Refrigeration System Design and Analysis

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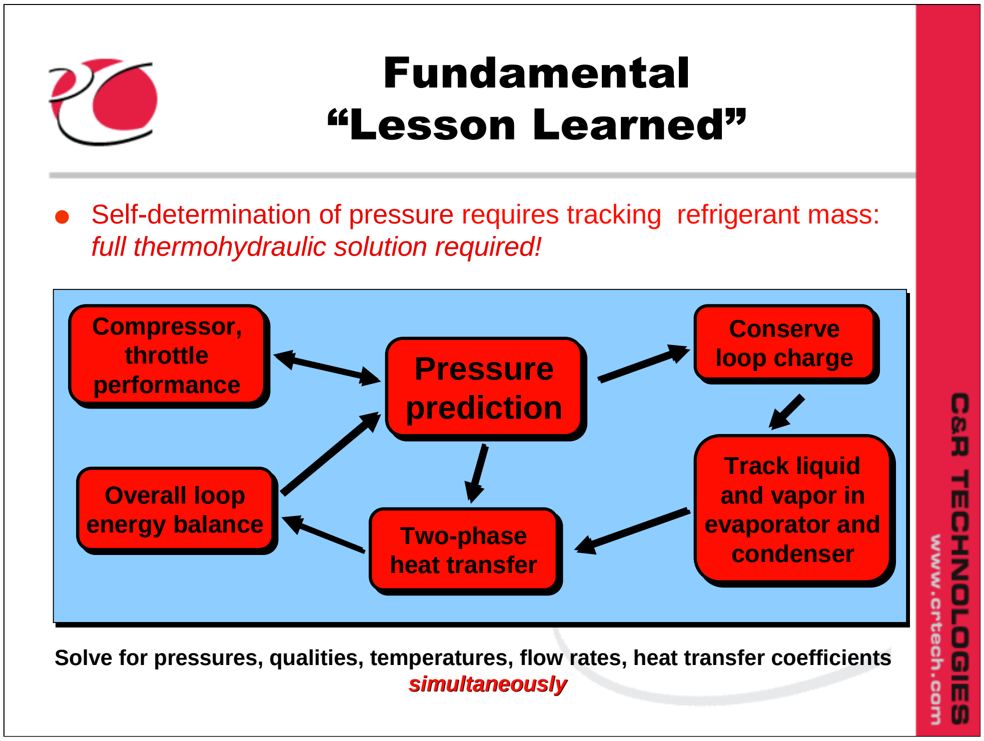
Vapor Compression (VC) refrigeration is relatively new to the electronics thermal management community, but is of increasing interest due to its ability to "generate extra deltaT" from junction to sink. It can therefore be used to either lower the junction temperature, or to reduce the size of heat acquisition and rejection footprints.

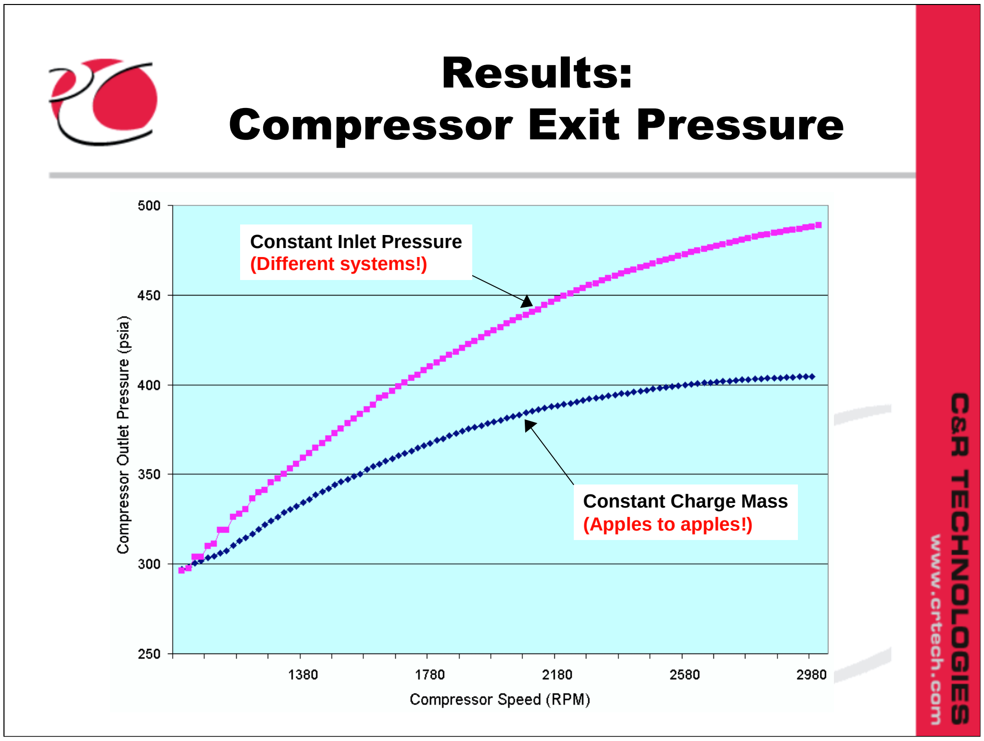
The purpose of this paper is to convey "lessons learned" from 6 years of VC cycle analysis by the automotive and industrial refrigeration industries.



