# Optimization Of Vapor Compression Systems Via Simulation

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# Optimization of Vapor Compression Systems via Simulation

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## ABSTRACT

VapCyc is a vapor compression refrigeration simulation tool which features charge estimates, component inter-changeability and is specifically geared towards optimization of system level variables using gradient based and genetic optimization routines. System level variables currently accounted for are: system refrigerant charge, COP, weight, capacity, cost and selection of individual component models. The optimization is being implemented as a single objective optimization subject to various constraints. This optimization is carried out over a given set of components as well as a variable set that may include any independent variable of the selected component models. VapCyc is introduced here in its early stages to demonstrate its usefulness for design and optimization, and thus justify further work on its simulation capabilities, component models and optimization routines. To this end, this paper presents several simple component models, and the resulting combinations of these components, which represent optima of several different objective functions and constraint sets.

## NOMENCLATURE

| | | | | | |
|---|---|---|---|---|---|
| Charge | Refrigerant Charge (kg) | $U$ | Overall Heat Transfer Coefficient (W/m$^2$ K) | $Cp$ | Specific Heat (J/kg K) |
| $\dot{Q}$ | Heat Rejected (W) | $\eta_v$ | Volumetric Efficiency | $P$ | Pressure (Pa) |
| $\dot{W}$ | Work Output (W) | $\eta_s$ | Isentropic Efficiency | $T$ | Temperature (K) |
| $\dot{m}$ | mass flow rate (kg/s) | $\Delta P$ | Pressure Drop (Pa) | $h$ | Specific Enthalpy (J/kg) |
| $D$ | Diameter (m) | $f$ | Fanning Friction Factor | $s$ | Specific Etropy (J/kg K) |
| $L$ | Length (m) | | | $\rho$ | Density (kg/m$^3$) |
| $V$ | Volume (m$^3$) | | | | |

## INTRODUCTION

Vapor compression refrigeration represents a large part of the United States energy consumption. Many computer simulations have been created over the years, dating back to approximately 1976. These simulations are created for the purposes of design, analysis, but rarely optimization of the system [1-3]. The large majority of the simulations created are specific to a single system, although some simulations have a large number of independent variables that can be specified, making them more general in application.

Even a simple vapor compression system can have many independent variables, making complete control of a system during experimentation difficult if not impossible. Simulation of vapor compression systems is therefore beneficial to establish system performance over a rigidly controlled set of independent system variables. Once simulation is established to reproduce the behavior of the system in question, optimization of the system's simulated performance can be conducted, and applied to the real system.

VapCyc is a steady-state vapor compression refrigeration simulation tool created expressly for this purpose. VapCyc combines four independent component models and simulates the performance of the set. Optimization is then carried out for a set of system level variables as a function of the system independent variables, as well as any relevant component independent variables. VapCyc currently allows for a set of system dependent variables consisting of: COP, capacity, weight and volume, and a set of independent variable, consisting of: system charge, and component models.

This paper presents VapCyc, as a tool for vapor compression refrigeration system simulation and optimization. In addition, this paper presents simplified component models used to validate the VapCyc system model and offer examples of system level optimization. Two examples are presented to demonstrate the usefulness of such a tool, and justify further work on the system simulation tool, optimization routine and component models.

# VapCyc

## Premise

VapCyc is a tool for a steady-state vapor compression refrigeration system simulation and optimization. The simulation focuses on a system consisting of a compressor, condenser, expansion device and evaporator connected in series. Although the configuration of the system is fixed, the models for each component are variable. Once the individual component models and a value for the refrigerant charge are chosen, the complete set of independent variables for the system is determined. The simulation is achieved through the solution of the system level conservation laws of mass, and energy, which are satisfied, through the evaluation of the performance relations of individual component models.

While the configuration of the VapCyc system is fixed, the components themselves can be changed. This component inter-changeability is similar to the "real world" model of a system, where an off-the-shelf component is selected and inserted into the system. VapCyc allows the individual components to be selected by name, similar to ordering from a catalog.

Component inter-changeability, coupled with a solver for the run-time determined set of independent variables is achieved through a two level object oriented scheme, consisting of a system level object; responsible for system conservation laws and component level objects; responsible for the reporting of the individual component refrigerant charge and energy interactions with the environment.

