CYCLE_D-HX:
NIST Vapor Compression Cycle Model Accounting for Refrigerant Thermodynamic and Transport Properties

Version 2.0
User's Guide

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NIST

National Institute of
Standards and Technology
U.S. Department of Commerce

NIST Technical Note 2134

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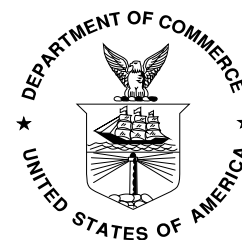
Version 2.0
User's Guide

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January 2021

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ABSTRACT

The CYCLE_D-HX software package simulates the performance of single-component refrigerants and refrigerant blends in subcritical vapor-compression refrigeration cycles. The basic system simulated by CYCLE_D-HX consists of a compressor, discharge line, condenser, expansion device, evaporator, compressor suction line, and an optional liquid-line/suction-line heat exchanger. The other cycles may contain a second compressor, one or two economizers, or an intercooler.

In contrast to simplified vapor compression cycle models, which require refrigerant saturation temperatures in the evaporator and condenser as input, CYCLE_D-HX establishes saturation temperatures in the heat exchangers using the temperatures profiles of heat source and heat sink and the mean effective temperature differences (ΔT_{hx}) in the evaporator and condenser, respectively, which are specified as inputs to the program. This representation of heat exchangers facilitates the inclusion of both thermodynamic and transport properties in cycle simulations and makes CYCLE_D-HX suitable for comparative evaluations of different refrigerants, particularly when applied in systems relying on forced-convection heat transfer of refrigerant in the heat exchangers. This software package was developed by the National Institute of Standards and Technology (NIST), is not subject to copyright protection, and is in the public domain.

KEY WORDS

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1. INTRODUCTION

The CYCLE_D-HX software package simulates the performance of single-component refrigerants and refrigerant blends in subcritical vapor-compression refrigeration cycles. The basic system simulated by CYCLE_D-HX consists of a compressor, discharge line, condenser, expansion device, evaporator, compressor suction line, and an optional liquid-line/suction-line heat exchanger. The other cycles may contain a second compressor, one or two economizers, or an intercooler. These advanced cycles do not include the optional liquid-line/suction-line heat exchanger (Brignoli et al., 2017).

In contrast to simplified vapor compression cycle models, such as CYCLE_D (Brown et al., 2017), which require refrigerant saturation temperatures in the evaporator and condenser as input, CYCLE_D-HX establishes saturation temperatures in the heat exchangers using the temperatures profiles of heat source and heat sink and the mean effective temperature differences (ΔT_{hx}) in the evaporator and condenser, respectively, which are specified as input to the program. This representation of heat exchangers facilitates the inclusion of both thermodynamic and transport properties in cycle simulations and makes CYCLE_D-HX suitable for comparative evaluations of different refrigerants, particularly when applied in systems relying on forced-convection heat transfer of refrigerant in the heat exchangers.

All cycle calculations are based on refrigerant properties as represented in the National Institute of Standards and Technology (NIST) Reference Fluid Thermodynamic and Transport Properties Program – REFPROP, Version 10.0 (Lemmon et al., 2018).

2. INSTALLATION

2.1 System Requirements

- Personal computer capable of running Microsoft Windows 7, 8, 10, or XP with Service Pack 3
- Hard disk with 114 MB for the installation process. Once the installation is completed, the program will occupy 15 MB of disk space.
- Screen resolution should be set to 800 x 600 or higher to view images in their entirety.

2.2 Installation Procedure

The CYCLE_D-HX installation file cycle_d-hx_setup.zip is available for free download at https://www.nist.gov/ services-resources/software/cycled-hx-nist-vapor-compression-cycle-model-accounting-refrigerant-0. Download it and extract to a folder of your choice to obtain Setup.exe and Cycle_D-HX.msi. Execute Setup.exe and follow installation instructions. Once installed, execute CYCLE_D-HX using the Start Menu.

3. MODELING APPROACH

3.1 Thermodynamic Cycle

The CYCLE_D-HX model builds on the concept of using temperature profiles of the heat transfer fluids (HTFs) and mean effective temperature differences (ΔT_{hx}) for the evaporator and condenser (Domanski and McLinden, 1992), which facilitates the accounting for effects of refrigerant thermophysical properties, pressure drop, and heat transfer performance on the cycle performance (Brown et al., 2002a and 2002b).

In its simplest form, the simulated system consists of a compressor, condenser, adiabatic expansion device, and evaporator. Figure 1 shows the cycle and key thermodynamic states for this system on the temperature-entropy diagram. The basic cycle simulation requires the following specifications:
- refrigerant
- HTF temperature profiles (inlet and outlet temperatures to the evaporator and condenser)
- ΔT_{hx} (or UA_{hx}, overall heat transfer conductance) and refrigerant pressure drop in the heat exchangers
- net system cooling capacity (evaporator capacity adjusted for the heat added by the indoor coil fan)
- parameters characterizing hardware components, except the expansion device, which is modeled as being isenthalpic (depend on the selected cycle configuration, see Sections 4.2.2 and 4.2.3).

The user has the option to specify the power requirements of the indoor fan, outdoor fan, and controls for the system.

CYCLE_D-HX has two options for representations of heat exchangers, 'Impose' or 'Simulate'; these terms reflect whether ΔT_{hx} (or UA_{hx}) and refrigerant pressure drop are specified (imposed) by the user or simulated. The

'Impose' option is the basic simulation mode of CYCLE_D-HX and must be executed first. It requires the user to specify the values of ΔT_{hx} (or UA_{hx}) and refrigerant pressure drop in the evaporator and condenser at the operating conditions used in the current cycle simulation. These values can be taken from laboratory tests or can be estimated based on typical values reported for the studied application.
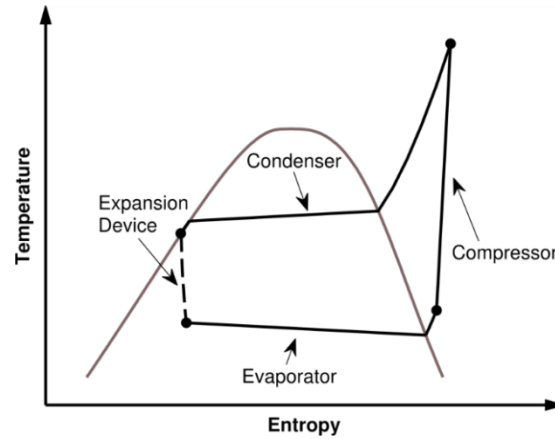
Figure 1. Basic vapor compression cycle

The 'Simulate' option becomes available when a cycle simulation with the 'Impose' option was executed first with a checked box instructing CYCLE_D-HX to 'Establish Reference Parameters'. In this case, the program will establish heat transfer and pressure drop parameters for the evaporator and condenser and will use them during a 'Simulate-option' cycle simulation run for simulating heat exchangers' UA_{hx} (and ΔT_{hx}) and pressure drop at different operating conditions or with a different refrigerant, as explained in the Section 3.2. Thus, CYCLE_D-HX accounts for the effect of thermophysical properties on heat exchanger performance on a relative basis with reference to performance in the 'Impose' cycle simulation run. In other words, the 'Impose-option' cycle simulation run is a 'Reference' run that establishes 'Reference Parameters' for 'Simulate-option' cycle simulation runs. Note that the 'Simulate' option is applicable only to systems relying on forced-convection heat transfer in the heat exchangers because of the analysis and correlations employed; i.e.., to serpentine air-to-refrigerant, not shell-and-tube heat exchangers.

Aside from the different ways of deriving ΔT_{hx} (or UA_{hx}) and refrigerant pressure drop values, the cycle iteration scheme is the same for the 'Impose' and 'Simulate' cycle simulation runs. For given ΔT_{hx} (or UA_{hx}) and refrigerant pressure drop values, the solution sequence starts with estimating refrigerant saturation temperatures in the evaporator and condenser. Based on the thermodynamic cycle with established refrigerant temperature profiles and HTF temperature profiles, the model calculates ΔT_{hx} values and compares them to the values given at the outset. The model iterates evaporator and condenser saturation temperatures until the computed ΔT_{hx} values approach the input values within a convergence parameter. The model also iterates the refrigerant mass flow rate to match the specified system cooling capacity.

3.2 Evaporator and Condenser

The evaporator and condenser can be counterflow, crossflow, or parallel flow. They are represented by the mean effective temperature difference between the refrigerant and HTF, as defined by Eq. (1):

$$\Delta T_{hx} = Q_{hx}/UA_{hx} \tag{1}$$

where capacity, Q_{hx}, is the product of refrigerant mass flow rate and enthalpy change in the evaporator or condenser, as appropriate.

CYCLE_D-HX calculates ΔT_{hx} considering individual heat exchanger sections with different flow regimes, e.g., superheated vapor, two-phase refrigerant, and subcooled liquid may exist in a condenser. Assuming the same overall heat transfer coefficient in each section of the heat exchanger, an equation is obtained in which ΔT_{hx} is a harmonic mean weighted with a fraction of heat transferred in individual sections (Domanski and McLinden, 1992):

$$\frac{1}{\Delta T_{hx}} = \frac{Q_1}{Q_{hx} \Delta T_1} + \frac{Q_2}{Q_{hx} \Delta T_2} \ldots = \frac{1}{Q_{hx}} \sum \frac{Q_i}{\Delta T_i} \tag{2}$$

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At the outset of iteration for a condenser, the model calculates ΔT_{hx} based on sections corresponding to the superheated vapor, two-phase refrigerant, and subcooled liquid. Then, the model bisects each section and uses Eq. (2) to calculate a new value of ΔT_{hx}. The model repeatedly bisects each subsection until the ΔT_{hx} values obtained from two consecutive evaluations agree within a convergence parameter. CYCLE_D-HX calculates ΔT_{hx} each time the cycle iteration scheme assigns a new saturation temperature in a heat exchanger.

The use of the 'Simulate' option requires the 'Impose' option simulation run to be executed first with the 'Establish Reference Parameters' box checked. In this case, the program will also solicit the following heat exchanger geometry inputs:
- tube inner diameter and length
- tube inner surface (smooth or enhanced)
- number of tubes per circuit
- number of refrigerant parallel circuits.

For the purpose of heat transfer analysis, CYCLE_D-HX considers the total resistance to heat transfer in a heat exchanger (R_{hx}) to consist of the resistance on the refrigerant side (R_r) in the two-phase section only, and combined resistances of the heat exchanger material and HTF ($R_{tube} + R_{HTF}$):

$$R_{hx} = 1/UA_{hx} = R_r + (R_{tube} + R_{HTF}) \tag{3}$$

where: $R_r = 1/(h_r \cdot A_r)$
A_r = heat transfer area on the refrigerant side (m^2) $\tag{4}$

Once the cycle simulation has converged and refrigerant mass flow rate and capacity have been determined, the h_r, and UA_{hx}, can be calculated leading to the value of ($R_{tube} + R_{HTF}$). Following the assumption that R_{HTF} is independent of HTF temperature profiles, ($R_{tube} + R_{HTF}$) can be used for simulations with different refrigerants to determine UA_{hx} and ΔT_{hx}, through calculations of h_r, R_r, and R_{hx}.

In the above calculation scheme, for smooth tubes, CYCLE_D-HX uses correlations by Wojtan et al. (2005a and 2005b) and Shah (2009) for calculating the forced-convection heat-transfer coefficient for evaporation and condensation, respectively. For enhanced tubes, the model applies a correction to the smooth tube h_r value presented by Shlager et al. (1989).

