(0,min(1, (ca0/rpmf + ca1 + ca2*prat	volumetric efficiency

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

gas velocities), to model phasic nonequilibrium in quasi-stagnant volumes and within duct flows, 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 and vehicle vibrations and accelerations.

BUILT-IN SPREADSHEET

A built-in spreadsheet enables users to define custom (and perhaps interrelated) variables (Figure 1) call *registers*. Users 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.

The ability to create a SINDA/FLUINT model whose network parameters and logic are completely controlled by a few centralized registers enables high-level modules to be added. These optimization, data correlation, and statistical design modules are described later in the paper.

ACCESSIBILITY

Concurrent developments have made advanced design features in SINDA/FLUINT 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™.

Table 1: SINDA/FLUINT Hierachy of Modeling Options

Thermal/Fluid Models

- 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 (CAPILs)
  - Ties (heat transfer)
    - user-input conductance
    - program-calculation (convection) conductance
  - Duct macros (subdivided pipelines)
  - Capillary evaporator-pumps (CAPPMP macros)
  - 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
- Reliability Estimation
- Robust Design

WORKING FLUID CHOICES

SINDA/FLUINT has a built in library of 20 refrigerants including R12, R22, ammonia, propane, and water. However, the user can specify additional fluids such as nonvolatile liquids (e.g., oils), noncondensible perfect or real gases, and simple or complex two-phase fluids.

The last category of user-defined fluids includes the ability to develop links between SINDA/FLUINT and fluids properties databases either dynamically (through subroutine calls) or statically (via table look-ups). Although users can create their own reusable fluid property files, C&R provides these files for alternate fluids created from NIST's REFPROPS and other databases. Readily available fluids of interest to air conditioning systems include R134a, R123, and carbon dioxide (including the supercritical range).

In addition to the main working fluid, additional noncondensible gases and nonvolatile liquids (e.g., oils) can be added to the mixture. The code will track each such species individually, and the effects such as changes in heat transfer coefficients will be accounted for automatically.

Although not typically required in vapor compression cycle analysis, the capability exists to model the dissolution of gases into the condensate and into any oils that might be present.

Finally, dry or moist air mixtures can be used if desired to include models of fluid-to-fluid heat exchange in the condenser and evaporators, or possibly the psychrometic response of the passenger compartment or electronics cabinet.

VAPOR COMPRESSION CYCLE COMPONENTS

This section describes the main components within a typical vapor compression cycle. Being a building-block style code, both the arrangement of the components and the methods of modeling them are variable.

COMPRESSOR

As with all devices, there are many ways to model a compressor in SINDA/FLUINT depending on the information available and the detail desired.

While some organizations have developed models focussing on the internal operation of scroll and reciprocating compressors, most analyses of vapor compression cycle treat the compressor as a "black box" given isentropic and/or volumetric efficiencies.

If the input mechanical power and the isentropic efficiency are known, a simple prepackaged COMPRS utility can be used.

However, the compressor is more commonly modeled as volumetric flow rate calculated as a function of volumetric efficiency, and an outlet temperature calculated as a function of isentropic efficiency.* These calculations can be made using the spreadsheet-style expressions, arbitrarily complex concurrently executed user logic, or any combination of the two.

With the above method, the compressor volumetric flow rate is held constant during each time step or steady-state relaxation step. A modest (approximately 25%) speed improvement can be gained by specifying not only the volumetric flow rate, but also the slope of the flow rate versus pressure gain curve such that the code can adjust the flow rate implicitly during the solution step. This slope or derivative can be calculated either in closed form equations or by perturbations (finite differencing) in user logic. This additional step is not required, but is relatively straightforward to implement.†

If none of the above methods are applicable, then the compressor performance can be specified using curve fits, interpolation tables, or what ever other performance maps are available. As long as the flow rate and either the heat rate or the outlet temperature are ultimately specified, many variations and formats are possible due to the extreme extensibility of the SINDA/FLUINT architecture.

Finally, note that compressor speed can be regulated dynamically (i.e., during the steady or transient solution) as needed either to achieve some control purpose (perhaps as simple as on/off), or as needed to match a usage or load profile of compressor speed versus time.