## System level conservation laws

A specified set of four components must obey the system level conservation laws of mass and energy. A further constraint to the system is that it operates in steady state. For a system with a specified refrigerant charge, conservation of mass states:

$$Charge_{System} = Charge_{Compressor} + Charge_{Condenser} + Charge_{Expansion\ Device} + Charge_{Evaporator} \quad (1)$$

where "charge" refers to the amount of refrigerant contained within a component at its operating point.
Similarly, conservation of energy states:

$$0 = \dot{Q}_{Compressor} + \dot{W}_{Compressor} + \dot{Q}_{Condenser} + \dot{W}_{Condenser} + \dot{Q}_{Expansion\,Device} + \dot{W}_{Expansion\,Device} + \dot{Q}_{Evaporator} + \dot{W}_{Evaporator} \quad (2)$$

Note, equation (2) allows for each component in the system to have work and/or heat input.

Lastly, the steady-state system mandate, coupled with the fixed configuration forces a steady state component operation, resulting in:

$$\begin{aligned} \dot{m}_{Compressor} &= \dot{m}_{Condenser} \\ \dot{m}_{Compressor} &= \dot{m}_{Expansion\,Device} \\ \dot{m}_{Compressor} &= \dot{m}_{Evaporator} \end{aligned} \quad (3\text{-}5)$$

## System solution

The VapCyc simulation is described with three main data structures for use in energy system simulation; namely, components, ports and junctions. Components, meaning the refrigeration system components, are modeled as black box objects interacting with one another via a working fluid, through a series of ports and junctions, and possibly with their environment.

These components are represented by appropriate engineering models which themselves must satisfy all physical laws. A fluid flow enters or leaves a component through a port, which in turn communicates with a junction, and through this junction the fluid flow allows two or more components to communicate with one another.

Figure 1 shows a typical "black box" component, and a detailed component, which it may represent. In this case, the component to be simulated is a combination of two compressors and an inter-cooler. This component communicates with its environment through work and heat transfer, and has two ports, which communicate with two other system components through their respective junctions.

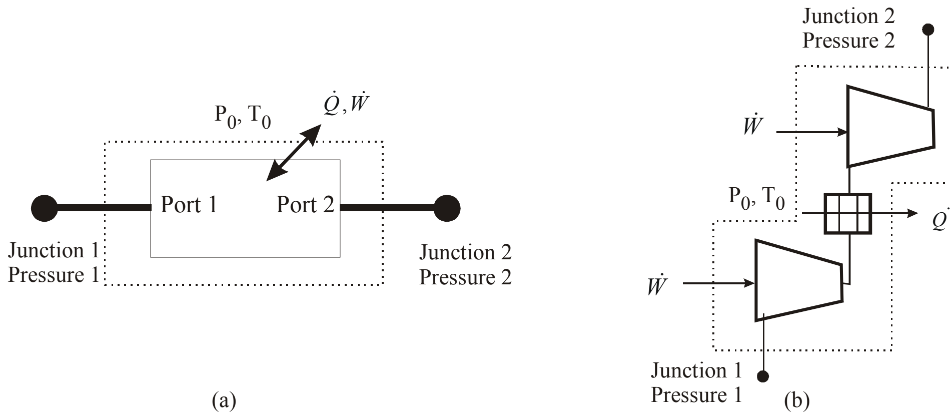


**Figure 1: A black box representation a system component**

The black box approach is used, to generalize the fixed configuration vapor compression system to one where the individual components themselves are allowed to have "non-traditional" work and heat transfer interactions with the environment. Examples would be a turbine expander, rather than the traditional expansion valve, or a heat exchanger that uses a centrifugal phase separator to mechanically separate liquid and vapor phases, at the expense of work input.

Figure 2 shows a schematic of the simple fixed configuration vapor compression refrigeration system simulated by VapCyc. Using the previously identified structures, namely, components, junctions, and ports, the proposed system has four components, with a total of eight ports connecting at four junctions. Assuming steady state, this system simulation is considered solved when the thermodynamic state is known at each of the four junctions, and conservation laws for the system are obeyed.[1]

