CYCLE_D VERSION 4.0: THEORETICAL VAPOR COMPRESSION CYCLE DESIGN PROGRAM

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ABSTRACT

This paper presents Version 4.0 of CYCLE_D, a vapor compression cycle design program. The model can simulate a basic subcritical or transcritical refrigeration cycle, both with or without a liquid-line/suction-line heat exchanger. In addition, the model can simulate a subcritical two-stage economizer cycle, a subcritical three-stage economizer cycle, and a subcritical two-stage compression cycle with intercooling. The model is a user-friendly tool for screening the performance of single-component refrigerants and refrigerant mixtures.

1. INTRODUCTION

The CYCLE_D Version 4.0 package simulates vapor compression refrigeration cycles that use single-component refrigerants or mixtures of refrigerants. The model can simulate a basic subcritical or transcritical refrigeration cycle, both with or without a liquid-line/suction-line heat exchanger. In addition, the model can simulate a subcritical two-stage economizer cycle, a subcritical three-stage economizer cycle, and a subcritical two-stage compression cycle with intercooling. CYCLE_D operates in a user-friendly environment on a standard PC that facilitates evaluating the performance of selected working fluids at different operating conditions. Calculations are based on refrigerant properties as represented in REFPROP (Lemmon et al., 2007). Note: most of the contents of this paper are extracted from the CYCLE_D Version 4.0 Users' Guide (Brown et al., 2009), which the reader may consult for more detailed information.

2. MODELLING APPROACH

The basic subcritical or transcritical system simulated by CYCLE_D consists of a compressor, a discharge line, a condenser for the subcritical cycle (a gas cooler for the transcritical cycle), an expansion device, an evaporator, and a compressor suction line. The other subcritical cycles may contain a second compressor, and one or two economizers or an intercooler. The basic subcritical and transcritical cycles can also include a liquid-line/suction-line heat exchanger (LLSL-HX). The user of the program has to specify the refrigerant and provide input data for the above listed hardware components, except for the expansion device, which is modeled as being isenthalpic. The user can also specify the auxiliary powers for the indoor fan, outdoor fan, and control unit of the system.

2.1 Refrigerants and Refrigerant Properties

Refrigerants available in CYCLE_D are those represented in REFPROP 8.0 (Lemmon et al., 2007). The list includes 48 single-component refrigerants, which can be selected as the working fluid or can be combined to form mixtures of up to five components, and 54 predefined mixtures.

CYCLE_D uses REFPROP 8.0 routines for calculating thermodynamic properties. Among different options available in REFPROP 8.0, CYCLE_D uses the default (NIST recommended) models for property predictions.

2.2 Condenser (or Gas Cooler) and Evaporator

The condenser and evaporator are represented by specifying the refrigerant temperature in each of these heat exchangers. The gas cooler is represented either by specifying the refrigerant pressure or allowing the program to optimize the refrigerant pressure, and the refrigerant exit temperature. Zero refrigerant pressure drop is assumed in each heat exchanger.

The refrigerant temperature in the condenser can be specified to be either a bubble-point temperature, a dew-point temperature, or an average temperature. The average temperature is calculated as an arithmetic mean of the dew-point and bubble-point temperatures. Additionally, the refrigerant subcooling at the condenser outlet can be specified.

The refrigerant temperature in the evaporator can be specified as either a dew-point temperature or an average temperature. The average temperature in the evaporator is calculated as an arithmetic mean of the dew-point temperature and the temperature of the refrigerant entering the evaporator. Additionally, the refrigerant superheat at the evaporator exit can be specified.

The above options for specifying the evaporator and condenser temperatures have no significance for single-component refrigerants, but they affect simulations with zeotropic mixtures since zeotropic mixtures undergo a temperature change during a phase change.

It is recognized that evaluation of the average temperature in the condenser and evaporator as a mean of refrigerant temperatures at the end of two-phase processes is a simplification for zeotropes whose temperature profile versus enthalpy in a two-phase region is not linear. However, this method is used to make CYCLE_D mimic the method used by industry for compressor calorimeter testing.

2.3 Compressor

For a basic subcritical cycle, CYCLE_D provides two options for representation of the compressor: the "Compressor Efficiency" option and the "Compressor Map" option. For other subcritical cycles and for the transcritical cycle, only the “Compressor Efficiency” option is available.