The modeling of evaporator and condenser refrigerant pressure drop relies on a similar concept to that for the heat-transfer process. For smooth tubes, the model determines a pressure multiplication factor from the 'Impose' run by dividing the imposed refrigerant pressure drop by the value predicted by applicable correlations (Eq. 5).

$$factor_{\Delta p} = \frac{\Delta P_{imposed}}{\Delta P_{predicted}} \tag{5}$$

where $\Delta P_{predicted}$ is calculated for smooth tubes by the Muller-Steinhangen and Heck (MSH) correlation (Muller-Steinhangen and Heck,1986). For enhanced tubes, the MSH value is corrected according to Choi et al. (2001).

3.3 Compressor

CYCLE_D-HX basic cycle provides two options for representation of the compressor: the 'Compressor Efficiency' option and the 'Compressor Map' option. For other advanced cycles, only the 'Compressor Efficiency' option is available.

The 'Compressor Efficiency' option requires input values of isentropic efficiency, compressor volumetric efficiency, 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 compression process occurs in stages, the isentropic efficiency for each stage can be independently specified. If the cycle includes two compressors, their inputs must be independently specified. If the value used for the electric motor efficiency is less than one, the entire heat rejected by the electric motor(s) is assigned as heat superheating the suction vapor within a hermetic compressor shell before the compressor's cylinder inlet.

For the single-stage cycle with the 'Simulate' option selected, CYCLE_D-HX offers the option of accounting for the dependence of isentropic efficiency on the compression ratio, as it was postulated by several researchers evaluating different refrigerants (Brown et al., 2002b). This dependence is expressed by Eq. (6).

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$\eta_s = C - 0.05\,\vartheta$ (6)

where ϑ is a ratio of the compressor discharge pressure to suction pressure.

Equation (6) has the same slope as the relation derived from experimental data by Brown et al. (2002b); C is a constant calculated within the 'Impose' run using the entered isentropic efficiency and pressure ratio established in this 'Impose' run for the reference refrigerant.

The 'Compressor Map' option uses compressor-map correlations, which are derived from compressor calorimeter tests for a specific refrigerant and can only be only with this refrigerant. Three types of correlations are allowed. They are described in Appendix C.

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 compressor capacity and power (calculated by compressor-map correlations) and for indoor and outdoor fan powers (entered by the user). Power for the system controls 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 that the system can provide the specified capacity; the compressor power is adjusted proportionally to the capacity. The power input to the indoor and outdoor fans and system controls are unaffected by the specified capacity value.

Compressor-map equations correlate the compressor performance at prescribed values of the suction superheat and condenser subcooling used during the calorimeter test. To allow simulations at user-specified conditions, the following steps and assumptions are employed 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 the 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 set during the calorimeter tests, adjusted for the different specific volume of the suction vapor caused by a different superheat.

3.4 Economizer(s) and Intercooler
The economizers and intercooler are represented by the refrigerant pressures for these intermediate components. For the economizer cycles, the user can specify the intermediate pressures or have them optimized by the program for the maximum coefficient of performance.

3.5 Suction Line and Discharge Line
The pressure drop in the suction and discharge lines can be specified by assigning a value of the corresponding saturation temperature drop of the refrigerant. CYCLE_D-HX assumes the lines are adiabatic.

3.6 Liquid-Line/Suction-Line Heat Exchanger
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 zero effectiveness denotes no LLSL-HX in the cycle.

3.7 Indoor Fan, Outdoor Fan, and Controls
The auxiliary powers are 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.

3.8 Refrigerant Line Sizing Calculations
After cycle calculations have been completed, CYCLE_D-HX 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 for a range of diameters of straight type L copper tubing.

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CYCLE_D-HX calculates refrigerant velocity and tube length using refrigerant state parameters and mass flow rate determined during the cycle simulation, and the predetermined pressure drop in the refrigerant lines. For the suction and discharge lines, the pressure drops are those specified by the user in the **Cycle Specifications** tab in terms of the refrigerant dew-point temperature drop. For the liquid line, CYCLE_D-HX calculates the line length for the pressure drop that would result in bringing the subcooled refrigerant to flashing. The refrigerant tube length is calculated by the following equation:

$$L = 2 \cdot \Delta P \cdot D \cdot \rho / (f \cdot G^2) \tag{7}$$

where: D = tube inside diameter (m)
        f = Darcy friction factor
        G = refrigerant mass flux (kg/m^2)
        L = tube length (m)
       ΔP = pressure drop (Pa)
       ρ = refrigerant density (kg/m^3)

For friction factor calculation with the Reynolds number (Re) less than 2000 (fully developed laminar flow), Eq. (8) is used (White, 2005):

$$f = 64/Re \tag{8}$$

For higher Reynolds numbers (turbulent flow) the Petukhov correlation is used (Petukhov et al., 1973):

$$f = 1/(1.58 \cdot \ln(Re) - 3.28)^2 \tag{9}$$

The calculations assume lubricant-free refrigerant flowing in adiabatic tubes and use refrigerant properties computed at the average of the inlet and outlet pressures.

The refrigerant velocity values presented by CYCLE_D-HX are those at tube inlets. Refrigerant velocity varies in a tube because of a pressure drop and change of specific volume. The lowest velocity, critical to oil return, is at the tube inlet because of the lowest specific volume. The program does not provide line length values for zero pressure drops; i.e., for zero condenser subcooling for the liquid line, and for zero drop in saturation temperatures for the vapor lines. Also, the program does not provide results for the liquid and suction lines if the system employs a liquid-line/suction-line heat exchanger.

Note that CYCLE_D-HX performs refrigerant line sizing calculations using several simplifications. The line sizing information is provided by CYCLE_D-HX for general orientation and should not be used as strict design criteria for field application.

3.9 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 circulated by the compressor. These results reflect refrigerant parameters only and are not affected by the auxiliary power input to the indoor fan, outdoor fan, and controls (Refer to Figure 17 and Table 1) .

If the electric motor efficiency is less than one, the user's allocation of the waste heat will affect the simulation results. The waste heat is calculated by the following equation:

$$q_{comp\ motor} = (1 - \eta_{comp\ motor})(h(3) - h(2)) \tag{10}$$

where: $q_{comp\ motor}$ = compressor motor waste heat (kJ/kg)
        $\eta_{comp\ motor}$ = compressor motor efficiency (fraction)
       $h(3)$ and $h(2)$ = refrigerant enthalpy at the cylinder outlet and inlet, respectively (kJ/kg).

The allocation of the waste heat as an extra evaporator load directly reduces the cooling capacity provided by the evaporator to its environment by the amount of the waste heat. Allocation of the waste heat as an extra condenser load directly increases the heating capacity provided by the condenser to its environment by the amount of the waste heat. In this case, cooling of the electric motor is implemented with the refrigerant pumped by a liquid pump from the condenser outlet to the motor, and then returned to the condenser inlet. The flow rate of the refrigerant pumped by the liquid pump is controlled so the refrigerant enthalpy after absorbing heat from the electric motor equals the enthalpy of refrigerant at the compressor outlet.

The allocation of waste heat as an extra evaporator or condenser load does not alter the state parameters of the thermodynamic cycle because cycle simulations are constrained by the specified saturation temperature (pressure) for the evaporator and the saturation temperature (pressure) and subcooling for the condenser. However, the state parameters of the thermodynamic cycle are altered by allocating the waste heat to the suction vapor, which increases refrigerant temperature at the cylinder inlet.

The compressor and system results are calculated based on the Cooling Capacity or Capacity Multiplier specified by the user. CYCLE_D-HX 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. The naming convention used for simulation results is explained in Appendix D.

3.10 Refrigerants and Refrigerant Properties

CYCLE_D-HX uses REFPROP 10.0 (Lemmon et al., 2018) routines for calculating thermodynamic properties of pure refrigerants and refrigerant mixtures and applies the default models recommended in REFPROP for property predictions. It includes 75 single-compound refrigerants, which can be selected as the working fluid. These pure refrigerants can also be combined to form blends of up to five components. In addition, CYCLE_D-HX includes 13 predefined mixtures. See Appendix A for the list of available single-compound refrigerants and Appendix B for the list of available predefined mixtures.

3.11 Uncertainties in Simulation Results

Uncertainties in the simulation results are directly related to the uncertainties of thermodynamic properties calculated by REFPROP routines incorporated into the CYCLE_D-HX package. CYCLE_D-HX uses the REFPROP default property models, which should provide the most accurate predictions. The user should be aware that the uncertainties in these models vary somewhat depending on the refrigerant, property, and thermodynamic state. It is thus impossible to give a simple, global statement of 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., 2018).

4.   USE OF CYCLE_D-HX

This section explains how to use CYCLE_D-HX: to specify a cycle/system, to run a simulation, to present simulation results, and to manage input/output files. In addition to this tutorial, users may refer to CYCLE_D-HX's **Help** menu.

Once CYCLE_D-HX is installed on your computer, double click on the **CYCLE_D-HX** icon to start the program. The opening screen will be displayed first. After clicking the **Continue button, t**he main CYCLE_D-HX screen will load. Figure 2 shows the main screen after a new session has been started (click on the most-left icon on the power bar) with a Refrigerant tab selected and the user has clicked on the 'Options' tab.
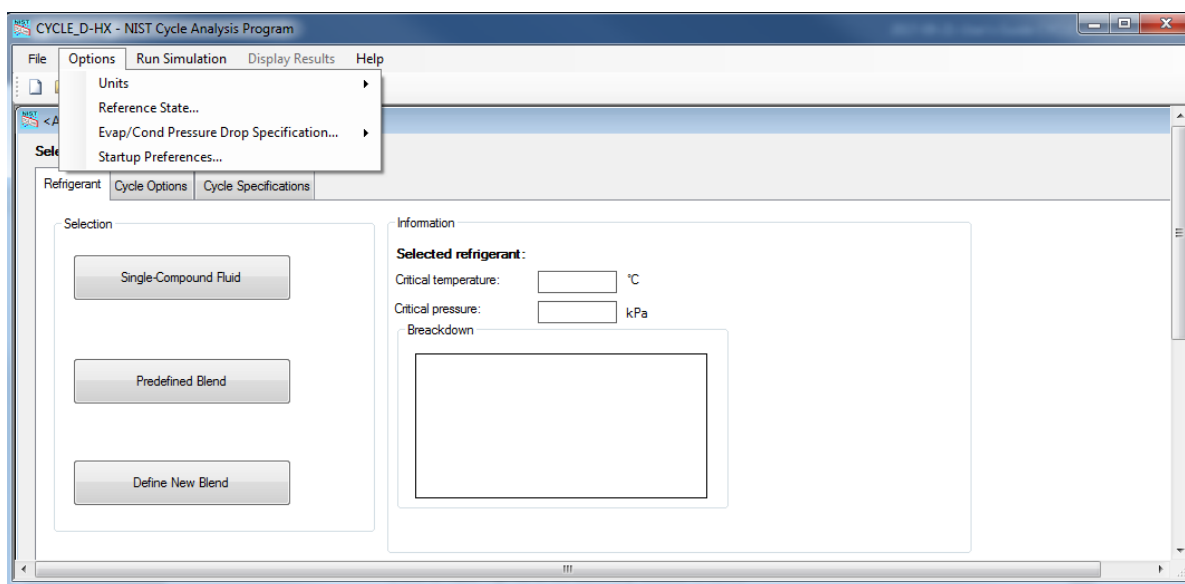

Figure 2. Main window with **Refrigerant** tab and activated **Options** pull-down menu

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4.1 Specifying User's Options

User's options are displayed under the **Options** pull-down menu. There are three options for units in the **Options/Units** menu item: (1) SI with temperatures specified in K, (2) SI with temperatures specified in °C, or (3) I-P with temperatures specified in °F.