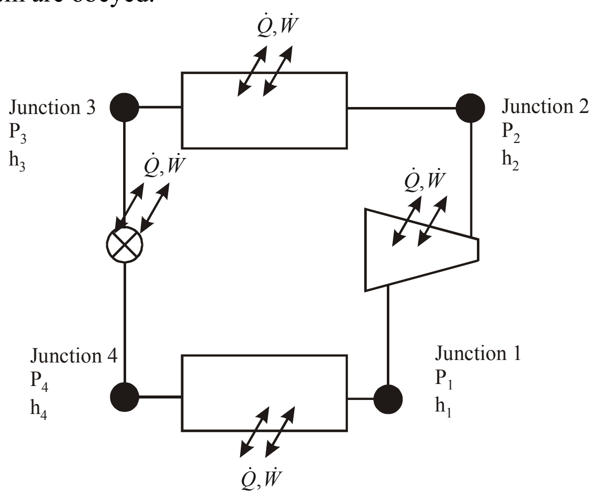


**Figure 2: Fixed configuration vapor compression refrigeration cycle**

This implies that two independent thermo-physical properties, pressure and specific enthalpy for example, at each junction in the system, will define the system's operating point such that mass and energy are conserved for the system. For this system, this implies a total of 8 unknowns.

Consider that in steady state, the discharge reservoir of a component has no thermal interaction with the performance of a component, but the discharge pressure does affect the mass flow rate through the component. From this, it can be determined that component flow rates and refrigerant exit conditions are functions of (a) the component performance relations, (b) the component inlet thermodynamic state, i.e. pressure and enthalpy, (c) the component discharge pressure(s) and (d) the component's environmental boundary conditions.

In the case of VapCyc, for selected components, i.e. fixed performance relations, and given environmental boundary conditions, this implies that although the four junction pressures are independent variables, three of the junction (exit) enthalpy values are dependent upon the performance and inlet enthalpy of the component preceding the junction. This leads to a conclusion that three of the junction enthalpy values are dependent variables of the sys-

[1] It is implicit that the components themselves satisfy their own conservation laws.

tem, reducing the number of unknowns in the system to five. The five unknowns can be solved through the five system level conservation laws given in equations (1)-(5).

## System Charge

At a given operating point, each component will contain a certain mass of refrigerant. The system charge is the sum of each of the individual component charges.

## System Level Performance and Optimization

Several "system level" variables can be defined for a given vapor compression refrigeration system. Some of these variables are independent, while others are dependent. It is conceivable that a given system can be assembled using a specific choice for compressor, condenser, expansion device and evaporator models, this system can then be given an arbitrary system charge of an arbitrary refrigerant. These six variables represent the set of independent system variables to be encountered in a vapor compression system. A second set of independent variables, which are properties of the components themselves, but not necessarily the system itself, represent a second class of independent variables. Examples of component independent variables can include: compressor speed, condenser fan speed or a superheat setting on an expansion valve. Dependent system variables are those that result from the performance of the system configuration. A set of dependent system variables can include COP, system capacity, condenser sub-cooling, evaporator superheat and others.

VapCyc is a tool allowing the specification of system and component independent variables to simulate the system and use the resulting performance to optimize system level dependent variables. VapCyc currently allows for the specification of system level constraints, thus offering a more realistic optimization problem. An example would be optimizing the COP of a system composed of a set of possible components, and subject to a capacity and/or weight range.

## Component Models

**Simplified Models**

Simple models are created to explore the functionality of VapCyc, and facilitate its testing, while keeping the computational demands low. These simplified components are created with two main goals in mind, namely: (a) model real life behavior and (b) solve quickly.

Two main features observed in real equipment which must be captured in the basic VapCyc components, namely, (a) variation of charge contained within as different boundary conditions are imposed and (b) a variation in mass flow throughput as different boundary conditions are imposed.

**Compressor Model**

A generic compressor model is a simple model, which offers a great deal of flexibility. This model is a "place-holder" for more complex models, such as those based upon the ARI 10-coefficient standard[2], or more detailed performance models.

The generic compressor model has the following inputs (and is provided with default values):

- Volumetric Efficiency, $\eta_v$
- Isentropic Efficiency, $\eta_s$
- RPM (Compressor speed in revolutions per minute)
- Displacement Volume (per revolution, V)

The compressor is assumed to be adiabatic. The inlet state to the compressor is calculated from the inlet pressure and enthalpy. From this inlet state and the other inputs to the model, the refrigerant mass flow rate is calculated from,

$$\dot{m} = \rho_{in} V\,Speed\,\eta_v \tag{4}$$

The refrigerant discharge state is given by the isentropic efficiency,

$$h_{out} = h_{in} + \frac{(h_s - h_{in})}{\eta_s}, \tag{5}$$

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[2] Models based upon this standard are to be provided with future versions of VapCyc.

where $h_s$ is enthalpy of the refrigerant at the compressor discharge pressure, were the compression isentropic.