CONDENSER AND EVAPORATOR

Condensers, evaporators, and in fact any fluid passage in which the temperature or pressure or quality can change are modeled in SINDA/FLUINT using discretized (subdivided) chains of *lumps* (control volumes) and *paths* (flow passages), as shown in Figure 2.

These situations are commonplace, and therefore special duct macrocommands ("*duct macros*") exist to facilitate such models. (Some duct macros are shown expanded in Figure 3.)

Such an approach is fundamentally different from codes that offer a single component labeled "evaporator" or "condenser." In those models, not only is usage presumed (i.e., the evaporator can't become a condenser if heat loads reverse and the device is used as a heat pump), but the boundary conditions are simplified: heat transfer connections between components and the environment are limited to a few temperatures.

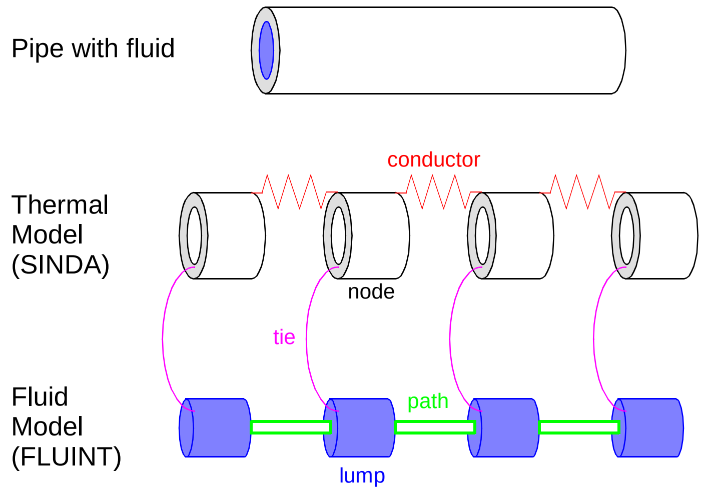


Figure 2: Discretization of a Line with Heat Transfer

SINDA/FLUINT, on the other hand, takes a "presume nothing" approach that solves the general problem, invoking default‡ heat transfer and pressure drop and flow regime mapping algorithms but otherwise letting the flow in the component resolve itself along with the rest of the system. If the wall is cold, condensation occurs. If enough condensation takes place, the liquid may be subcooled at the exit. This distinction is present for steady state solutions, but becomes critical for transient solutions.

<u>Liquid/Vapor Front Tracking</u>–One benefit of this generalized approach is that SINDA/FLUINT automatically tracks liquid and vapor within the evaporator, condenser, and elsewhere. At the exit of a condenser for example, very little heat transfer occurs in the subcooled region, which can essentially be considered "blockage," affecting the overall energy balance of the loop. Such effects are calculated automatically.

<u>Slip Flow</u>–SINDA/FLUINT is able to model slip flow: vapor and liquid flows are allowed to travel at different velocities according to the local flow regime (degree of interphase friction, apportionment of wall friction to each phase, etc.). This distinction may seem elaborate compared to a simplifying assumption of homogeneous codes, and indeed few thermohydraulic analyzers are able to make this distinction. However, it can be important for VC cycle modeling since it improves the prediction of void fraction: the relative amounts of liquid and vapor within components such as evaporators and condensers. Improved correlation to test data was found using the slip flow options, as reported in Reference 2.

* Normally, the temperature of a lump (such as the outlet of the compressor) is calculated in SINDA/FLUINT given the imposed heat rate, heat transfer, upstream conditions, etc. The HTRLMP ("heater lump") utility can be used to reverse this sequence, solving for the resulting heat rate as a function of the desired temperature.

† As part of normal usage support services, C&R can demonstrate such techniques given a specific application (i.e., compressor model). However, this method is also used in the Sinaps*Plus* prebuilt described later.

‡ These can be scaled, modified, or overridden.