To select the reference state for enthalpy and entropy calculations, click on the **Options/Reference State** menu item, after which Figure 3 appears. The reference states are completely arbitrary; however, three common ones are provided: (1) saturated liquid enthalpy and entropy values set to zero at the selected refrigerant's normal boiling point (designated as NBP), (2) saturated liquid enthalpy and entropy values set to zero at -40 °C (designated as ASHRAE), and (3) saturated liquid enthalpy and entropy set to 200 kJ/kg and 1 kJ/(kg·K), respectively (designated as International Institute of Refrigeration (IIR) convention). The first radio button option, if selected, uses the REFPROP default reference state for that particular refrigerant. If a blend is selected, the reference state is applied to the blend and not to each pure component. Note that the calculations of performance and energy transfers are not dependent on the reference state, rather, only the absolute values of enthalpy and entropy are affected.
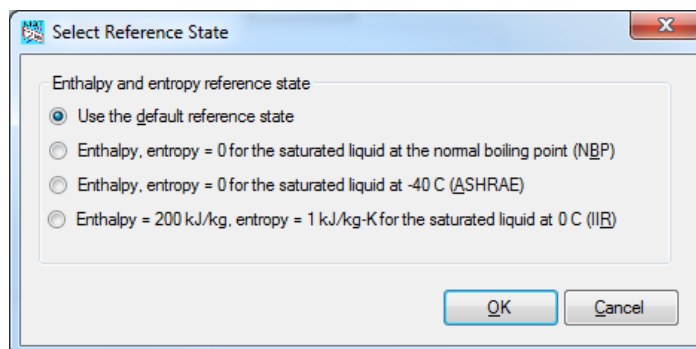
Figure 3. Selecting reference state for enthalpy and entropy calculations

Figure 4 shows the choices for **Startup Preferences.** When the user sets the option to load an initial file (which could be the last file used or a default file), the units and reference state preferences stored in that file become the current preferences for a given session. If desired, these preferences can be changed manually using the **Options** pull-down menu. Note that loading any existing file anytime during a simulation session will change the current preferences for this session to those stored in the loaded file.
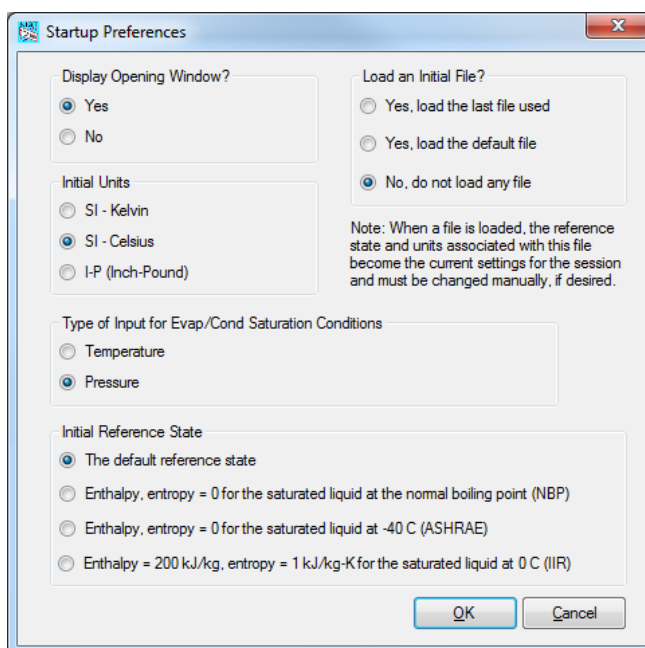
Figure 4. Selecting **Startup Preferences**

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4.2 Entering New Input Data

The user enters new input data using three tabs titled **Refrigerant**, **Cycle Options**, and **Cycle Specifications** shown in Figure 2. The sequence of using these tabs does not matter; however, it is recommended to follow the tab order because the choice made under the first tab may affect the options available of the second, and the choice made under the second may affect the input requirements on the third tab.

4.2.1 Refrigerant Tab

The **Refrigerant** tab provides three options: (1) **Single-Compound Fluid** (Figure 5), (2) **Predefined Blend** (Figure 7), and (3) **Define New Blend** (Figure 9).
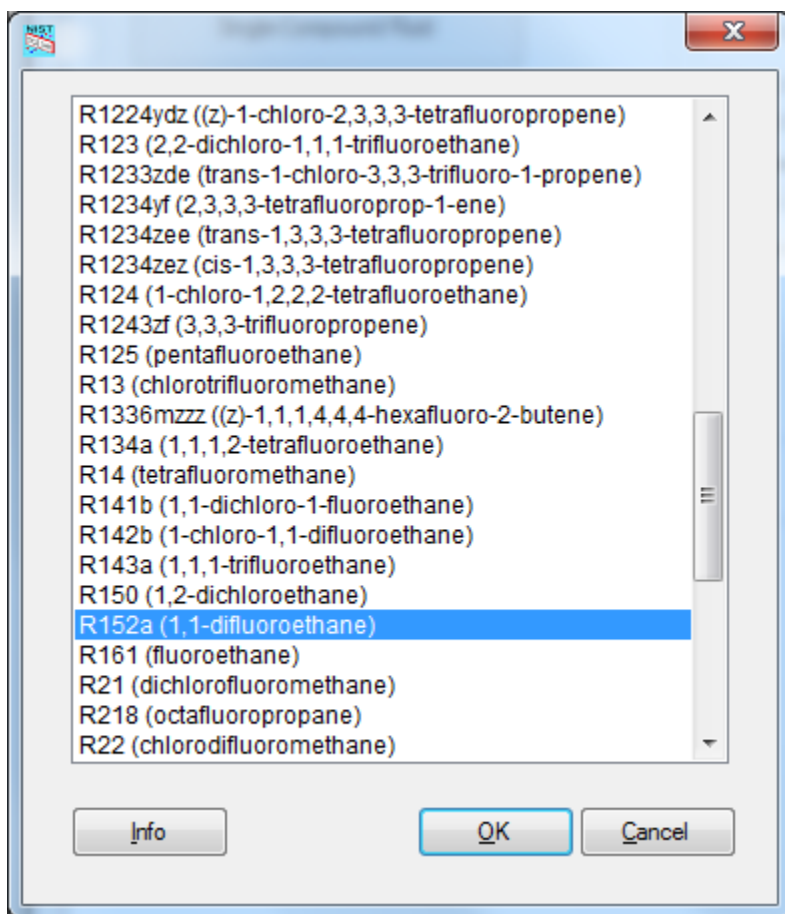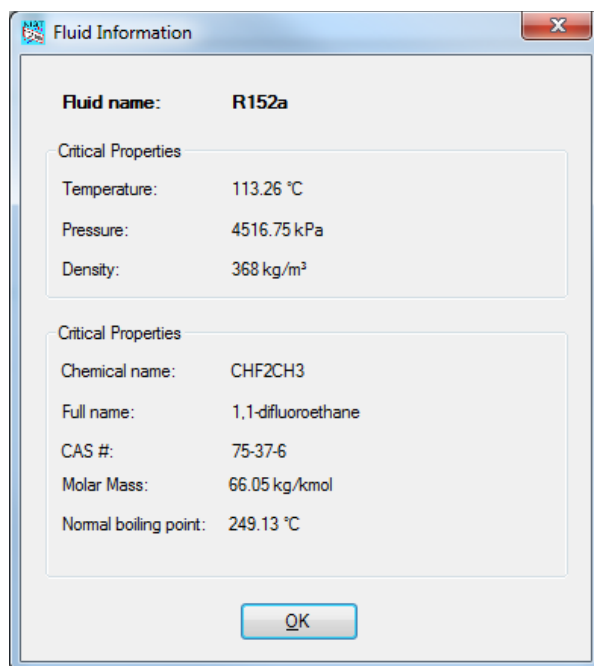
Figure 5. Selecting a single-compound fluid

The user may click the **Info** button, shown in Figures 5 and 7, to display information for the selected refrigerant, examples of which are shown in Figures 6 and 8 for a single-compound fluid and predefined blend, respectively.
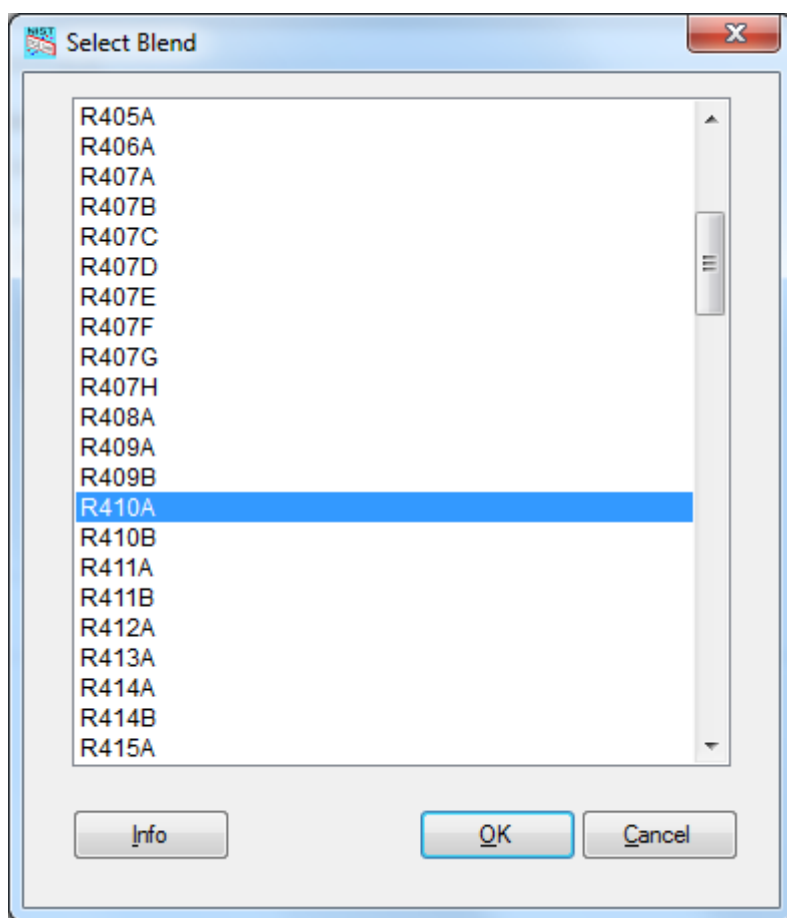
Figure 6. Information on a single-compound fluid

Figure 7. Selecting a predefined blend

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Figure 8. Information on a predefined blend