The "Compressor Efficiency" option requires input values of the compression process isentropic efficiency, the compressor volumetric efficiency, the electric-motor efficiency, and a target system Cooling Capacity, which is the evaporator capacity adjusted for the heat added by the indoor coil fan. If the value of the electric motor efficiency is less than unity, the entire heat rejected by the electric motor is assumed to heat the suction vapor before the compressor suction port. If the cycle includes two compressors, their inputs have to be independently specified.

The "Compressor Map" option uses compressor-map correlations, which are typically derived from compressor calorimeter tests. Three types of correlations are allowed. The "Compressor Map" option also requires a value for either the system Cooling Capacity or Capacity Multiplier. If Capacity Multiplier is specified, its value is used in the simulation as a multiplication factor for the compressor capacity (calculated by compressor-map correlations) and for indoor and outdoor fan powers (entered by the user). Power input to the system control unit is unaffected. If the system Cooling Capacity is specified, the simulations are performed for a system with a compressor of identical efficiency characteristics but with adjusted displacement, so the system could provide the specified capacity. Power input to the indoor and outdoor fans and system control unit are unaffected by the specified capacity value.

Compressor-map equations correlate compressor performance at a certain suction superheat and condenser subcooling. To allow simulations at user-specified superheat and subcooling, the following steps and assumptions are taken by the model:

- The isentropic efficiency of the compressor is calculated using the compressor-map correlations at user-specified saturation temperatures (or pressures) and at the superheat and subcooling levels used during the calorimeter tests. It is assumed that the isentropic efficiency is not affected by the level of superheat, and the calculated efficiency value is used in the cycle calculations.

- When calculating refrigerant mass flow rate, it is assumed that the compressor volumetric efficiency and speed (revolutions per minute, RPM) are not affected by the suction vapor superheat. Consequently, the refrigerant mass flow rate at the user-specified superheat equals the value of mass flow rate at the superheat maintained during the calorimeter tests, adjusted for the different specific volume of the suction vapor caused by a different superheat.

2.4 Minor System Components

The economizer(s) and intercooler are represented by specifying the refrigerant pressures. For the two-stage economizer cycle, the program can impose or optimize the intermediate pressure of the economizer.

The suction line and the discharge line are represented by pressure drops that are specified by the user in terms of a value of the corresponding saturation temperature drop of the refrigerant. CYCLE_D assumes the lines are adiabatic.

The liquid-line/suction-line heat exchanger (LLSL-HX) is specified by the user by assigning an effectiveness value of the heat exchanger. The assignment of effectiveness equal to zero denotes no LLSL-HX in the cycle.

The auxiliary powers are also specified by the user. The indoor and outdoor fan powers are used in the total power calculation and as heat in the capacity calculations for the evaporator and condenser. The control unit power is only used in the total power calculation.

2.5 Refrigerant Line Sizing Calculations

After cycle calculations have been completed, CYCLE_D can provide sizing information for the compressor suction and discharge lines and for the liquid line connecting the condenser and expansion valve. This information includes refrigerant velocity and tube lengths, and is provided for a range of diameters of straight type L copper tubing. The refrigerant mass flow rate determined during cycle simulations is used in these calculations.

The refrigerant velocity values presented by CYCLE_D are those at tube inlets. The refrigerant velocity varies in a tube because of pressure drop and change of specific volume. The lowest velocity, critical to oil return, is at the tube inlet because it has the lowest specific volume.

The program calculates tube lengths for the respective pressure drops imposed by the user in the simulated cycle (system). For the suction and discharge lines, these pressure drops are specified in the System Specifications tab in terms of the refrigerant dew point temperature drop. For the liquid line, CYCLE_D calculates the line length for the pressure drop that would result in bringing the subcooled refrigerant to flashing. Tube length calculations assume adiabatic tubes, lubricant-free refrigerant, and use refrigerant parameters corresponding to the average of inlet and outlet pressures. Note that CYCLE_D performs refrigerant line sizing calculations using several simplifications. The line sizing information is provided by CYCLE_D as general information and should not be used as strict design criteria for field application.