Custom Heat Exchangers–Evaporators and condensers are rarely simple tubes. At the very least, they are often parallel arrays of manifolded passages. SINDA/FLUINT permits the user to model each passage explicitly, but this level of detail is usually only required for predicting manifolding efficiencies, unevenness in the external (i.e., air) flows, or perhaps unsteady oscillations* between parallel passages. For faster top-level modeling, the user may exploit "duplication factors:" modeling one typical passage and then magnifying it according to the number of actual passages.

Many of the default correlations are for circular tubes. When applied to noncircular passages, the user has the choice of applying a scaling factor (perhaps automatically correlated to test data using the Solver module described later), choosing alternate correlations, or modifying or replacing any or all of the available correlations using user-supplied logic.

Integration with Condenser Air Flow Models–The air side of the condenser can be modeled simply, or in detail. A separate FLUINT submodel can be used to described the air flow across the condenser, perhaps interpolating velocities produced by a CFD code in the case of flow through an automobile radiator. In addition, heat exchange between the transport lines and the environment (perhaps the engine compartment in automotive applications) can be included.

Integration with Evaporator Air Flow Models–As with the condenser, the air side of the evaporator heat exchanger can be modeled simply, or in detail. This model can include moist air psychrometrics, including diffusion-limited condensation. Although no prepackaged FLUINT options include a solid phase, transient condensate freezing on the evaporator coils can be modeled using user logic and perhaps a thermal (SINDA) phase change utility. The model can also be extended to include the dry or moist air environment associated with the load (passenger compartment or electronics cabinet etc.). Figure 3 presents a Sinaps*Plus* representation of a counterflow heat exchanger with an R134a evaporator on one side and moist air on the other.

THROTTLING DEVICES

Orifices and Valves–Orifices and valves are usually modeled as simple loss (K-factor) devices adding a choked flow calculation. This choked flow calculation itself has several options, but good results are usually had by assuming a nonequilibrium expansion (i.e., the liquid does not have time to flash much within the restriction) plus a metastable method for the prediction of the sonic velocity within the two-phase throat. These options are simple choices within the CHOKER utility. Of course, the user may apply any algorithms, correlations, or test data available toward the modeling of these devices.

Temperature-control valves (TXV) can be modeled as a device with variable K (where the K factor is adjusted within expressions and/or user logic, perhaps using PID controller modeling utilities). However, a simpler method is to model them as back pressure regulating valves, where the back pressure is calculated as the appropriate saturation condition in the evaporator to yield the desired compressor inlet superheat. Again, this logic can be added as an expression and/or concurrently executed user logic.

Capillary Tubes–Long thin tubes (L/D >> 50) are modeled no differently from evaporators or condensers: duct macros may be applied. In fact, the only difference is that the fluid inertia in such lines is less negligible than in condensers and evaporators, which the amount of fluid within it *is* often negligible. In SINDA/FLUINT parlance, this simply means choosing the combination of junctions (negligible small control volumes) with tubes (flow passages with nonnegligible inertia).

The heat transfer and thermal environment on these capillary tubes can be arbitrarily complex, including regenerative interconnections with other components such as suction lines.

Orifice Tubes–The performance of orifice tubes (L/D < 20) is not well modeled using the first-principles approaches implicit in the standard SINDA/FLUINT building blocks. Therefore, these devices are modeled as "constant" flow rate devices,† where the flow rate is adjusted dynamically according to a user-provided correlation (perhaps generated from test data).

TRACKING CHARGE: SELF-DETERMINATION OF PRESSURE

Rankine cycles are taught in every introductory undergraduate thermodynamic course, and the basic vapor compression cycle used in most air conditioners is essentially a reverse Rankine cycle. In such simple treatises, pressures are specified and no consideration is given to conserving working fluid mass.

In a real application, of course, the air conditioning unit is charged with a fixed mass, and the high and low pressures will vary as will the COP of the unit. The prediction of these pressures is more complicated than one might think.

* Although not usually applicable to VC cycles, it is even possible to solve unsteady two-phase flow oscillations to the point of tracking pressure waves and other short time-scale events using phasic nonequilibrium options.