For the **Define New Blend** option (Figure 9), refrigerants from the left-hand list can be added to the blend (right-hand list) via the **Add** button. Refrigerants can be deleted from the mixture by using the **Remove** button. After specifying the blend and clicking **OK**, Figure 10 appears. The composition can be modified by typing the appropriate values in the boxes and clicking **OK**. The composition can be specified in terms of mass fractions or mole fractions by toggling the combo box. Note that the mass and mole fractions must sum to one; if they do not, an error message will appear. The new blend can be stored by clicking the **Store** button. If the blend is stored by the user, it will thereafter appear in the list of predefined blends (Figure 7).
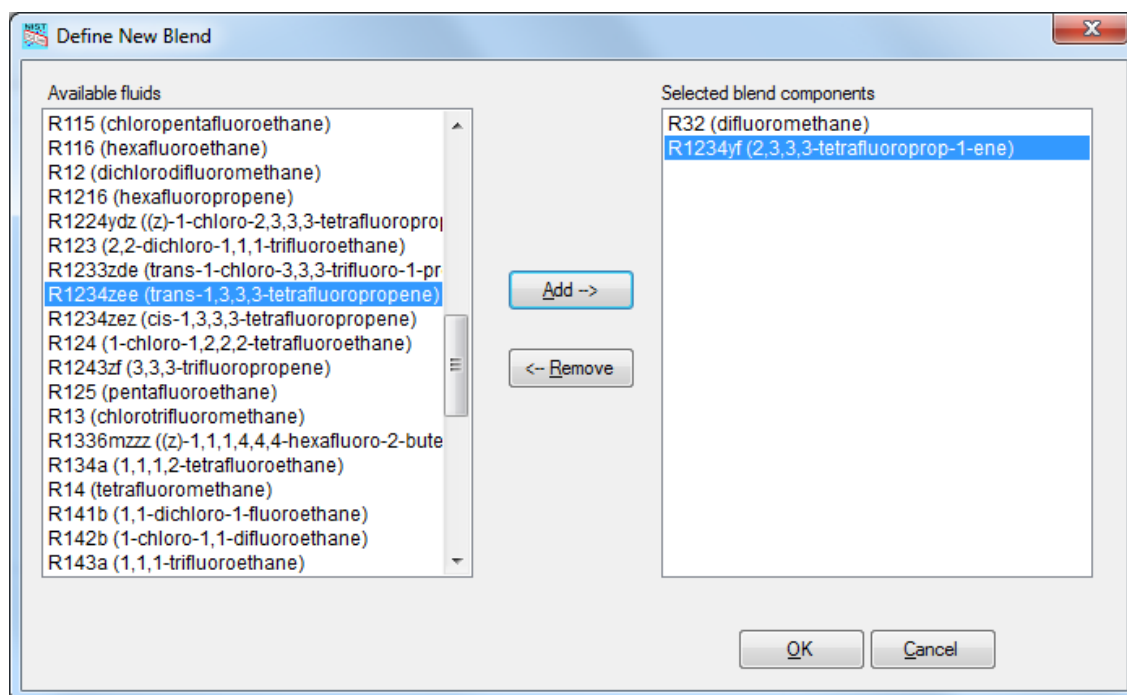
Figure 9. Defining a new blend
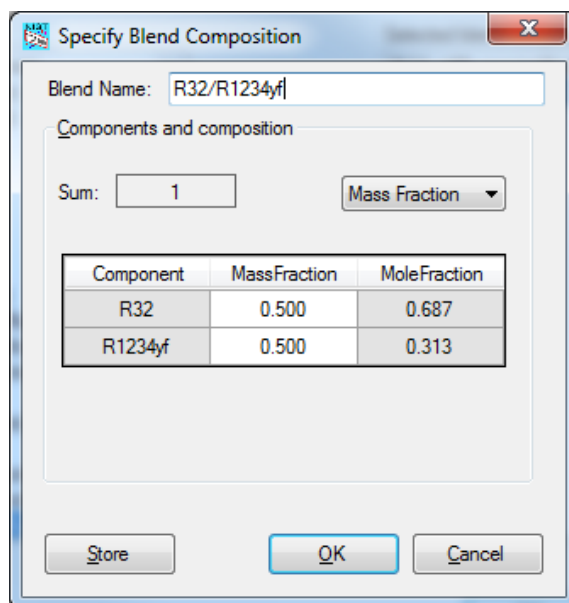
Figure 10. Specifying the new blend composition

The 'fluids', 'mixtures' and 'UserDefinedMixture' folders containing REFPROP fluid and mixture files are located in C:\Users\[UserID]\AppData\Local\CYCLE_D_HX\CYCLE_D-HX 2.0\1.0.0.0. This path may be hidden according to the Windows setting. To get the path visible, on 'Windows Search' type 'Folder Options', open the 'Folder Options' window, select the 'View' tab, under 'Hidden files and folders' check 'Show hidden files, folders and drives'. A REFPROP fluid or predefined mixture file can be added to the 'fluids' or 'mixtures' folders respectively, and will appear in the corresponding selection list when the program runs (if the list window is already opened, close and reopen it to get the list refreshed).

4.2.2 Cycle Options Tab

The **Cycle Options** tab presents the following cycle choices (Figure 11):
- Single-stage cycle with or without a LLSL-HX
- Two-stage cycle with an economizer, which includes an option to optimize the intermediate pressure
- Two-stage cycle with an intercooler
- Three-stage cycle with an economizer, which includes an option to optimize the intermediate pressure.
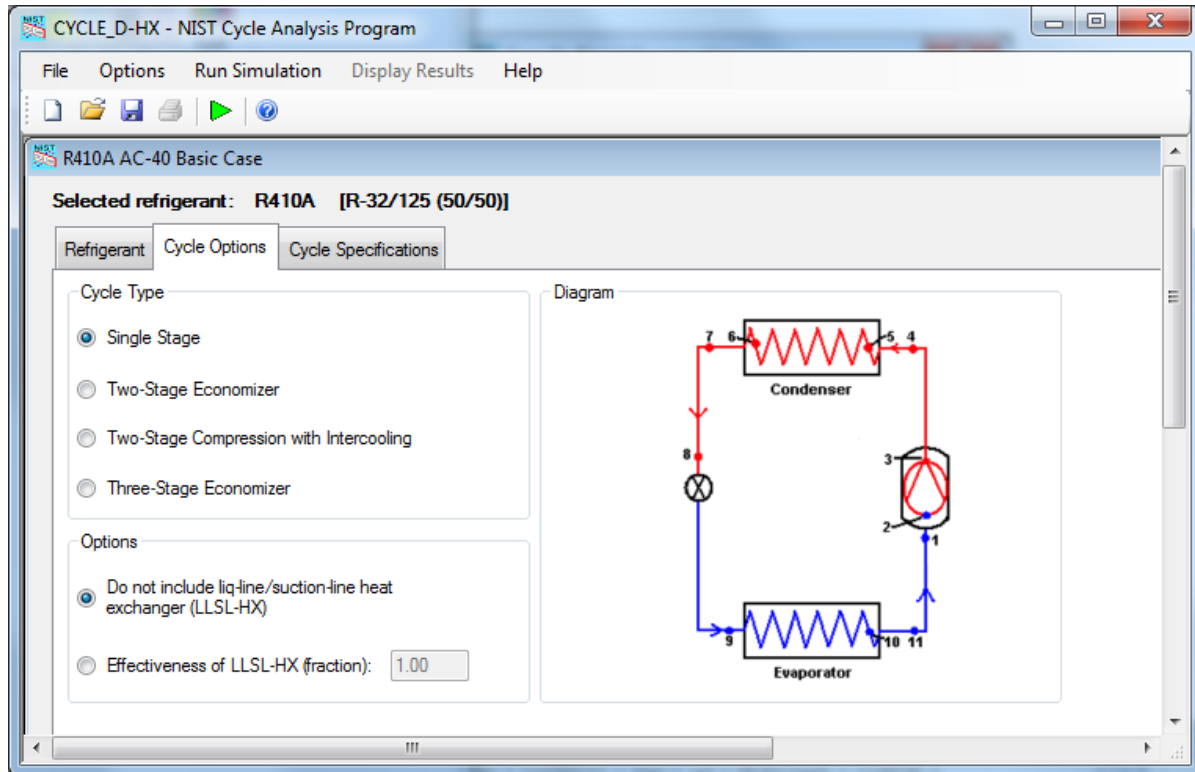
Figure 11. **Cycle Options** tab

Figure 11 shows the selection of the single-stage cycle without the LLSL-HX. For two-stage economizer cycles, click the **Two-Stage economizer** radio button; immediately the program will display a window with two radio buttons providing the compressor option to **Impose same efficiencies for both stages** or to **Specify different efficiencies for the two stages.** This selection affects the input requirements under the **Cycle Specifications** tab. Additionally, the cycle with **Two-stage economizer** requires the user to make a choice between the option to **Impose intermediate pressure** and to **Optimize intermediate pressure,** by clicking on the appropriate radio button.

For two-stage compression with intercooling cycles, click the **Two-Stage Compression with Intercooling** radio button and then input the **Intermediate pressure**. This cycle is not available for refrigerant blends.

For three-stage economizer cycles, click the **Three-Stage Economizer** radio button; immediately the program will display a window with two radio buttons providing the compressor option to **Impose same efficiencies for both stages** or to **Specify different efficiencies for the two stages.** This selection affects the input requirements under the **Cycle Specifications** tab. Additionally, the cycle with the **Three-Stage Economizer** requires the user to make a choice between the option to impose the intermediate pressures (**Intermediate pressure for high-pressure stage** and **Intermediate pressure for low-pressure stage**) and the option to **Optimize intermediate pressure,** by clicking on the appropriate radio button.

4.2.3 Cycle Specifications Tab

The set of input data required within this tab depends on the cycle type (selected under the **Cycle Options** tab), input option for the evaporator and condenser ('Impose' or 'Simulate'), and representation of the compressor by either its efficiencies or performance map.

4.2.3.1 'Impose' Heat Exchanger ΔT_{hx} (or UA_{hx}) and Pressure Drop

Figure 12 shows an example of specification input for a single-stage system with the 'Impose' option and compressor efficiencies. The left-hand-side box contains inputs for the 'Heat Exchangers'. The radio button at the top indicates the selection of the 'Impose' option. The check on the radio button in the second line indicates that CYCLE_D-HX will use ΔT (as opposed to UA) to represent the performance of the evaporator and condenser. The check box located just below the text 'Establish Reference Parameters' is unchecked, hence the program will not calculate 'Reference Parameters' within this simulation run (Section 3.2). (Note that the software package shows the symbol ΔT in place of ΔT_{hx} used in this User's Guide.)

Figure 12. **Cycle Specifications** tab for a single-stage cycle with 'Impose' option and efficiency-based representation of compressor

Inputs specific to the evaporator and condenser are entered in individual columns. These inputs include:
- Heat exchanger type (counterflow, parallel flow, and crossflow)
- HTF inlet and outlet temperatures
- ΔT (or UA)
- Refrigerant saturation temperature drop (or pressure drop, depending on the selection made under the **Options** pull-down menu)
- Refrigerant superheat at the evaporator outlet and subcooling at the condenser outlet.

The middle box contains inputs for the 'Compressor'. In this single-stage example, the compressor is specified by the compressor isentropic efficiency, compressor volumetric efficiency, and compressor electric motor efficiency, all expressed in fractions. For multi-stage cycles the **Cycle Specifications** tab will solicit input for intermediate pressure(s), which is not applicable to the single-stage system.

The inputs in the right-hand-side boxes include the net system **Cooling Capacity** (evaporator capacity adjusted for the heat added by the indoor coil fan), **Vapor Lines Pressure Drop** in terms of a drop of dew-point temperature, and **Auxiliary Power** inputs. Once the required input data have been entered, a click on the start button on the power bar (green arrow) will initiate a simulation run. Refer to Section 5.5 for a presentation of simulation results.