2.6 Simulation Results

Simulation results are generated in two categories: (1) for the thermodynamic cycle and (2) for the compressor and system. The cycle category presents the results obtained per unit mass of refrigerant. These results reflect refrigerant parameters only and are not affected by the auxiliary power to the indoor fan, outdoor fan, and controls. The compressor and system results are calculated for the system Cooling Capacity or Capacity Multiplier as specified by the user. CYCLE_D calculates line sizing information using the thermodynamic parameters identified throughout the cycle and the refrigerant mass flow rate needed to obtain the target system capacity.

2.7 Uncertainties in Simulation Results

Uncertainties in the simulation results are directly related to the uncertainties of thermodynamic properties calculated by the NIST REFPROP 8.0 (Lemmon et al., 2007) property routines incorporated into the CYCLE_D package. CYCLE_D uses the REFPROP default property models. The user should be aware that the uncertainties in these models vary considerably depending on the refrigerant, property, and thermodynamic state. It is thus impossible to give a simple, global statement regarding uncertainties. Even for the most-studied fluids with equations of state based on accurate, wide-ranging data, uncertainties are complicated functions of temperature and pressure. For details, refer to the original literature sources listed in Lemmon et al. (2007).

3. USING CYCLE_D

CYCLE_D consists of several menus and tabs, which allow the user to specify the cycle of interest.

3.1 Entering New Data

The user enters new data through three main tabs for inputting the refrigerant, cycle options, and system specifications. The **Refrigerant** tab provides three options: (1) single-compound fluid, (2) predefined blend, or (3) define new blend, all of which function similarly to the REFPROP 8.0 visual interface.

The **Cycle Options** tab presents the following cycle choices (Figure 1):

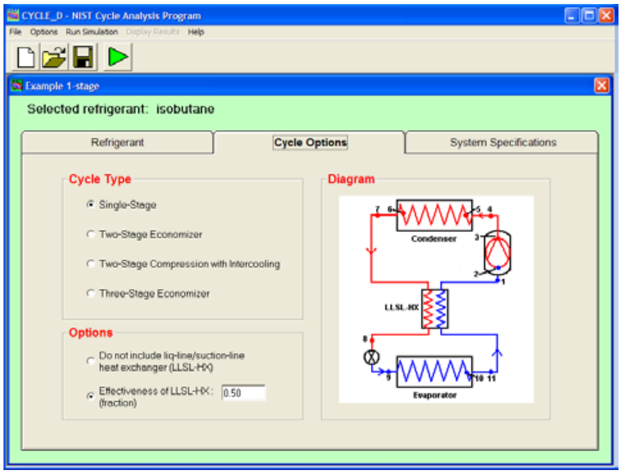
(1) Single-stage cycle with or without a LLSL-HX;
(2) Two-stage cycle with an economizer, including an option to optimize the intermediate pressure;
(3) Two-stage cycle with an intercooler;
(4) Three-stage cycle with an economizer.

The **System Specifications** tab facilitates entering a set of data specifying the system, which depends on the simulated cycle type. As an example, Figure 2 presents the specification input for a single-stage system operating in a subcritical regime. Rather than entering new data, the user may opt to open a previously stored input data file and modify it.

3.2 Presentation of Simulation Results

When the simulation is complete, a window with summary results is displayed. Four other windows are available by clicking on the icons shown on the power bar. Figure 3 shows all five windows, namely: (1) Summary Results (an example is shown as the top-most window in Figure 3), (2) System Schematic (an example is shown in Figure 4), (3) a *P-h* State Diagram (an example is shown in Figure 5), (4) *T-s* State Diagram (an example is shown in Figure 6), and (5) Line Sizing Information (an example is not shown here).

The user can then (1) modify the appearance of the *P-h* and *T-s* state diagrams, (2) save the simulation results, (3) print the simulation results, (4) modify the input data, refrigerant, or cycle type and re-run a simulation, or (5) quit the program.