† "Constant" only implies that the flow rate is invariant within each steady state relaxation step or within each transient time step. Almost every parameter within SINDA/FLUINT can be adjusted between (and sometimes within) these solution steps according to expressions or logic.

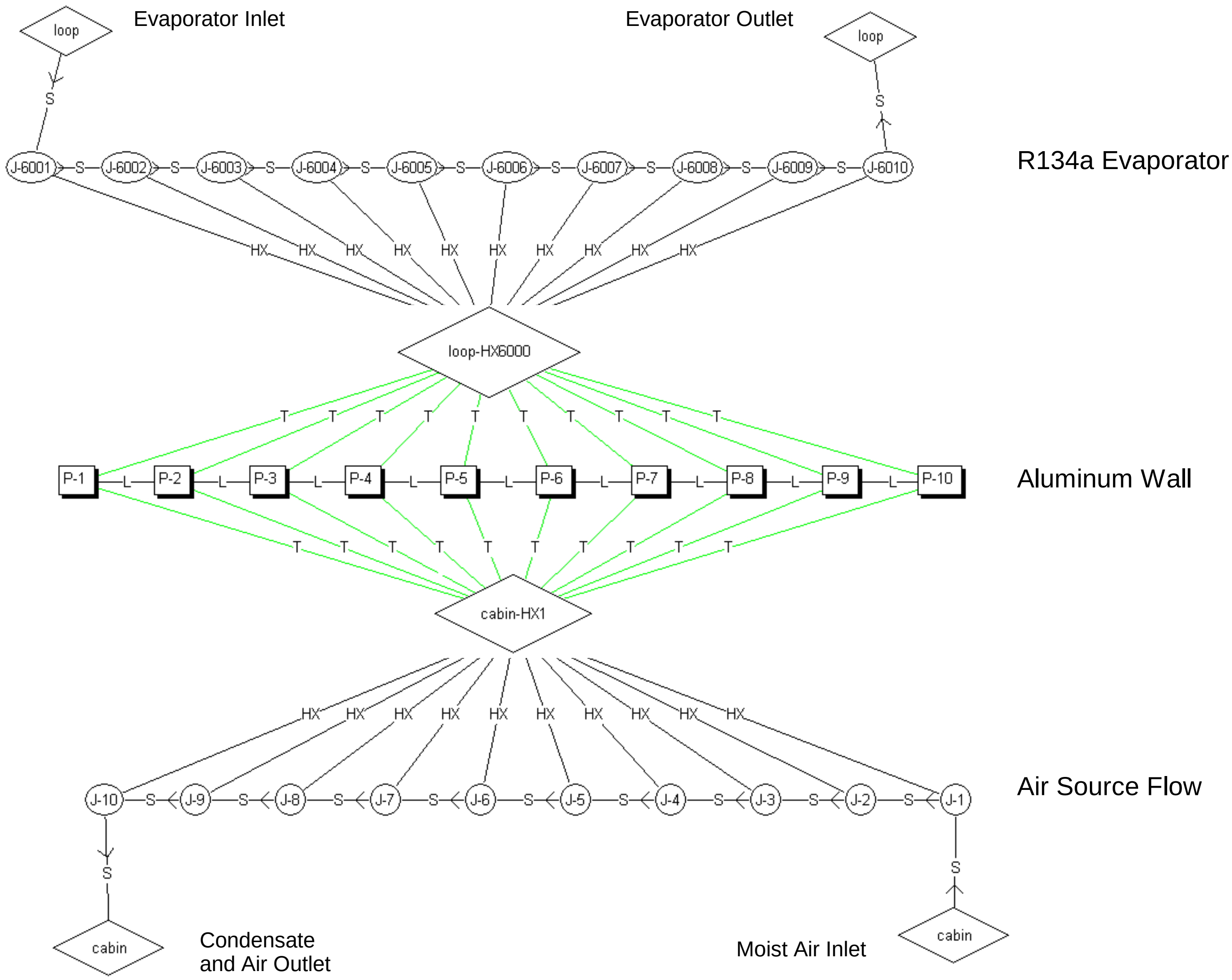


Figure 3: Moist Air Counterflowing with R134a in One Possible Evaporator Model

UNDERSTANDING THE PROBLEM

Models of compressors and throttling devices must predict pressure rises and drops accurately. But it may not be as obvious that nearly isobaric devices such as the condenser and evaporator have a strong influence on the resulting pressure levels, *because it is in those components that the amount of working fluid charge varies the most.*