4.2.3.2 'Impose' Heat Exchanger ΔT_{hx} (or UA_{hx}) and Pressure Drop with Calculation of 'Reference Parameters' ('Reference' Run)

Figure 13 shows input data for the same single-stage system as shown in Figure 12, but with the option to 'Establish Reference Parameters' (checked box), which requires additional information on the evaporator and condenser. The additional solicited information consists of:
- Tube inner diameter
- Tube length
- Number of tubes per circuit
- Number of circuits.

Figure 13. **Cycle Specifications** tab for single-stage cycle with 'Impose' option, efficiency-based representation of compressor, and the option to 'Establish Reference Parameters' (includes the 'Heat Exchangers Parameters' box obtained from a completed simulation run)

Based on the provided input, the interface calculates the refrigerant-side 'Heat Transfer Area' in the evaporator and condenser, and it displays these values in the bottom line of the 'Heat Exchangers' box. Note that the specified 'Number of Circuits' must be a positive number but does not need to be an integer. Often a number with a decimal fraction is suitable for representing a complicated refrigerant circuitry that may have several parallel circuits with different number of tubes and circuitry split points.

Figure 13 is a screen capture after the simulation run has been completed. For this reason, it includes the 'Heat Exchangers Parameters' box with the values calculated during this run. The values under the heading 'Recent Simulation Run' (refrigerant mass flux, refrigerant-side heat-transfer resistance), and two 'Reference Parameters' (HTF-Side Thermal Resistance and the ratio of imposed to simulated pressure drops) are displayed so the user could judge whether the heat exchanger inputs to the program were realistic. CYCLE_D-HX retains the 'Reference Parameters' [HTF-Side Thermal Resistance and (Imposed ΔP) / (Predicted ΔP)] for use in subsequent simulations

with the 'Simulate' radio button checked. Thus, this 'Impose-option' run serves as a 'Reference' run for subsequent 'Simulate-option' runs. It is prudent to save the 'Reference Parameters' for future reference by saving the current file (Section 4.6)

Verification of input data used to 'Establish Reference Parameters'
It is recommended to carefully examine the input data to the 'Impose' run and simulation results since unrealistic input data and run results may lead to unreliable results and circuit optimizations for the subsequent 'Simulate-option' runs. The first input parameter that merits verification is ΔT (or UA) because of its strong influence on simulation results and the difficulty in accurate estimating its value from laboratory data. For a given temperature profile of the HTF, a properly selected ΔT value results in refrigerant saturation temperature in heat exchanger that will match the value measured in the laboratory. Thus, the user can adjust the input ΔT to obtain agreement between the simulated and measured values.

Refrigerant mass flux in the evaporator and condenser should also be examined. It is affected by the Tube Inner Diameter, Number of Circuits, and the Cooling Capacity; the last input determines the refrigerant mass flow rate through the heat exchangers. The Tube Inner Diameter and the target Cooling Capacity are usually known; this leaves the Number of Circuits as the most likely candidate parameter for adjustment. (It approximates the layout of sometimes rather complicated refrigerant circuitry.)

The refrigerant mass flux affects the pressure drop, which is also affected by the Tube Diameter and Tube Length. The 'Heat Exchanger Parameters' box displays the pressure drop ratio [(Imposed ΔP) / (Predicted ΔP)] to assist the user in judging the consistency of input data. This pressure drop ratio is expected to be greater than one because CYCLE_D-HX calculates refrigerant pressure drop in the heat exchanger tubes only and does not account for the flow resistance in connecting tubes and return bends, which is included in experimental measurement and input pressure drop for the 'Impose' run. The magnitude of pressure drop in connecting tubes and return bends depends on the heat exchanger configuration (e.g., tube length, geometry of return bends). Often this pressure drop is comparable to that in the tubes.

In summary, the verification of the input data is very important in particular for simulation runs with optimization of refrigerant circuitries. For example, too small of specified refrigerant pressure drop in relation to refrigerant mass flux can drive the optimization run to exceedingly high refrigerant mass flux to benefit from improvements in refrigerant heat transfer when the penalty of pressure drop is underpredicted.

4.2.3.3 'Simulate' heat exchanger ΔT_{hx} (or UA_{hx}) and pressure drop
Figure 14 shows input data for a subsequent simulation, in which a relative performance of another fluid will be evaluated, propane in this example. The new fluid was assigned using the **Refrigerant** tab. This simulation will be performed at the same target cooling capacity originally specified for the reference fluid (R-410A in this case). In the 'Heat Exchangers' box, the 'Simulate' radio button was checked; this instructs the program to calculate the values of ΔT_{hx} and pressure drop in the evaporator and condenser in relation to those for the reference fluid, following the analysis presented in Section 3.2.

In Figure 14, the greyed-out data boxes block the user from entering new data. The shown values of ΔT_{hx} and pressure drop for the evaporator and condenser were used in the 'Impose' (reference) run but will be simulated in the 'Simulate' run. The other values in the greyed-out data boxes will be used unchanged as displayed. All other input data remain unchanged, including those selected previously under the **Cycle Options** tab.

Figure 14 is a screen capture after the simulation run have been completed. Hence, it shows 'Heat Exchanger Parameters' calculated for propane, which are different than those obtained previously for R-410A due to differences in thermophysical properties of these fluids. However, the 'Reference Parameters' remained the same. Refer to Section 5.5 for a presentation of all simulation results. The 'Number of Circuits' remained unchanged in this 'Simulate' run, but it would be altered should the user checked 'Yes' on the radio button instructing the program to 'Optimize the Number of Circuits'. For fair evaluation of alternative refrigerants, it is important to 'Optimize number of circuits' (Brignoli et al., 2017).

CYCLE_D-HX - NIST Cycle Analysis Program

File   Options   Run Simulation   Display Results   Help

R410A AC-40 Basic Case

Selected refrigerant: propane

Refrigerant | Cycle Options | **Cycle Specifications**

Heat Exchangers

ΔT/UA and Pressure Drop:
- ( ) Impose   (•) Simulate

Heat Exchanger Representation:
- (•) ΔT   ( ) UA

Establish Reference Parameters:
- [ ] Check for Yes

Heat Exchanger Type	Evaporator	Condenser
	( ) Counter ( ) Parallel (•) Cross	( ) Counter ( ) Parallel (•) Cross
HTF Temp In:	24.30 ℃	31.70 ℃
HTF Temp Out:	15.30 ℃	34.70 ℃
ΔT	9.00 ℃	7.30 ℃
Sat. Temperature Drop:	0.70 ℃	0.70 ℃
Superheat:	5.00 ℃	
Subcooling:		5.00 ℃
Tube Inner Surface:	( ) Smooth (•) Enhanced	( ) Smooth ( ) Enhanced
Tube Inner Diameter:	0.00914 m	0.00772 m
Tube Length:	0.80000 m	1.32000 m
Number of Tubes per Circuit:	12.0	12.0
Number of Circuits:	5.8	5.5
Optimize Number of Circuits:	( ) Yes (•) No	( ) Yes (•) No

Heat Transfer Area
Refrigerant Side: 1.60 m²   2.11 m²

Compressor

(Fractions)
- Isentropic Efficiency: 0.70
- [ ] Check to account for pressure ratio
- Volumetric Efficiency: 1.00
- Electric Motor Efficiency: 1.00

[Swich to Maps]

System Cooling
Cooling Capacity: 11.81 kW

Vapor Lines Pressure Drop
(Dew Point Temperature Drop)
- Suction Line: 0.00 ℃
- Discharge Line: 0.00 ℃

Auxiliary Power
- Indoor Fan: 0.00 kW
- Outdoor Fan: 0.00 kW
- Power for Controls: 0.00 kW

Heat Exchanger Parameters

Recent Simulation Run:	Evaporator		Condenser	
Refrigerant Mass Flux:	102.8	kg/(m²s)	151.9	kg/(m²s)
Refrigerant-Side Thermal Resistance:	0.1147	℃/kW	0.0896	℃/kW

Reference Parameters:

HTF-Side Thermal Resistance:	0.6558	℃/kW	0.4313	℃/kW
(Imposed ΔP) / (Simulated ΔP):	1.849		2.185	

Figure 14. **Cycle Specifications** tab for single-stage cycle with efficiency-based representation of compressor for simulating performance of propane in reference to R-410A (includes propane 'Heat Exchangers Parameters' obtained from a completed simulation run)

4.2.3.4 Using a Compressor Map

Figure 15 shows the **Cycle Specifications** window with the 'Compressor' box allowing the user to select a compressor map from the created list of compressors, create a new compressor map, and edit or delete the exiting selection. The compressor map option is implemented by clicking on the **Switch to Maps** button (shown in Figure 12). Once a compressor map is chosen, the user needs to select either the system **Cooling Capacity** or **Capacity Multiplier** option displayed in the 'System Cooling' box. For simulating a system with a capacity provided by the selected compressor, input the value 1 in the **Capacity Multiplier** input box.

Figure 15. **Cycle Specifications** tab for a single-stage cycle with 'Impose' option and compressor map-based representation of compressor

Each compressor map is associated with a specific refrigerant. This refrigerant becomes the current refrigerant once a given compressor maps has been selected, i.e., selection of a compressor map overrides the prior selection of the refrigerant within the **Refrigerant** tab (Figure 2).

Appendix C explains how to input a new or modify an existing compressor map.

4.3 Loading an Existing File with Input Data

Rather than entering data, the user may opt to open a previously stored input data file and modify it. To open an existing file, click of the **File/Open** menu item or click on the **Open File** button on the power bar. The window shown in Figure 16 will appear. Windows Operating System steps are applicable for opening and storing files. After a file is selected and opened, the user may modify the input data. The default location of CYCLE_D-HX folder with input data files is C:\...\My Documents\CYCLE_D-HX.

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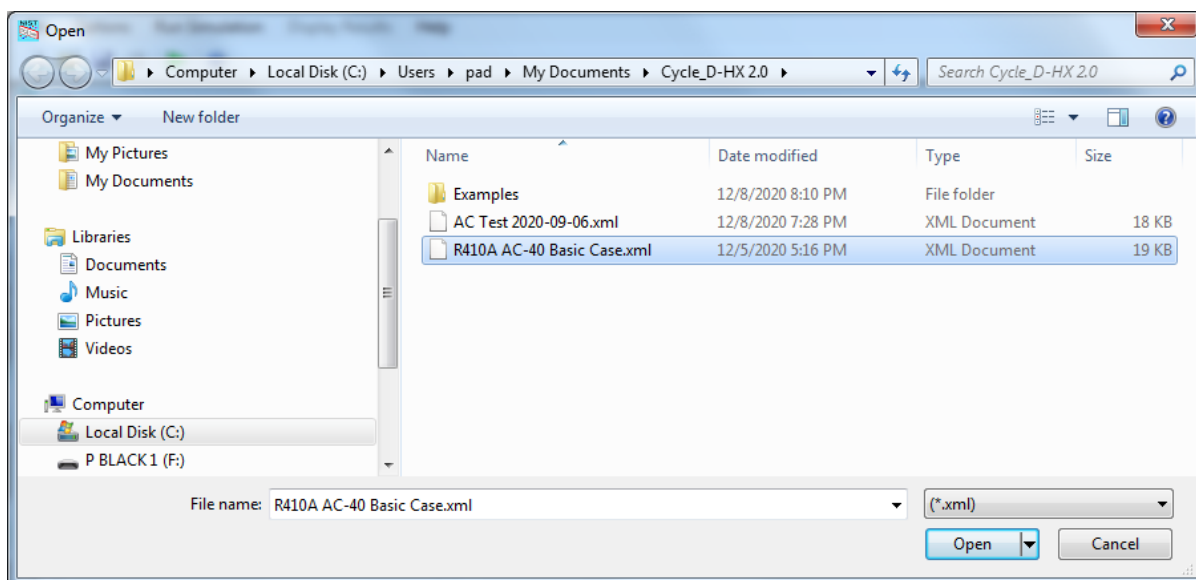
Figure 16. Opening a previously stored input data file

4.4 Executing a Simulation Run

To execute a simulation run, use the **Run Simulation** pull down menu or click on the **Run Simulation** button (the green arrow located on the power bar). The program will first perform various checks to ensure that the input data are valid, and then will proceed with the simulation calculations.