Selected refrigerant: isobutane

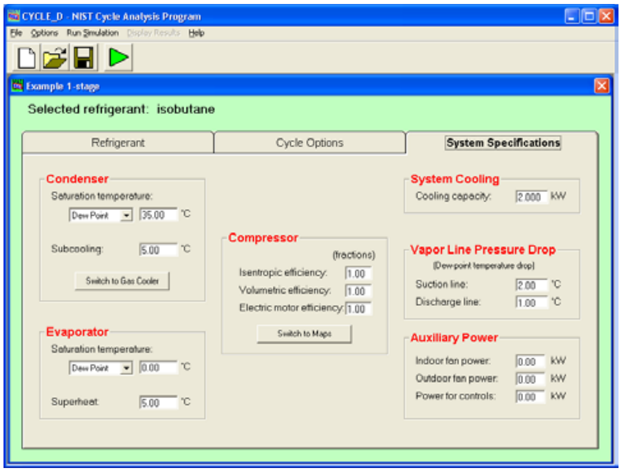
Cycle Type

- ● Single-Stage
- ○ Two-Stage Economizer
- ○ Two-Stage Compression with Intercooling
- ○ Three-Stage Economizer

Options

- ○ Do not include liq-line/suction-line heat exchanger (LLSL-HX)
- ● Effectiveness of LLSL-HX: (fraction) 0.50

Figure 1. Cycle Options tab.



Selected refrigerant: isobutane

Condenser

Saturation temperature: Dew Point 35.00 °C

Subcooling: 5.00 °C

Evaporator

Saturation temperature: Dew Point 0.00 °C

Superheat: 5.00 °C

Compressor (fractions)

Isentropic efficiency: 1.00

Volumetric efficiency: 1.00

Electric motor efficiency: 1.00

System Cooling

Cooling capacity: 2.000 kW

Vapor Line Pressure Drop (Dew-point temperature drop)

Suction line: 2.00 °C

Discharge line: 1.00 °C

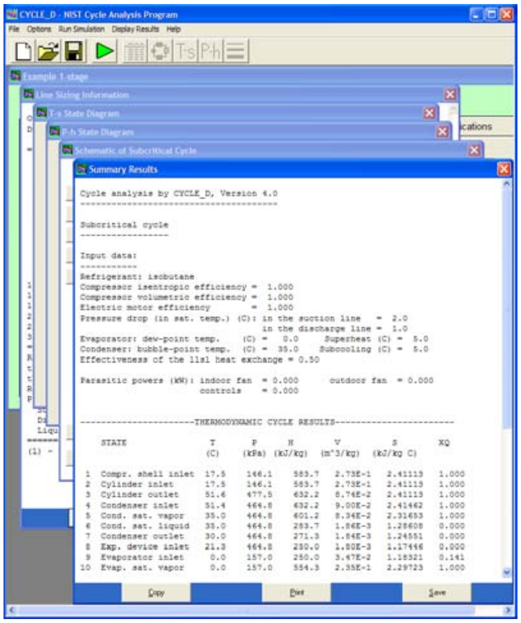
Auxiliary Power

Indoor fan power: 0.00 kW

Outdoor fan power: 0.00 kW

Power for controls: 0.00 kW

Figure 2. System Specifications tab.



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Cycle analysis by CYCLE_D, Version 4.0
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Subcritical cycle
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Input data:
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Refrigerant: isobutane
Compressor isentropic efficiency =  1.000
Compressor volumetric efficiency =  1.000
Electric motor efficiency        =  1.000
Pressure drop (in sat. temp.) (C): in the suction line   =  2.0
                                   in the discharge line =  1.0
Evaporator: dew-point temp.    (C) =   0.0     Superheat (C) =  5.0
Condenser: bubble-point temp.  (C) =  35.0    Subcooling (C) =  5.0
Effectiveness of the llsl heat exchange = 0.50

Parasitic powers (kW): indoor fan  = 0.000      outdoor fan  = 0.000
                       controls    = 0.000


----------------------THERMODYNAMIC CYCLE RESULTS----------------------

   STATE                   T       P       H        V          S         XQ
                          (C)    (kPa)  (kJ/kg)  (m^3/kg)   (kJ/kg C)

 1  Compr. shell inlet   17.5    146.1    583.7   2.73E-1   2.41113   1.000
 2  Cylinder inlet       17.5    146.1    583.7   2.73E-1   2.41113   1.000
 3  Cylinder outlet      51.6    477.5    632.2   6.74E-2   2.41113   1.000
 4  Condenser inlet      51.4    464.8    632.2   9.00E-2   2.41462   1.000
 5  Cond. sat. vapor     35.0    464.8    601.2   8.34E-2   2.31653   1.000
 6  Cond. sat. liquid    35.0    464.8    283.7   1.86E-3   1.28608   0.000
 7  Condenser outlet     30.0    464.8    271.3   1.84E-3   1.24551   0.000
 8  Exp. device inlet    21.3    464.8    250.0   1.80E-3   1.17446   0.000
 9  Evaporator inlet      0.0    157.0    250.0   3.47E-2   1.18321   0.141
10  Evap. sat. vapor      0.0    157.0    554.3   2.35E-1   2.29723   1.000
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Figure 3. Simulation results window.