At any instantaneous operating point, the energy flows through the loop must balance (neglecting transient thermal and thermodynamic storage terms*). This means that the heat transfer coefficients (and degree of single-phase "blockage") in the condensers and evaporators must be calculated accurately. This in turn means that the regimes and thermodynamic qualities within the condensers and evaporators must be calculated accurately, conserving total charge mass in the system.

To predict the upper and lower operating pressures at any steady operating point, or to track changes in those pressures during dynamic cycle operation, requires that the code be able to track and conserve charge mass, and to determine its distribution. Because the resulting pressures in turn influence the operating conditions with the evaporator and condenser, ***a surprisingly tightly coupled and detailed solution is required to correctly predict the performance,*** as depicted in Figure 4.

This figure is not meant to depict any SINDA/FLUINT algorithm. In fact, SINDA/FLUINT solves for all of these interrelated effects simultaneously, making it specifically capable of meeting the challenges of vapor compression cycle modeling.

* These terms need not be neglected in SINDA/FLUINT.

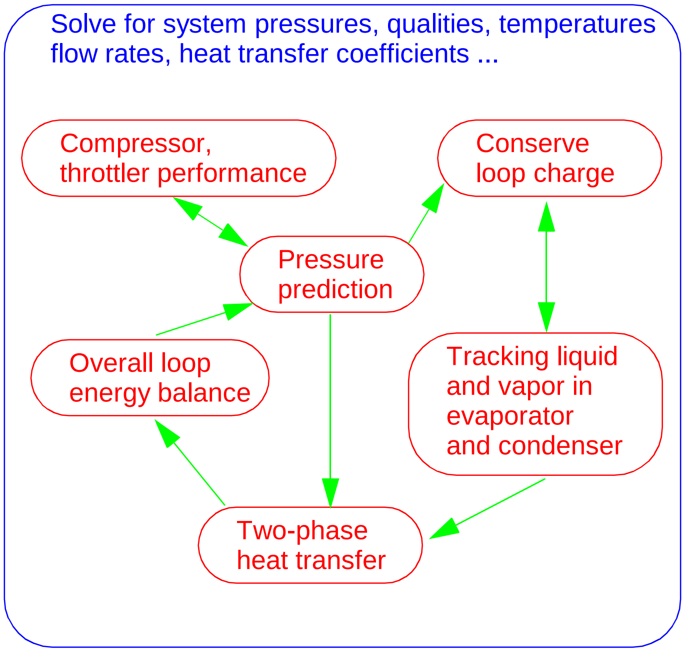


Figure 4: Tightly Coupled Analysis is Required

The following subsections explain various trade-offs that can be made when modeling VC cycles whose pressures are not known. These trade-offs result from the fact that FLUINT *tanks* (finite size control volumes) determine their own pressure based on conservation of mass and energy, while FLUINT *junctions* (zero size control "volumes") are faster executing approximations that rely on tanks or plena in the loop to ultimately determine the pressure.

SOLUTION #1: USING ALL TANKS

The simplest solution to explain and to implement is to simply use tank-type lumps to model most if not all of the loop. Small volumes such as capillary tubes, orifices, tees, etc. can still be modeled using junctions, but otherwise tanks are used elsewhere (especially within the evaporators and condenser).

Such a model is slow to solve, however, requiring time steps that are on the order of 0.1 second (0.01 to 1 second). Unless the dynamics of the first few seconds of compressor start-up are of interest, then this choice is inappropriate for environmentally-dominated transients or parametric steady-state runs.