The fundamental “lesson learned” is that one must track and conserve *charge mass:* the amount of refrigerant within any one loop. This is caused by tight interactions requiring simultaneous solutions of two-phase thermohydraulics.

To do otherwise (e.g., evaporator efficiency approaches, mappings, etc.) loses the ability to predict pressures reliably: you are no longer analyzing a single system under different conditions, you are changing the charge and therefore analyzing different systems at each point.

This distinction is critical for transient simulations, but also affects many sizing parametrics, sensitivity, and optimization studies.

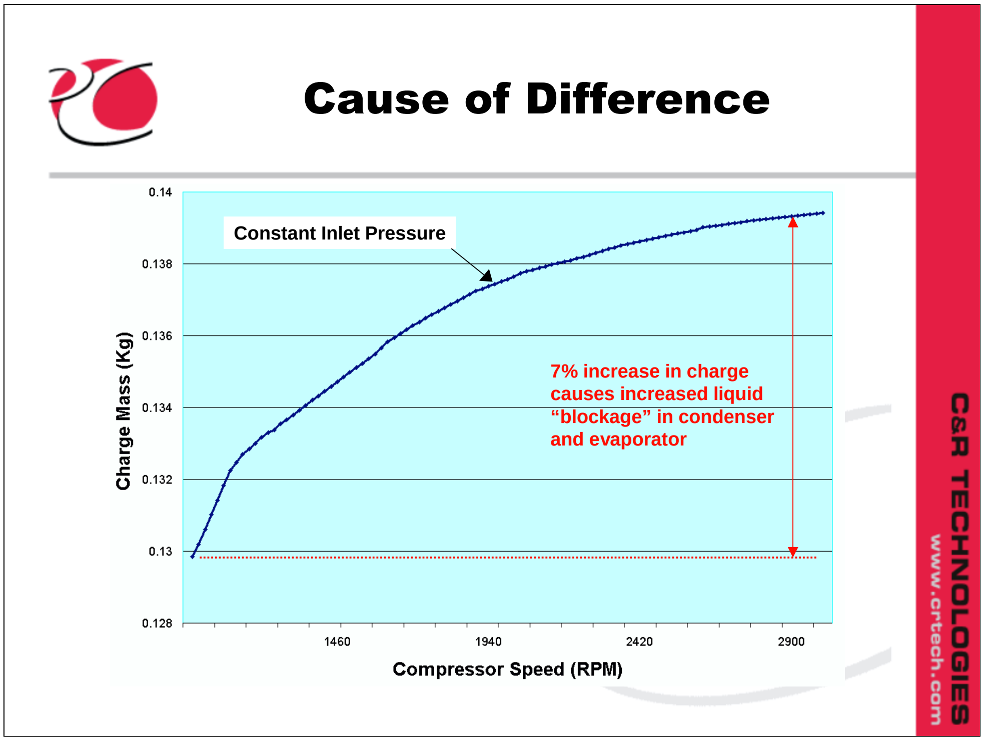


Take, for example, the same VC design analyzed parametrically as a function of

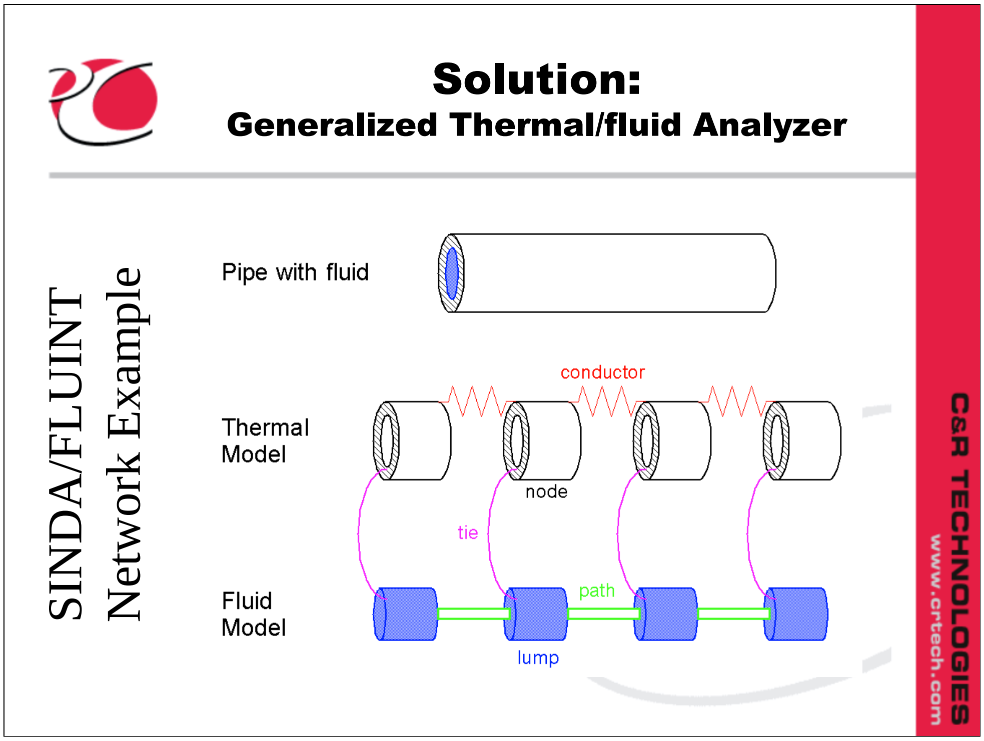