The component level dependent variables that are necessarily reported back to the system level object, to satisfy equations (1-5) are calculated by,

$$\begin{aligned} &(Inlet)\,\dot{m}_{Port,1} = -\dot{m} \\ &(Outlet)\,\dot{m}_{Port,2} = \dot{m} \\ &(Outlet)\,h_{Port,2} = h_{out} \\ &WorkOut = \dot{m}(h_{in} - h_{out}) \\ &HeatOut = 0 \\ &Charge = 0 \end{aligned} \tag{6}$$

The **Alpha series** compressor is built upon the Generic Compressor model. Each compressor in the Alpha series has an identical isentropic efficiency (0.65), volumetric efficiency (0.95), speed (1000 RPM) but a distinct displacement volume. The displacement volume is chosen to give a unique (nominal) refrigeration capacity at a specified rating point. The Alpha series compressors are sized to have nominal capacities of 1.24, 2.44, 3.60, 5.00, 10.0, 11.0 and 20.0 kW, respectively.

In addition to different capacities, the Alpha Compressors each carry a distinct mass and physical volume. These mass and volume dimensions are chosen from a manufacturer's catalog of real compressors with similar capacities at a similar nominal rating point. This establishes the Alpha Compressor line in VapCyc; where an increase in the compressor capacity increases the compressor, and therefore the system, size, volume and weight.

The **Beta series** compressor line is similar to the alpha compressor line, but is a high-efficiency compressor line, with identical volumetric efficiency, but a higher isentropic efficiency. For simplicity, the Beta series compressor is assumed to occupy the same volume as the Alpha series (for the same nominal capacity), but the mass is increased by 10%, which is assumed to be the cause of the increase in efficiency.

Similarly, the **Gamma series** compressor line is a low-efficiency compressor line with volumetric efficiency identical to the Alpha series, but a lower isentropic efficiency. As with the Beta compressor, the volume of the Gamma compressor is identical to the Alpha (for a given nominal capacity), but the mass is reduced by 10%, which is assumed to be the cause of the decrease in efficiency.

**Heat Exchanger Model**

The generic condenser/evaporator model is a single externally finned tube, with refrigerant flowing on the inside, and air flowing in a cross-flow configuration on the outside. The following model assumptions apply to both the condenser and evaporator

- Infinite air flow rate (no temperature change from heat transfer)
- Constant heat transfer coefficients
- Constant friction factor
- All of the (refrigerant) pressure drop for the component occurs in the thermodynamic regime (vapor, two phase or liquid) of the entering fluid, and over the entire length of the heat exchanger

A relation between mass flow and pressure drop of the following form is used,

$$\dot{m} = \frac{\pi}{4} D^{5/2} \sqrt{\frac{\Delta P \rho}{2 f L}} \,. \tag{7}$$

Taking the heat exchanger inlet properties, and using the entire heat exchanger length as the parameter L, allows for a simple approximation of the heat exchanger mass flow rate as a function of pressure difference, inlet density (via the known enthalpy) and heat exchanger geometry.

This radical simplification may differ greatly from the actual behavior one may expect in the laboratory, but it captures qualitatively the behavior looked for from the model, namely a decrease in flow with decreased pressure drops and/or increased inlet superheats. The main benefits of the simplification are the reduced calculation time and elimination of the need for iteration in the heat exchanger model. More complex models are currently under development, and will be included in future versions of VapCyc.

Heat transfer between air and refrigerant during single-phase modes is modeled with a simple relation,

$$Q_{ref} = \dot{m}_{ref} Cp\left(T_{ref,Out} - T_{ref,In}\right)$$
$$Q_{\text{ref}} = UA\left(T_{air,In} - \frac{\left(T_{ref,in} + T_{ref,out}\right)}{2}\right) \tag{8}$$

Combining the two expressions in (8), and rearranging terms, allows the refrigerant outlet temperature to be expressed as,

$$T_{ref,out} = \frac{2\dot{m}C_p T_{ref,in} + UA(2T_{Air,in} - T_{ref,in})}{2\dot{m}C_p + UA} \tag{9}$$

Heat transfer between air and refrigerant (either evaporating or condensing) is modeled through a simple relation,

$$Q_{Air} = UA\left(T_{air,In} - T_{Evap/Cond}\right)$$
$$Q_{\text{Ref}} = -Q_{Air} = \dot{m}_{ref}(h_{ref,out} - h_{ref,in}) \tag{10}$$

The condenser model incorporates "zoning", where each refrigerant phase regime (vapor, two phase, liquid) is treated as a zone. The zone is rated, with a known length, and the refrigerant exit condition examined, i.e. with the given heat exchange area, will the vapor refrigerant begin to condense/evaporate. If the refrigerant exit condition is inconsistent with the zone's phase regime, the zone is then sized knowing the refrigerant exit condition, and the remaining heat exchange area used to calculate subsequent zone sizes.