4.5 Presenting Simulation Results

4.5.1 Summary Results

The simulation results shown here are based on the input data of Figure 12. When the simulation is completed, the **Summary Results** window will appear (Figure 17). The user can scroll this window for full review, or copy and paste the results into any document, as shown in the Table 1. By using either the **Display Results** pull-down menu or the four buttons located on the right-hand side of the icon bar, the user can also display the corresponding windows showing a system schematic with refrigerant thermodynamic parameters in the key system locations (Figure 18), thermodynamic diagrams (Figures 19 and 20), and line sizing information (Table 2).
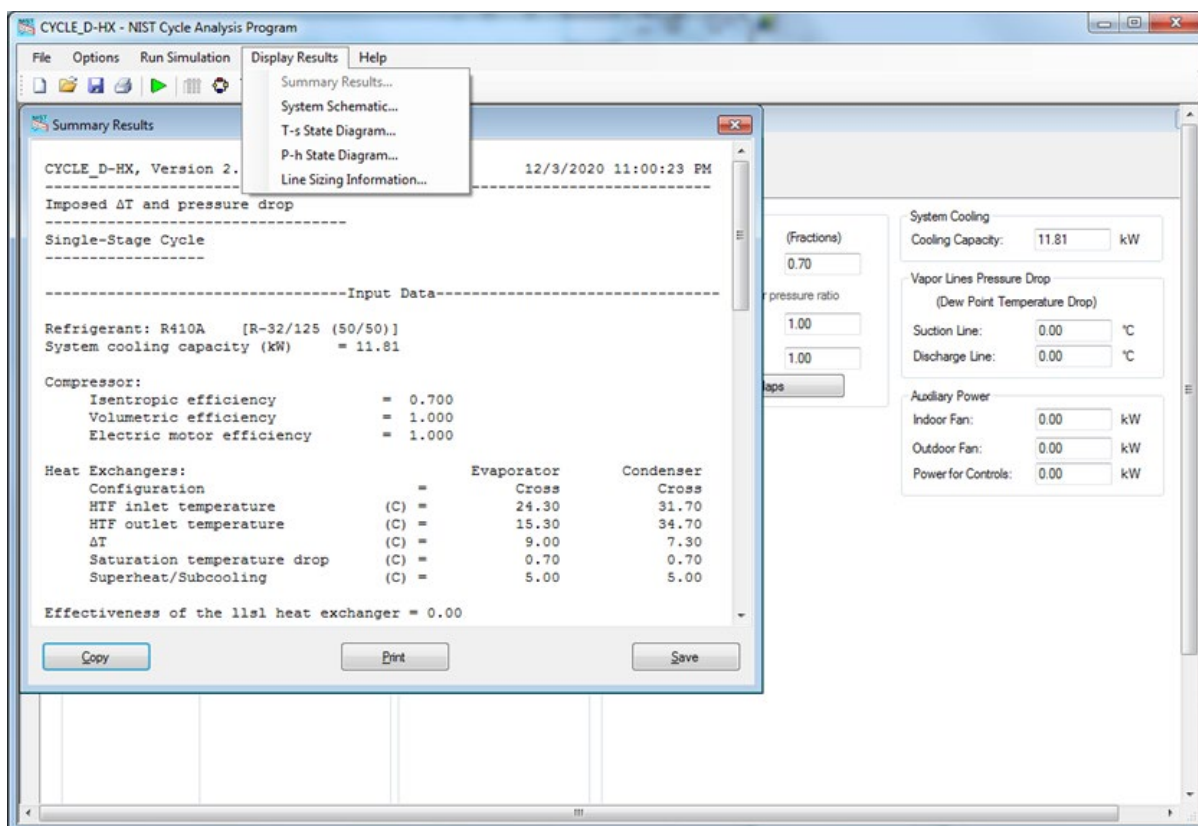
Figure 17. Window with simulation results

Table 1. Summary results

```
CYCLE_D-HX, Version 2.0                            12/3/2020 11:00:23 PM ------------
---------------------------------------------------------------
Imposed ΔT and pressure drop; HX reference data calculated
---------------------------------------------------------------
Single-Stage Cycle
------------------


--------------------------------Input Data--------------------------------

Refrigerant: R410A    [R-32/125 (50/50)]
System cooling capacity (kW)    = 11.81

Compressor:
     Isentropic efficiency            =  0.700
     Volumetric efficiency            =  1.000
     Electric motor efficiency        =  1.000

Heat Exchangers:                               Evaporator      Condenser
     Configuration                =       Cross           Cross
     Tube Inner Surface           =      Enhanced        Enhanced
     HTF inlet temperature      (C) =       24.30           31.70
     HTF outlet temperature     (C) =       15.30           34.70
     ΔT                         (C) =        9.00            7.30
     Saturation temperature drop (C) =        0.70            0.70
     Superheat/Subcooling       (C) =        5.00            5.00
     HTF-side area            (m^2) =        1.00            1.00
     Refrigerant-side area    (m^2) =        1.60            2.11
     Tube diameter             (m) =     0.00914         0.00772
     Number of circuits           =         5.8             5.5

Effectiveness of the llsl heat exchanger = 0.00

Saturation temperature drop in the suction line   (C) =   0.0
Saturation temperature drop in the discharge line (C) =   0.0

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 14.7  1074.0   429.8  2.51E-2  1.81271  1.000
 2  Cylinder inlet     14.7  1074.0   429.8  2.51E-2  1.81271  1.000
 3  Cylinder outlet    65.8  2440.8   462.3  1.23E-2  1.84177  1.000
 4  Condenser inlet    65.8  2440.8   462.3  1.23E-2  1.84177  1.000
 5  Cond. sat. vapor   40.4  2440.8   425.2  9.57E-3  1.72765  1.000
 6  Cond. sat. liquid  39.6  2399.7   265.5  1.02E-3  1.21843  0.000
 7  Condenser outlet   34.6  2399.7   256.2  9.89E-4  1.18830  0.000
 8  Exp. device inlet  34.6  2399.7   256.2  9.89E-4  1.18830  0.000
 9  Evaporator inlet   10.3  1096.5   256.2  5.28E-3  1.19829  0.193
10  Evap. sat. vapor    9.7  1074.0   423.9  2.41E-2  1.79184  1.000
11  Evaporator outlet  14.7  1074.0   429.8  2.51E-2  1.81271  1.000

     Work =  32.46 kJ/kg   Qevap = 173.67 kJ/kg   Qcond = 206.13 kJ/kg
                          COPc  =    5.349       COPh  =   6.349
     Two-phase glide:  evaporator =   0.6 C    condenser =   0.8 C
     Condenser superheat        =  25.5 C     P(3)/P(2) =   2.27
     Liquid line subcooling due to llsl heat transfer   =   0.0 C
     Suction vapor superheat due to llsl heat transfer  =   0.0 C
     Volumetric capacity:    cooling            heating
       @ vol. eff. = 1.00   6932.2 kJ/m^3          8228.0 kJ/m^3


--------------------COMPRESSOR AND SYSTEM RESULTS--------------------------

Compressor power           =   2.208 kW
Compressor COP: COPc        =   5.349               COPh =   6.349
Compr. suc. vol. flow rate  =   6.133 m^3/h

Refrigerant mass flow rate = 6.8003E-02 kg/s  Total power =   2.208 kW
Cooling capacity: evaporator= 11.810 kW        system  =  11.810 kW
Heating capacity: condenser = 14.018 kW        system  =  14.018 kW
     System COP: COPc,sys  =   5.349           COPh,sys =   6.349


-------------------------HEAT EXCHANGERS RESULTS--------------------------
                                          Evaporator      Condenser
Refrigerant mass flux       (kg/(m^2 s) =      178.7           264.1
UA                             (kW/C) =        1.312           1.920
```

4.5.2 System Diagram Window

Figure 18 shows an example **System Diagram** window with refrigerant thermodynamic parameters at the key system locations. To display temperature, pressure, density, enthalpy, or entropy values at the various state points, click on the appropriate control button located on the left side of the screen.
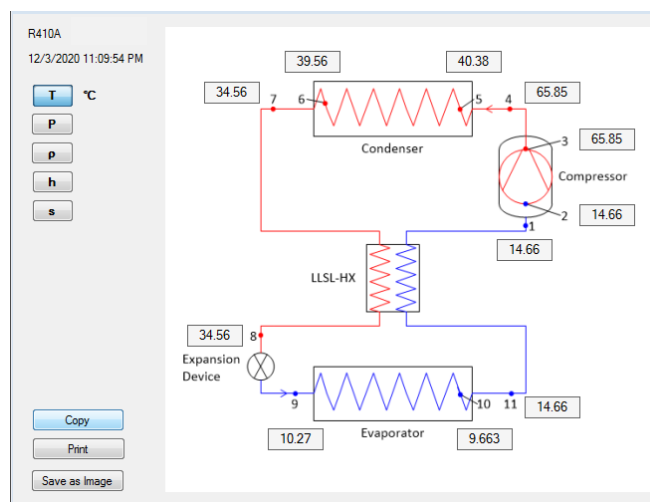
Figure 18. **System Diagram** window with key refrigerant parameters

4.5.3 State Diagram Windows

Figure 19 shows an example **P-h State Diagram**, and Figure 20 shows an example **T-s State Diagram**. The minimum and maximum tick marks were modified for both figures within CYCLE_D-HX program. Double-click on the figure (after which Figure 21 appears) to modify (1) the axis labels, (2) the minimum, maximum, and intervals between major tick marks, (3) the font size, (4) the number formatting, (5) the presence or non-presence of gridlines, (6) the specification of the axes in linear or logarithmic scales, and/or (7) the line/symbol type and color for the saturated liquid line, saturated vapor line, or process lines. Note: the **P-h State Diagram** and the **T-s State Diagram** must be modified independently of one another.