compressor RPM. If the compressor inlet pressure is held constant (a common assumption in "effective component performance" analyses), the resulting pressures are much higher than if the charge is held constant.

In the latter case (constant charge), the same system is being exposed to different

conditions. In the former case (constant inlet pressure) *each point represents a different system*: the same design, but a different charge level.

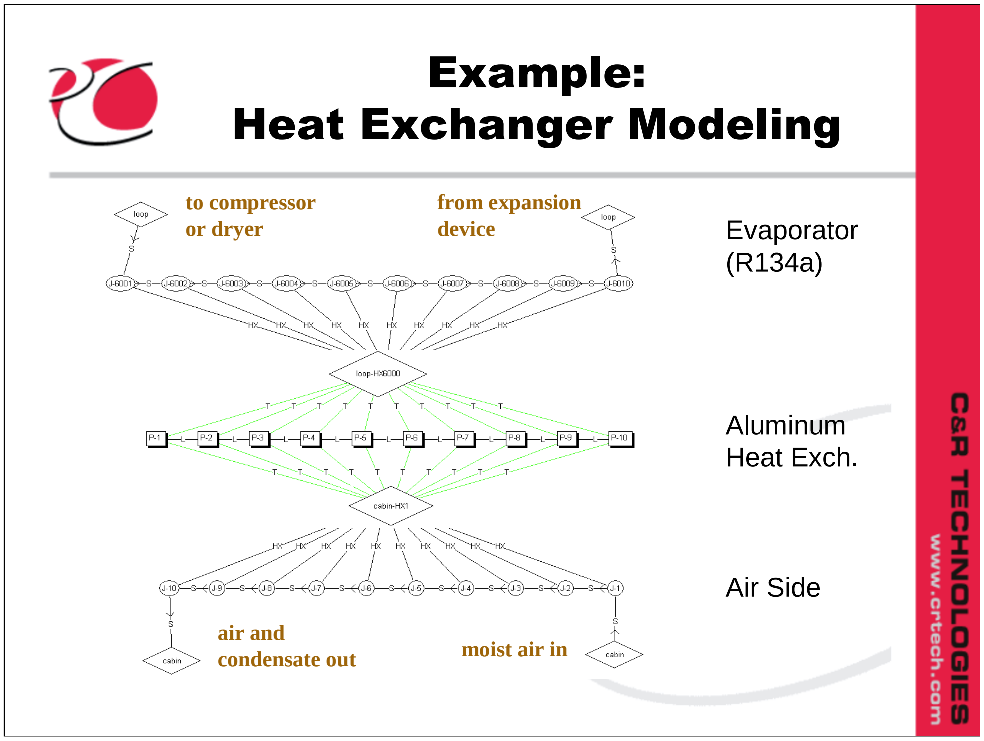


Why does this happen? Because as the charge mass increases, it "blocks" more of the evaporator and especially the condenser. This effect can only be seen if the solution method subdivides those components and adjusts the heat transfer within them according to the local single- or two-phase flow conditions.