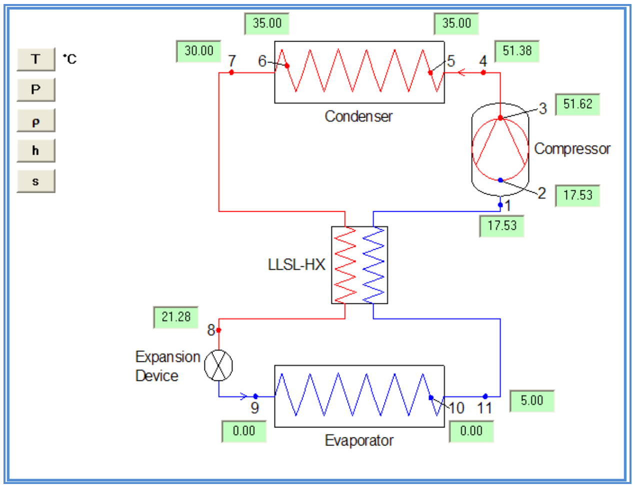

Fig. 4. System schematic window.

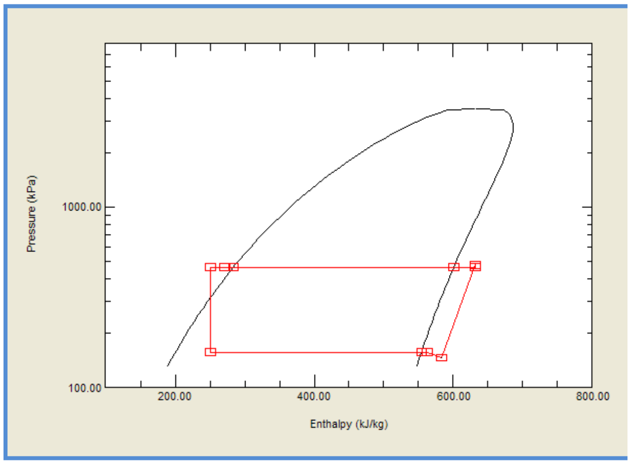

Figure 5. *P-h* state diagram.

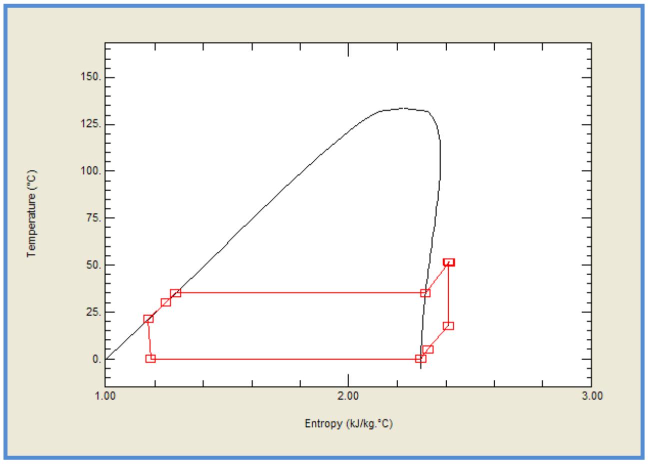

Figure 6. *T-s* state diagram.