SOLUTION #2: USING SOME TANKS

Another method is to use fewer, larger tanks. For example, the condenser can be subdivided axially into halves or thirds, using junctions within each segment but connecting the segments with tanks representing the volume of the segment. In other words, the volume of the component is lumped into one or two tanks, but the two-phase gradients within the component are captured using junctions.

In a Sinaps*Plus* example model, the condenser was been modeled using tanks and tubes, but the other components filled mostly with vapor (such as the evaporator and suction lines) were modeled using faster executing junctions and STUBE connectors, and components with small volumes (such as a capillary tube) were modeled using junctions and tubes. Whenever junctions were used for speed, the volume of the component was applied to adjacent tanks. This model runs with approximately 1 second time steps, limited mostly by hydrodynamic events occurring in the condenser.

SOLUTION #3: USING ALL JUNCTIONS

A model using all junctions solves very quickly, but must have at least a plenum (fixed pressure lump) present as a reference pressure. Usually, the plenum is teed off the compressor outlet, although any location will work. In such a model, the pressure of the plenum must then be adjusted to yield the correct charge.

Parameterizing Charge–If the charge is unknown or variable, then the above model serves well for steady-state analyses. The pressure of the plenum can be varied parametrically, and the resulting performance plotted against either the pressure or the charge.

Using the Solver–If only steady state analyses are required, then the Solver module can be used to automatically find the plenum pressure that results in the desired charge.

Using Control Logic–If transient analyses are required, then the plenum pressure must be controlled such that the correct charge is present in the system. This control cannot be perfect. Rather, the goal of the control logic is to make sure the error in charge is acceptably small while not causing long run times. (After all, if long run times result, the user is better off switching to tanks and eliminating the error all together.)

Such control logic has been written and examples are available, but such logic is usually specific to each cycle. A more generalized solution is to use a PID controller, perhaps even tuning the P, I, and D gains using the Solver.

TRANSIENT SIMULATIONS

Several different levels of transients can be run, depending on the time scales of interest.

For example, events whose total duration is on the order of 1 to 10 seconds can be modeled, including compressor start-up surges, valve transients, and pseudo-steady oscillations and instabilities within condensers and evaporators.

More typically, however, the events of interest are on the order of minutes and hours, involving transient changes to loads, environment, compressor speed, etc. At those long time scales, thermal lags and control system responses are of interest instead of hydrodynamic transients.

Within SINDA/FLUINT, the time scale of interest is chosen indirectly by selecting time-dependent versus instantaneous network elements. A fully transient thermohydraulic model would be composed largely of *tanks, tubes,* and *diffusion nodes.* Neglecting hydrodynamic transients, junctions can be elected instead of tanks,* perhaps retaining inertial *tubes* for long and thin passages such as capillary tubes. A model with instantaneous hydrodynamics (junctions and STUBE connectors) can still retain lag in the thermal/structural model (via the use of *diffusion node*s instead of *arithmetic nodes*), and can still employ variable boundary conditions such as loads and environments.

Thus, the term "transient" encompasses various levels of detail, which analysts are free to mix and match as needed to achieve efficient simulation of the phenomena of interest to them, excluding spurious details.

INTEGRATION: APPLICATION-LEVEL MODELING

A key advantage of using SINDA/FLUINT to model vapor compression (VC) cycle air conditioners is that it is not written specifically to address such systems: the general-purpose nature of the code can be exploited to integrate the VC cycle model with detailed models of the application (vehicle, building, electronics cabinet, etc.).

In other words, it is possible to include more realistic boundary conditions by modeling the remainder of the vehicle or enclosure explicitly. The condenser model can be integrated with models of radiators or other heat sinks. The evaporator can be combined with models of cabins or compartments that include air-water psychrometrics. The overall system can include solar loading, electronic dissipations, etc. as needed to achieve a complete model of thermal energy transport. Codes such as C&R's Thermal Desktop® and RadCAD® can be used to develop geometric thermal models including radiation loading and transport.

SINDA/FLUINT submodels are key to this top-level modeling: separate submodels can be used for each fluid, compartment, subsystem etc. Submodels may be swapped in and out of the analysis, even during the execution of a single run.