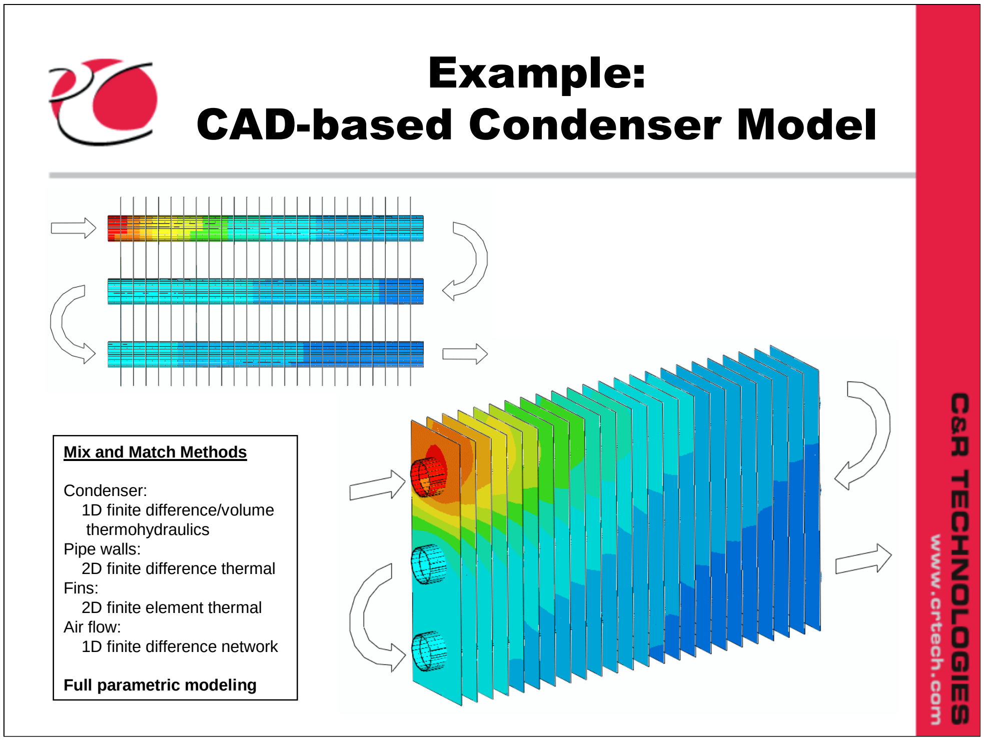


A generalized thermal/fluid network solver attacks the problem using just this type of approach: by subdividing the active heat transfer components (condenser, evaporator, and perhaps capillary tube and suction tube) instead of assuming effective performance etc.

This approach in turn allows the solver to keep track of how much mass each component contains to make sure the total system charge is conserved.



The "FNM" (Flow Network Modeling) approach applied to an evaporator and the air source (including treatment of psychrometrics). Each component has been axially discretized into ten subsections, though more resolution is often used in practice.