4. SOME EXAMPLES

In this section, some brief examples, without presenting detailed results or analyses, are provided to demonstrate some of the capabilities of CYCLE_D. In the first example, operating conditions for typical unitary air conditioners (Calm and Domanski, 2004) are used to simulate the performance potentials of thirty nine single-component refrigerants (of the total 48); these 39 are the ones that have sufficiently high critical temperatures to ensure subcritical cycles. The condensing temperature is 46.1 °C, the evaporation temperature is 10 °C, and the compressor isentropic efficiency is 70 %. First, the simulations were conducted for evaporator superheat and condenser subcooling values of zero. Second, the simulations were conducted for evaporator superheat and condenser subcooling values of 5 °C. Third, the simulations were conducted for evaporator superheat and condenser subcooling values of zero, but now using an LLSL-HX. The results are plotted in Figure 7. Note: (1) each abscissa location represents a different refrigerant; (2) the results have been sorted in order of increasing volumetric cooling capacity (VCC) for the baseline case (first case); (3) the data points are connected by lines simply to aid the reader, and do not have physical significance. It is interesting to note that all of the cycles with subcooling and superheat values of 5 °C have better coefficient of performance (COP) and VCC values than the baseline cases; whereas, some of LLSL-HX cycles have better and some have worse COP and VCC values than the baseline cases, implying that the LLSL-HX helps some refrigerants and penalizes others.

A second example is to consider transcritical cycles for five of the remaining nine single-compound refrigerants; these five refrigerants are ones where the high-side temperature and the evaporation temperature are such that the cycles are transcritical. The evaporation temperature is 10 °C, the compressor isentropic efficiency is 70 %, and the evaporator superheat is 0 °C. The cycle uses the optimum high-side gas cooling pressure with the gas cooler refrigerant outlet temperature specified as 35 °C, and a LLSL-HX with an effectiveness value of 75 %. The simulation results are presented in Table 1.

Table 1. Transcritical cycle simulations for 5 fluids.

Refrigerant	COP	VCC ($kJ\ m^{-3}$)	Optimum Gas Cooler Pressure (kPa)
R-116	3.057	6785	4734
R-13	3.556	8102	4750
R-170	3.844	9800	5391
R-23	3.441	11136	6359
R-744	3.625	15875	8484

A third example is the transcritical CO_2 cycle. The evaporation temperature is 10 °C, the compressor isentropic efficiency is 70 %, and the evaporator superheat is 0 °C. The cycle uses the optimum high-side pressure and a LLSL-HX with an effectiveness value of 75 %. The gas cooler refrigerant outlet temperature is varied from 32 °C to 48 °C and the results are plotted in Figures 8 and 9. Figure 8 shows the COP and VCC values and Figure 9 shows the optimum gas cooler refrigerant pressure, both as functions of the gas cooler refrigerant exit temperature.

A fourth and final example is for the two-stage economizer cycle for R-410A. The evaporation temperature is 10 °C, the condensation temperature is 46.1 °C, the compressor isentropic efficiency is 70 %, and the evaporator superheat and condenser subcooling values are zero. The intermediate pressure is varied from 1100 kPa to 2700 kPa, and the results are plotted in Figure 10.

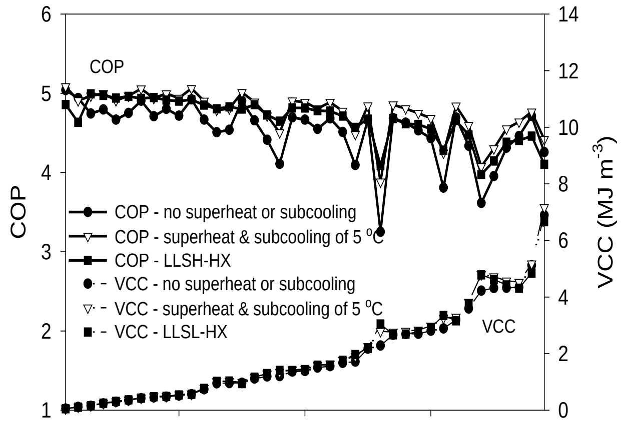

Figure 7. COP & VCC for subcritical cycles for 39 single-component refrigerants.

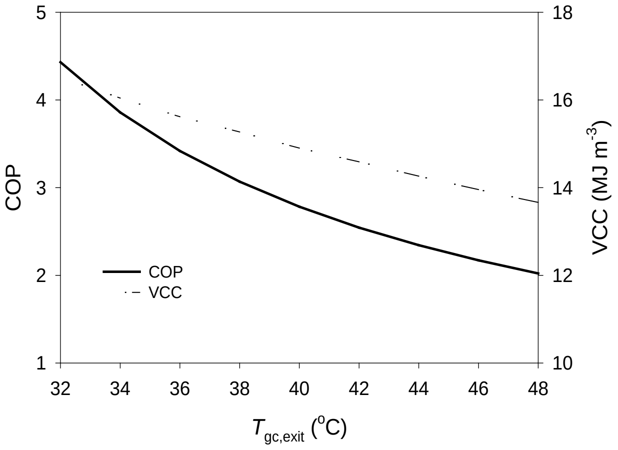

Figure 8. COP & VCC for a CO_2 transcritical cycle as a function of gas cooler exit temperature.