In addition to the thermodynamic output, the heat exchangers have a charge contained within them. Refrigerant charge in the single-phase sections of the heat exchangers (vapor and liquid) use an arithmetic mean density multiplied by the volume of the heat exchanger sub-section. The two-phase section charge model used is given in [4], where vapor quality varies linearly along the length of the two-phase sub-section. The total heat exchanger charge is the sum of the sub-section charges. It should be noted that it is possible to use more detailed charge correlations for the heat exchangers.

The component level dependent variables that are necessarily reported back to the system level object, to satisfy equations (1-5) are calculated by,

$$(Inlet)\,\dot{m}_{Port,1} = -\dot{m}$$
$$(Outlet)\,\dot{m}_{Port,2} = \dot{m}$$
$$(Outlet)\,h_{Port,2} = h_{ref,out} \tag{11}$$
$$WorkOut = 0$$
$$HeatOut = \dot{m}(h_{ref\ in} - h_{ref\ out})$$
$$Charge = \sum_{i=1}^{N_{Sub-Sections}} Charge_i$$

Similar to the compressor lines, an **Alpha series** of condensers and evaporators has been created for use in VapCyc that consist of heat exchangers sized to yield a nominal capacity at a given operating point. Each individual member of the series carries with it a distinct set of physical variables, namely weight and volume.

## System Optimization

Optimization of the refrigeration system as an entity is a general optimization problem in that a variable set of independent parameters can be changed in some manner to optimize (maximize or minimize) a variable set of dependent parameters. Table 1 shows several possible independent and consequently dependent variables one may encounter in a vapor compression refrigeration system.

A system's dependent variables are not only numerous, and subject to individual user requirements, but allow for an infinite number of options when mathematical combinations of individual variables are allowed. Also seen in table 1 are entries such as "Evaporator Inlet Air Temperature", which suggests the evaporator has an inlet air stream. The concept behind VapCyc is object-oriented insertion of components, and it is conceivable that an evaporator, such as a cold plate, does not have an inlet air stream. Thus, a priori knowledge of the dependent and/or independent system variables is not possible.

An optimization of this type is a difficult problem, presenting two main challenges, namely (a) determining the optimization variables, and (b) optimizing this highly irregular solution space.

**Table 1: Possible dependent and independent system variables**

| Independent System Variables | Dependent System Variables |
|---|---|
| Compressor Speed | COP |
| Compressor Piston Diameter | Capacity |
| Refrigerant Charge | System Weight |
| Evaporator Inlet Air Temperature | COP - 0.5 (System Weight) |
| Evaporator Inlet Air Flow Rate | COP - $\Phi1_{penalty}$ (System Weight) |
| Condenser Tube Diameter | COP - $\Phi1_{penalty}$ (System Weight) - $\Phi2_{penalty}$ (Capacity) |
| Condenser Tube Length | COP - $\Phi1_{penalty}$ (System Weight) - $\Phi2_{penalty}$ (Volume) |

## Objective Function Solution Space

A second major challenge for a general optimization routine is the characterization of the objective function(s) that may take on. The optimization routine requires some objective function of the independent variables to operate upon; a simple example would be the system's COP. As the independent variables to the system simulation are (a) varied and dependent upon component model, (b) discrete, for choices in component model and (c) not known prior to run time, the range of the objective function solution space, as well as its character are unknown. This objective function is possibly discontinuous, and likely non analytic.

Typically, optimization of multi variable, non-linear functions is carried out using heuristic approaches, with calculus and geometry based solvers; however these approaches are typically used for functions that are continuous and analytic, making them inappropriate for this class of optimization problems.

Evolutionary programming techniques have shown success in dealing with difficult optimization problems including: discrete variable sets, large differences in sequential variables and a wide range of the variable space needs to be searched. Consequently, the VapCyc optimization engine operating on the objective function implements them.