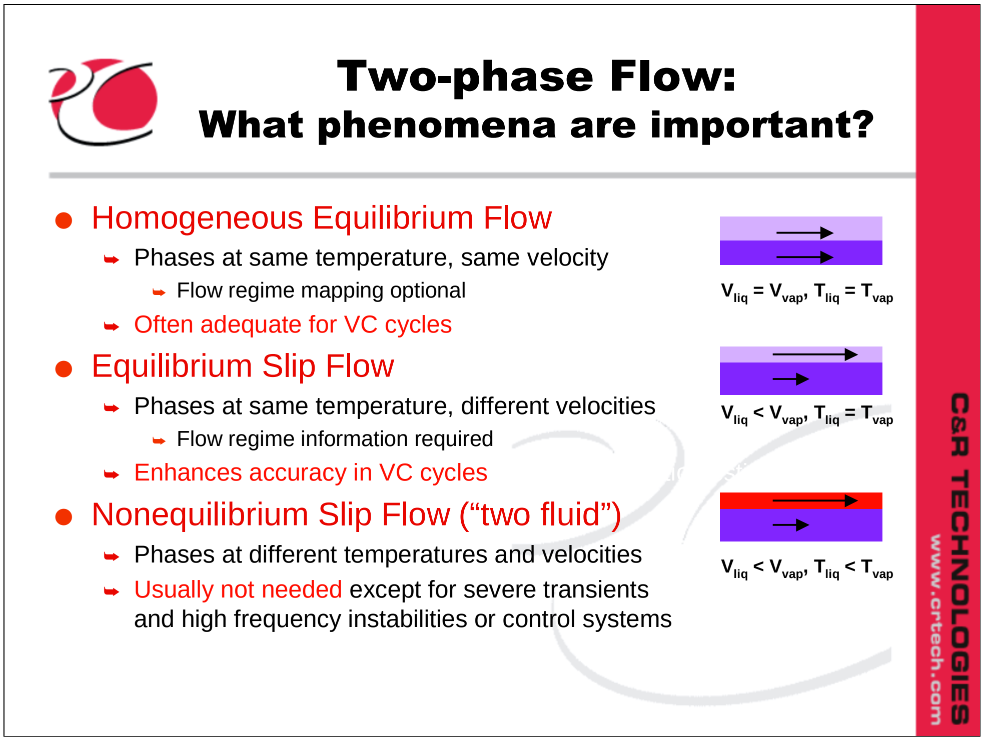


This does not imply that only “schematic style” analyses are possible. The same

approaches can underlie both FDM and FEM models of complex thermal structures.

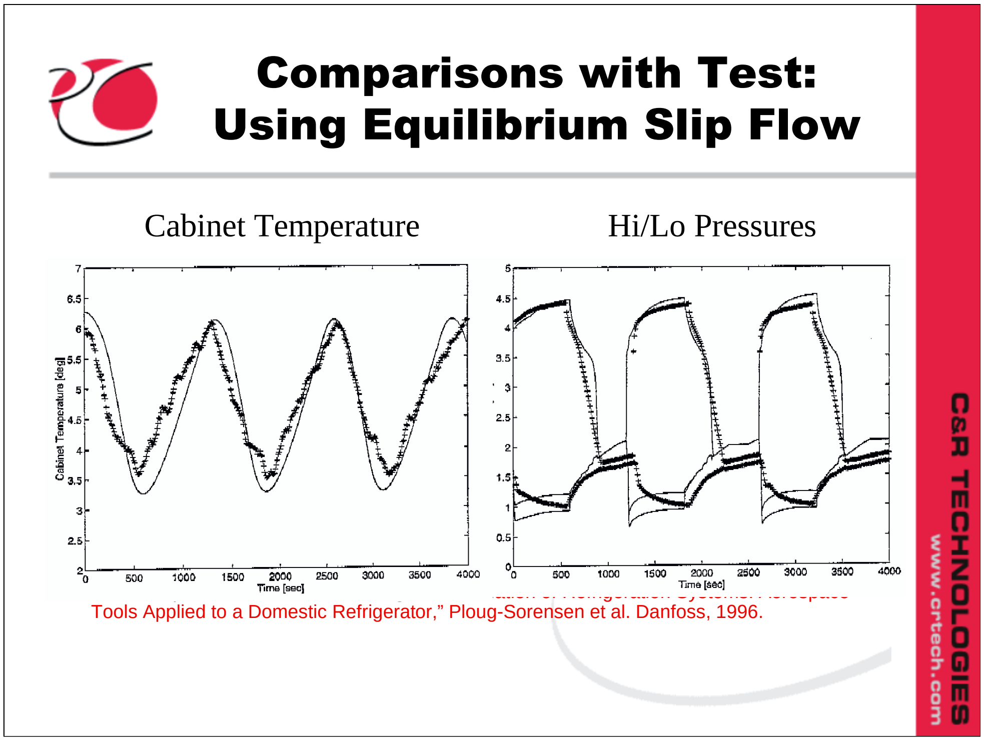
In the above chart, two-phase 1D flow networks convect to 2D FDM condenser tube

models, which are brazed to FEM models of fins, which convect to 1D or CFD models of air flow.



When a full two-phase thermohydraulic solver is applied to VC systems, there are many choices available: it is possible to do either very simplified pseudo-steady analyses or complex two-fluid transients including mixture effects.

Experience has shown that, unless fast time scale control events are being analyzed, simple methods such as homogeneous equilibrium (vapor and liquid assumed to be at the same temperature and velocity) are usually adequate.



… however, at least one user has reported improved match to test data using “slip flow” capabilities: letting liquid and vapor travel at different velocities. (This affects void fraction predictions and therefore improves somewhat the tracking and conservation of total system charge mass … again underscoring its importance.)

Conclusions

- Charge mass must be conserved in transients, parametric sweeps, sensitivity studies, etc.
  - Component-level approaches (effectiveness, average coefficients, etc.) *are not* suitable: limited to concept-level trade studies
  - Finite difference/volume subdivision of condenser and evaporator *is* suitable: tracks mass and "blockage" effects
- Two-phase flow is *not* amenable to CFD approaches
  - but flow network modeling (FNM) *is* well suited for the task
- Slip flow has been shown to improve accuracy, but full nonequilibrium nonhomogeneous ("two fluid") modeling is usually not necessary

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