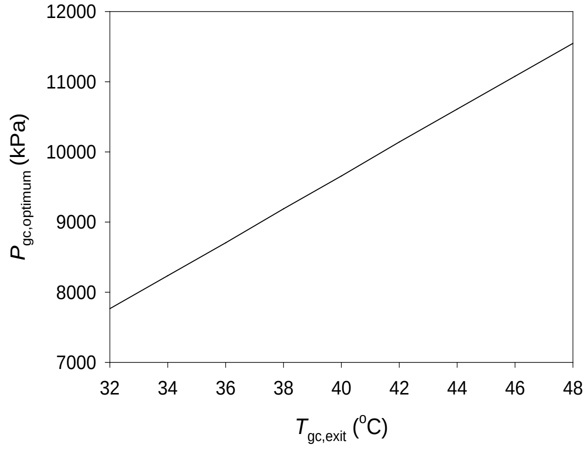

Figure 9. Optimum gas cooler pressure for a CO_2 transcritical cycle as a function of gas cooler exit temperature.

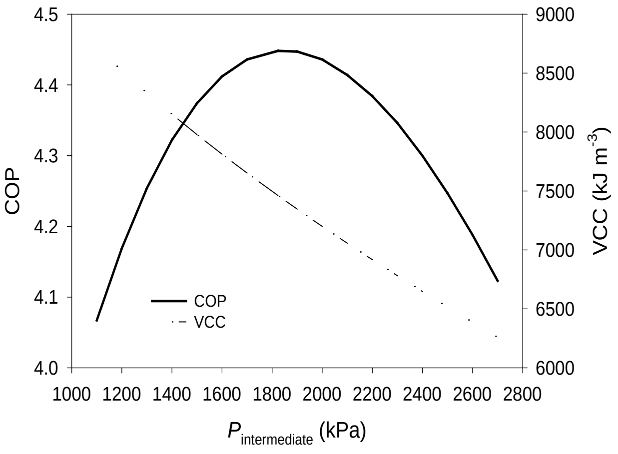

Figure 10. COP & VCC for a two-stage economizer cycle as a function of intermediate pressure.

5. CONCLUSIONS

This paper presents Version 4.0 of the NIST Standard Reference Database 49 – CYCLE_D: NIST Vapor Compression Cycle Design Program. CYCLE_D Version 4.0 simulates vapor compression refrigeration cycles that use single-component refrigerants or refrigerant mixtures. The model can simulate a basic subcritical or transcritical refrigeration cycle, both with or without a liquid-line/suction-line heat exchanger. In addition, the model can simulate a subcritical two-stage economizer cycle, a subcritical three-stage economizer cycle, and a subcritical two-stage compression cycle with intercooling.

ACKNOWLEDGEMENTS

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NOMENCLATURE

COP	Coefficient of Performance	h	enthalpy (kJ kg^{-1})
LLSL-HX	liquid-line/suction-line heat exchange	P	pressure (kPa)
T	temperature (K or °C)	s	entropy (kJ kg^{-1} K^{-1})
VCC	Volumetric Cooling Capacity (kJ m^{-3})	ρ	density (kg m^{-3})

Subscripts

gc,exit	gas cooler exit
gc,optimum	gas cooler optimum value
intermediate	two-stage economizer cycle intermediate value

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Calm, J.M. and Domanski, P.A., 2004. R-22 replacement status. ASHRAE J. 46 (8), 29-39.

Lemmon, E.W., Huber M.L., and McLinden, M.O., 2007. NIST Reference Fluid Thermodynamic and Transport Properties-REFPROP. NIST Standard Reference Database 23, Version 8.0, http://www.nist.gov/srd/nist23.htm, National Institute of Standards and Technology, Gaithersburg, MD.

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