HIGH-LEVEL DESIGN MODULES

Without the high-level modules, SINDA/FLUINT is used in a traditional point-design fashion: given a specific and deterministic design and a fixed environment and usage scenario, steady-state and/or transient simulations are run to determine how the design performed. This method is *not,* however, a natural way of performing common engineering tasks. Rather, this *point design evaluation method* is readily available because it is what is "easily" achieved using numerical solutions. Because this type of software is all that has been available, a generation of engineers has been trained in these point-design evaluation methods, forgetting perhaps what the original intent of using them was: to produce good designs, and not just to evaluate point designs.

The SINDA/FLUINT Solver module (Ref 3) represents an automation of the design process itself, and not an automation of a subprocess (point-design evaluation). Using the Solver, engineers can:

1. calculate inputs given outputs (reverse solutions)
2. optimize a design, sizing or selecting components subject to arbitrarily complex rules
3. automatically correlate a model to available test data

Another high-level module is Reliability Engineering (Ref 4), which allows uncertainties to be treated statistically, providing estimates of the probability of meeting performance requirements.

Combining the Solver and Reliability Engineering yields Robust Design: factoring reliability into the automated process of design synthesis itself, and thereby producing a design that quantitatively balances risk and cost without blindly stacking up margins, factors of safety, and worst-case scenarios.

HIGH-LEVEL DESIGN APPLICATIONS TO VC CYCLES

Parametrics, optimization, test correlation, and statistical design methods all have application to VC cycle design, as listed in this section in the form of brief examples.

Almost every input in SINDA/FLUINT, including key parameters such as diameters, lengths, throttling resistances, compressor speeds, film coefficients (or scaling factors for built-in correlations), etc., can be defined algebraically (vs. hard-coded numeric inputs). Changes to any of these user-defined parameters can be made at any time during the solution. Series of parametric steady state or transient runs can be easily made varying important dimensions, boundary conditions, etc. Such runs are important for testing modeling and design sensitivities.

The Solver optimization module can also be used to determine the best values of these parameters: to size dimensions, compressor speeds, resistances, etc. Volume or charge in the loop can be minimized, or coefficient of performance can be maximized, or some other complex function (perhaps involving cost) can be used to direct the optimization. Similarly, many arbitrarily complex constraints can be imposed: "don't let the compressor RPM exceed 4000," or "don't let the compressor inlet superheat drop

* Refer, however, to the previous subsection regarding self-determination of pressure.

below 10 degrees" or "don't allow condensate freezing on the evaporator coils."

The Solver can also be used to "back out" or reverse calculate uncertainties such as two-phase film coefficients given test data.

In the preliminary design stages, of course such test data is unavailable. Other parameters (environments, as-built performance metrics, tolerances) are intrinsically uncertain.

Uncertainties in manufacturing or usage scenarios (including weather) can be treated as the stochastic phenomena that they are, producing predictions of the success of meeting many simple or complex failure limits using the Reliability Engineering module. For example, the probability of keeping the evaporator temperature below a threshold can be calculated given uncertainties in radiator air velocity and temperature, compressor efficiency, and two-phase film coefficients.

Finally, optimization and statistical design can be combined to design for reliability: to size or select heat exchangers, compressors, etc. on the basis of cost, reliability, and other considerations. Alternatively, these modules can be used to determine what tolerances are acceptable.

HEAD START: A VC TEMPLATE

As either a demonstration of the application of SINDA/FLUINT to VC cycle modeling, or as a template for customized model development, a Sinaps*Plus*® prebuilt VC cycle model is available (Figure 5). This model demonstrates