The user can read the coordinate values by checking the 'Pointer' box and placing the pointer tip on the diagram. The **State Diagrams** can be zoomed by checking the Zoom box.
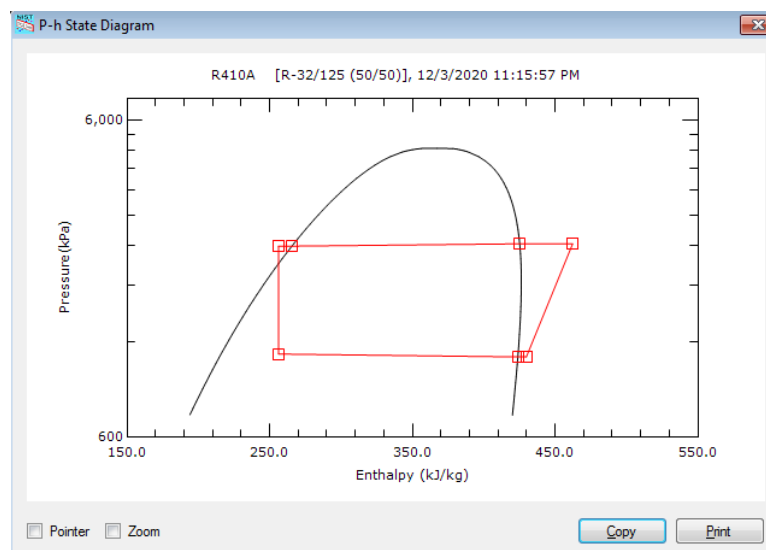
Figure 19. **P-h State Diagram**
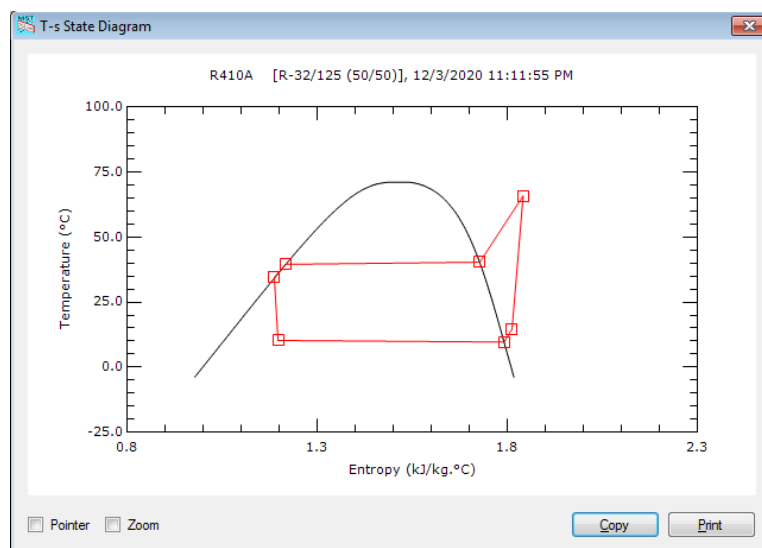
Figure 20. **T-s State Diagram**
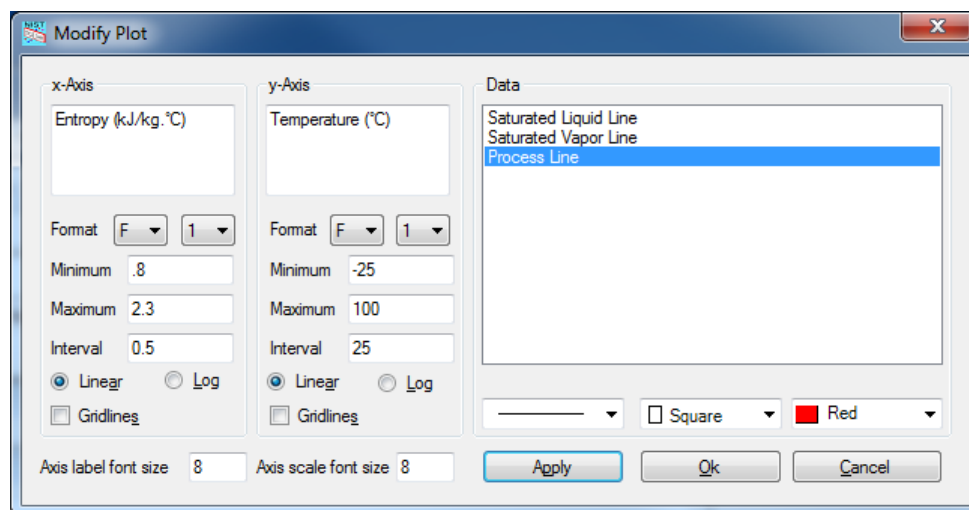
Figure 21. Modifying **T-s State Diagram** (Figure 20)

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4.5.4 Line Sizing Information

Table 2 shows the content of the **Line Sizing Information** window.

Table 2. Line sizing information

```
Outside     Length       Vapor       Length       Vapor      Length      Liquid
Diameter Suction line  Velocity   Discharge line  Velocity  Liquid line  Velocity
 (mm)       (m)        (m/min)        (m)         (m/min)      (m)        (m/min)
=============================================================================
  9.520     (1)       2.034E+03      (1)         9.973E+02  1.377E+02   8.025E+01
 12.700     (1)       1.091E+03      (1)         5.353E+02  6.106E+02   4.307E+01
 15.880     (1)       6.795E+02      (1)         3.332E+02  1.895E+03   2.682E+01
 19.050     (1)       4.552E+02      (1)         2.232E+02  4.930E+03   1.796E+01
 22.220     (1)       3.273E+02      (1)         1.605E+02  1.082E+04   1.292E+01
 28.580     (1)       1.919E+02      (1)         9.413E+01  3.857E+04   7.575E+00
 34.920     (1)       1.262E+02      (1)         6.187E+01  1.046E+05   4.979E+00
 41.280     (1)       8.900E+01      (1)         4.365E+01  2.396E+05   3.512E+00
 53.980     (1)       5.120E+01      (1)         2.511E+01  8.892E+05   2.020E+00
 66.680     (1)       3.319E+01      (1)         1.628E+01  2.480E+06   1.310E+00
 79.380     (1)       2.326E+01      (1)         1.141E+01  5.746E+06   9.180E-01
 92.080     (1)       1.720E+01      (1)         8.433E+00  1.173E+07   6.786E-01
104.780     (1)       1.323E+01      (1)         6.486E+00  2.177E+07   5.219E-01
130.180     (1)       8.489E+00      (1)         4.163E+00  6.182E+07   3.350E-01
155.580     (1)       5.905E+00      (1)         2.896E+00  1.451E+08   2.330E-01
206.380     (1)       3.380E+00      (1)         1.658E+00  5.363E+08   1.334E-01
257.180     (1)       2.177E+00      (1)         1.068E+00  1.499E+09   8.593E-02
307.980     (1)       1.508E+00      (1)         7.396E-01  3.531E+09   5.952E-02
=============================================================================
Refrigerant line length and velocity values are for straight type L tubing for
the refrigerant mass flow rate and pressure drops used in the cycle simulation.
For the liquid line, the line length is calculated for the pressure drop
that would result in bringing the subcooled refrigerant to flashing.
Refrigerant mass flow rate:   244.8 kg/h
Pressure drops
  Suction line:       0.0 kPa
  Discharge line:     0.0 kPa
  Liquid line:      278.5 kPa
=============================================================================
(1) - Zero pressure drop or subcooling was inputted for the cycle simulation.
```

4.6 Saving Input Data

To save the current input data set, use either the **Save** button located on the power bar or one of the options available under the **File** menu item.

4.7 Diagnostic Messages

CYCLE_D-HX provides stable solutions if the specified cycle operating conditions do not extend beyond the range for which REFPROP 10.0 (Lemmon et al., 2018) property routines were validated for a refrigerant (single-compound refrigerant or refrigerant blend). If CYCLE_D-HX encounters problems during a cycle simulation, the interface will display a note that diagnostic messages were generated and will provide the option to read and save them. Note that refrigerant property routines can become unstable in the neighborhood of the critical point.

4.8 Help Menu

Click on the **Help** menu item to access online help. The help file consists of three tabs: **Contents**, **Index** and **Search**. The **Index** tab contains detailed help topics arranged alphabetically. The Contents tab allows the user to search the contents by the help topics. The **Search** tab allows the user to search the contents using keywords. Figure 22 shows a list of help topics under the **Contents** tab.
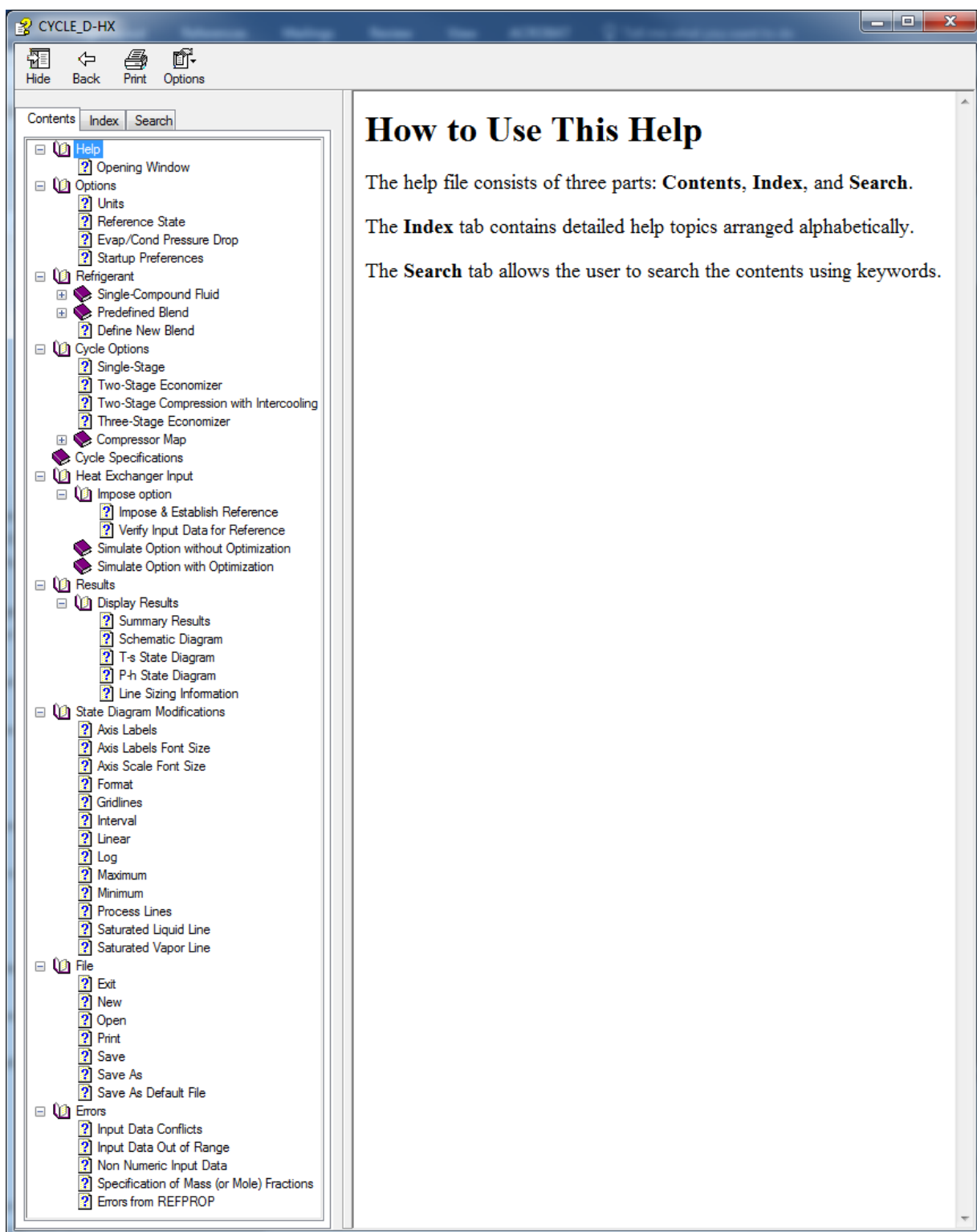
Figure 22. List of topics of the pull-down **Help** menu under the **Contents** tab