VapCyc employs a common genetic optimization approach via mapping the system independent variables to "genes", which are binary numbers, used to represent the set of independent variables. The genes are then decoded, the simulation run, and the results processed. The objective function is then the objective variable (ex: COP), which is then penalized if the solution violates constraints. In this case the constraints include not only the user-specified constraints, but also a "valid configuration" constraint. The valid configuration constraint is violated when the proposed set of dependent variables results in the VapCyc system solver's inability to achieve a solution. This often occurs when components are extremely mis-matched, such as a nominal 20 kW compressor in a system composed of 1 kW nominal heat exchangers and expander.

## Optimization Examples

The current state of the optimization capabilities of VapCyc is demonstrated by two examples, namely a charge optimization for a given set of components, and a compressor model selection optimization.

**Example 1: Charge Optimization**

Vapor compression refrigeration systems typically have a charge that results in a maximum COP for a given environmental condition. Figure 3 shows a curve of COP vs. system charge for the Alpha 3.60 kW system [with TXV set at 4.5 K SH], which is obtained using VapCyc. Using a gradient-based optimization technique to optimize this single objective function over a single independent variable, VapCyc returns a COP of 3.19 at a charge of 0.58 kg, which is consistent with the parametric plot.

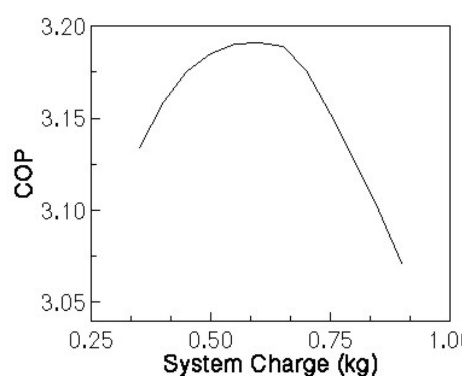


**Figure 3: COP Vs System Charge for Alpha 3.6 kW System**

**Example 2: Component Selection**

Given a component set consisting of the Alpha Evaporator-3600, Alpha Condenser-3600 and Alpha Orifice-3600, VapCyc is used to choose from the existing compressor library, the compressor that offers a maximum in a dependent variable. The available dependent variables are: COP, capacity, weight, and volume. Restricting the available compressors for the system to be those that are nominally 3.60 kW, the system can exploit a maximum from the given independent variables (in this case compressor models). As each of the Alpha, Beta and Gamma compressors has identical values for volume, for a given nominal capacity, no optimum exists for volume. VapCyc returns the Beta-3600 compressor as the optimal compressor for COP, while it returns the Gamma-3600 compressor for optimal capacity and weight. Table 2 shows the results for running the proposed system with the three compressors, and validates the choice VapCyc has made. Although this optimization is carried out over a relatively small set of independent variables, the distinct models result an optimization over a discrete variable set, and thus the genetic algorithms are applied to the problem.

It is seen from table 2 that although the COP of the system varies greatly with compressor model, the different compressors offer very similar capacities. Also seen from the table is the variation in system weight (material), which may translate directly to the compressor cost. Table 2 leads to a conclusion that a multi-objective optimization routine, or one that would take into account more than one decision variable is helpful for this class of optimization problems. This multi-objective approach is currently handled through the use of constraints.

**Table 2: Alpha system with different compressors**

| Compressor Model | COP | Capacity (W) | System Weight (kg) |
|---|---|---|---|
| Alpha-3600 | 3.18 | 3603 | 792 |
| Beta-3600 | 4.02 | 3599 | 809 |
| Gamma-3600 | 2.51 | 3606 | 774 |

## CONCLUSIONS

This paper presents an initial version of VapCyc, as a steady state vapor compression simulation tool with potential for both design and optimization. The premise is presented as a single tool, which through the use of object oriented programming techniques allow for the inter-changeability of components, offering a very large set of potential system combinations, and independent variable inputs through a common simulation vehicle. Simple models, which capture the relevant behavior of real models, are used to validate the solution and optimization routines. Gradient techniques are used for charge optimization, while genetic algorithms are employed for system optimization. The use of genetic algorithms allows a very large set of independent variables to be optimized over, including individual component models, as well as subjecting the optimization to constraints. Examples presented here demonstrate that the routines generate optima in the chosen objective variable. Results, coupled with the general component interface design offer encouraging signs that the use of more complex component models will offer robust simulation and optimization. To this end, work is justified for further development of the simulation tool (speed), the optimization routine (speed, greater flexibility for objective function, constraints and independent variables) and component models (increase the current component library size, and model complexity).

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