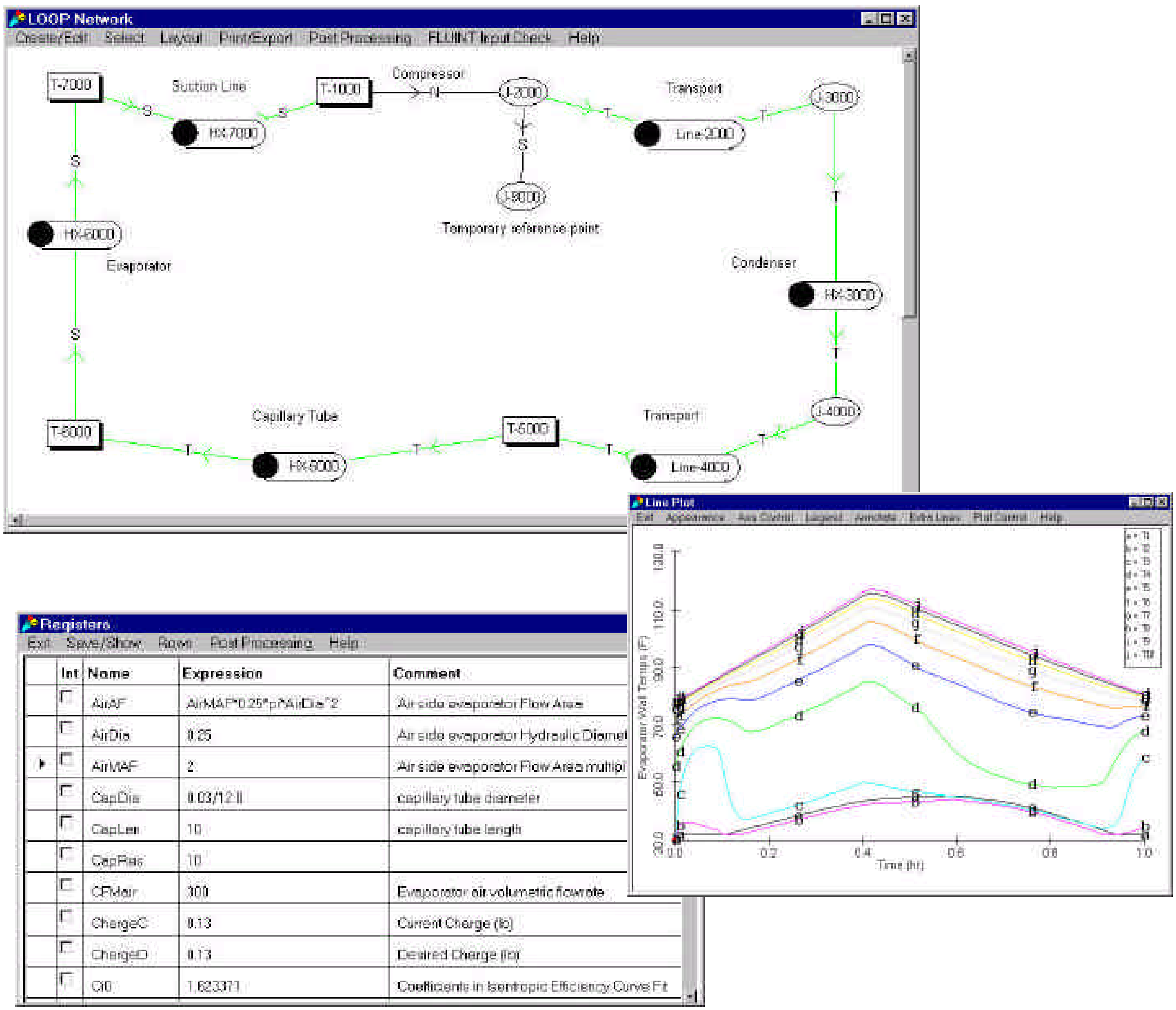


Figure 5: SinapsPlus-based Example and Template

some of the concepts described in this paper, but also provides a template that can be used as a starting point for custom model development.

CONCLUSIONS

A fully featured thermal/fluid simulation and design environment exists that has been satisfactorily applied to many vapor compression cycles. It is able to handle the difficult problem of dynamic modeling and self-determination of pressure by using simultaneous solutions of two-phase thermodynamic and hydrodynamic equations.

The software enables high-level modeling of the entire vehicle or system, and supports sizing/selection, sensitivity studies, reliability estimations, and robust design. It is available with a variety of pre- and post-processing programs for ease of use and for production of quality presentation and report materials.

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REFERENCES

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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