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ACKNOWLEDGMENTS

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Appendix A

SINGLE-COMPOUND REFRIGERANTS AVAILABLE IN CYCLE_D-HX

Short Name	Full Chemical Name	T_{crit} (°C)	T_{crit} (°F)
R-11	trichlorofluoromethane	198.0	388.3
R-12	dichlorodifluoromethane	112.0	233.6
R-13	chlorotrifluoromethane	29.2	84.6
R-13I1	trifluoroiodomethane	123.3	253.9
R-14	tetrafluoromethane	-45.6	-50.2
R-21	dichlorofluoromethane	178.3	353.0
R-22	chlorodifluoromethane	96.2	205.1
R-23	trifluoromethane	25.9	78.7
R-32	difluoromethane	78.1	172.6
R-40	methyl chloride	143.2	289.7
R-41	fluoromethane	44.1	111.4
R-50	methane	-116.7	-82.7
R-113	1,1,2–trichloro–1,2,2–trifluoroethane	214.1	417.3
R-114	1,2–dichloro–1,1,2,2–tetrafluoroethane	145.7	294.2
R-115	chloropentafluoroethane	80.0	175.9
R-116	hexafluoroethane	19.9	67.8
R-123	1,1–dichloro–2,2,2–trifluoroethane	183.7	362.6
R-124	1–chloro–1,2,2,2–tetrafluoroethane	122.3	252.1
R-125	pentafluoroethane	66.2	151.1
R-134a	1,1,1,2–tetrafluoroethane	101.1	213.9
R-141b	1,1–dichloro–1–fluoroethane	204.2	399.6
R-142b	1–chloro–1,1–difluoroethane	137.1	278.8
R-143a	1,1,1–trifluoroethane	72.9	163.2
R-150	dichloroethane	288.5	551.2
R-152a	1,1-difluoroethane	113.3	235.9
R-161	fluoroethane	102.2	215.9
R-170	ethane	32.2	89.9
R-218	octafluoropropane	161.5	72.0
R-227ea	1,1,1,2,3,3,3–heptafluoropropane	102.8	217.0
R-236ea	1,1,1,2,3,3–hexafluoropropane	139.3	282.7
R-236fa	1,1,1,3,3,3–hexafluoropropane	124.9	256.9
R-245ca	1,1,2,2,3–pentafluoropropane	174.4	346.0
R-245fa	1,1,1,3,3–pentafluoropropane	154.1	309.3
R-365mfc	1,1,1,3,3-pentafluorobutane	186.9	368.3
R-290	propane	96.7	206.1
R-C318	octafluorocyclobutane	115.2	239.4
R-600	butane	152.0	305.6
R-600a	isobutane or 2–methylpropane	134.7	274.5
R-717	ammonia	132.3	270.1
R-744	carbon dioxide	31.1	87.9
R-1123	trifluoroethylene	58.9	137.4
R-1150	ethylene	9.2	48.6
R-1216	hexafluoropropene	85.8	186.4
R-1224yd(Z)	cis-1-chloro-2,3,3,3-tetrafluoroprop-1-ene	155.5	312.0
R-1233zd(E)	1-chloro-3,3,3-trifluoroprop-1-ene	166.5	330.1
R-1234yf	2,3,3,3-tetrafluoroprop-1-ene	94.7	202.5
R-1234ze(E)	trans-1,3,3,3-tetrafluoropropene	109.4	228.9
R-1234ze(Z)	cis-1,3,3,3-tetrafluoropropene	150.1	302.2
R-1243zf	3,3,3-trifluoroprop-1-ene	103.8	218.8
R-1270	propylene or propene	92.4	198.4
R-1336mzz(Z)	cis-1,1,1,4,4,4-hexafluoro-2-butene	171.3	340.3
R-E143a	methyl-trifluoromethyl-ether	104.8	220.6
R-E170	dimethylether (DME) or ethylene oxide	127.2	260.9
R-E245cb2	methyl-pentafluoroethyl-ether	133.7	272.6
R-E245fa2	2,2,2-trifluoroethyl-difluoromethyl-ether	171.7	341.1
R-E347mcc	methyl-heptafluoropropyl-ether	164.6	328.2
CH3CH2CH=CH2	1-butene	146.1	295.1
Cyclo-C3H6	cyclopropane	125.2	257.3
C2H6O	ethanol or ethyl alcohol	240.8	465.4
CH(CH3)3	isobutene or 2-methyl-1-propene	144.9	292.9

Short Name	Full Chemical Name	T_{crit} (°C)	T_{crit} (°F)
(CH3)2CH(CH2)2CH3	isohexane or 2-methylpentane	224.6	436.2
(CH3)2CHCH2CH3	isopentane or 2-methylbutane	187.2	369.0
CH3OH	methanol	239.5	463.0
CH3-3(CH2)-CH3	pentane	196.6	385.8
C3H6O	acetone	235.0	454.9
C4H8	cis-butene or cis-2-butene	162.6	324.7
C4H8	trans-butene or trans-2-butene	155.5	311.8
C5F12	perfluoropentane or dodecafluoropentane	147.4	297.3
C5H12	neopentane or 2,2-dimethylpropane	160.6	321.1
C6H6	benzene	288.9	552.0
C6H12	cyclohexane	280.5	536.9
C6H14	hexane	234.7	454.4
C7H16	heptane	267.0	512.6
C12H26	dodecane	385.0	724.9
SF6	sulfur hexafluoride	45.6	114.0

The user can add new fluids to CYCLE_D-HX by placing new fluid files into the 'fluids' folder. The fluid file must be compatible with REFPROP and its name must start with 'R' or 'r' (e.g., Rnew2.fld or r754.fld will be recognized by CYCLE_D-HX as fluid files). The added fluids will appear in the selection list when the program runs (if the list window is already opened, close and reopen it to get the list refreshed).

The 'fluids' folder is located in C:\Users\[UserID]\AppData\Local\CYCLE_D_HX\CYCLE_D-HX 2.0\1.0.0.0. This path may be hidden according to the Windows setting. To get the path visible, on 'Windows Search' type 'Folder Options', open the 'Folder Options' window, select the 'View' tab, under 'Hidden files and folders' check 'Show hidden files, folders and drives'.

Appendix B

PREDEFINED REFRIGERANT BLENDS AVAILABLE IN CYCLE_D-HX

ASHRAE Designation	Composition Components	(mass %)	T_{crit} (°C)	T_{crit} (°F)
R-401A	R-22/152a/124	53/13/34	106.9	224.3
R-401B	R-22/152a/124	61/11/28	104.6	220.0
R-401C	R-22/152a/124	33/15/52	111.7	233.1
R-402A	R-125/290/22	60/2/38	74.8	166.6
R-402B	R-125/290/22	38/2/60	82.1	179.7
R-403A	R-290/22/218	5/75/20	84.0	183.2
R-403B	R-290/22/218	5/56/39	75.4	167.8
R-404A	R-125/143a/134a	44/52/4	72.1	161.8
R-405A	R-22/152a/142b/C318	45/7/5.5/42.5	104.3	219.8
R-406A	R-22/600a/142b	55/4/41	115.5	239.8
R-407A	R-32/125/134a	20/40/40	82.3	180.1
R-407B	R-32/125/134a	10/70/20	74.8	166.6
R-407C	R-32/125/134a	23/25/52	86.1	187.1
R-407D	R-32/125/134a	15/15/70	91.6	196.9
R-407E	R-32/125/134a	25/15/60	88.6	191.5
R-407F	R-32/125/134a	30/30/40	82.6	180.7
R-407G	R-32/125/134a	2.5/2.5/95	99.5	211.0
R-407H	R-32/125/134a	32.5/15/52.5	86.5	187.8
R-408A	R-125/143a/22	7/46/47	82.9	181.3
R-409A	R-22/124/142b	60/25/15	110.1	230.1
R-409B	R-22/124/142b	65/25/10	107.6	225.7
R-410A	R-32/125	50/50	71.3	160.4
R-410B	R-32/125	45/55	70.8	159.5
R-411A	R-1270/22/152a	1.5/87.5/11.0	88.9	191.9
R-411B	R-1270/22/152a	3/94/3	95.7	204.2
R-412A	R-22/218/142b	70/5/25	107.1	224.8
R-413A	R-218/143a/600a	9/88/3	95.3	203.6
R-414A	R-22/124/600a/142b	51/28.5/16.5	111.4	232.5
R-414B	R-22/124/600a/142b	50/39/1.5/9.5	110.7	231.3
R-415A	R-22/152a	82/18	96.7	206.0
R-415B	R-22/152a	25/75	109.9	229.9
R-416A	R-124/R134a/600	39.5/59.0/1.5	106.3	223.3
R-417A	R-125/134a/600	46.6/50.0/3.4	85.4	185.8
R-417B	R-125/134a/600	79.0/18.3/2.7	74.1	165.3
R-417C	R-125/134a/600	19.5/78.8/1.7	94.6	202.2
R-418A	R-290/22/152a	1.5/96/2.5	95.6	204.2
R-419A	R-125/134a/DME	77/19/4	83.5	182.3
R-419B	R-125/134a/DME	48.5/48/3.5	91.1	196.0
R-420A	R-134a/142b	88/12	104.8	220.6
R-421A	R-125/134a	58/42	82.8	181.0
R-421B	R-125/134a	85/15	72.4	162.3
R-422A	R-125/134a/600a	85.1/11.5/3.4	70.7	159.3
R-422B	R-125/134a/600a	55/42/3	82.0	179.6
R-422C	R-125/134a/600a	82/15/3	72.1	161.7
R-422D	R-125/134a/600a	65.1/31.5/3.4	78.2	172.8
R-422E	R-125/134a/600a	58/39.3/2.7	81.1	178.0
R-423A	R-134a/227ea	52.5/47.5	99.1	210.5
R-424A	R-125/134a/600a/600/601a	50.5/47/0.9/1/0.6	84.7	184.4
R-425A	R-32/134a/227ea	18.5/69.5/12	93.9	210.4
R-426A	R-125/134a/600/601a	5.1/93/1.3/0.6	99.0	210.2
R-427A	R-32/125/143a/134a	15/25/10/50	85.5	185.9
R-428A	R-125/143a/290/600a	77.5/20/0.6/1.9	68.0	154.4
R-429A	DME/152a/600a	60/10/30	122.0	251.5
R-430A	R-152a/600a	76/24	107.0	224.6
R-431A	R-290/152a	71/29	91.8	197.2
R-432A	R-1270/DME	80/20	97.3	207.1
R-433A	R-1270/290	30/70	94.4	201.9
R-433B	R-1270/290	5/95	96.3	205.4
R-433C	R-1270/290	25/75	94.8	202.6
R-434A	R-125/143a/134a/600a	63.2/18/16/2.8	74.1	165.5
R-435A	DME/R-152a	80/20	123.1	253.5
R-436A	R-290/600a	56/44	115.9	240.6

ASHRAE Designation	Composition Components	(mass %)	T_{crit} (°C)	T_{crit} (°F)
R-436B	R-290/600a	52/48	117.4	243.4
R-437A	R-125/134a/600/601a	19.5/78.5/1.4/0.6	95.5	203.9
R-438A	R-32/125/134a/600/601a	8.5/45/44.2/1.7/0.6	83.8	182.9
R-439A	R-32/125/600a	50/47/3	70.3	158.6
R-440A	R-290/134a/152a	0.6/1.6/97.8	112.7	234.8
R-441A	R-170/290/600a/600	3/55/6/36	118.5	245.2
R-442A	R-32/125/134a/152a/227ea	31/31/30/3/5	82.1	179.9
R-443A	R-1270/290/600a	55/40/5	96.0	204.8
R-444A	R-32/152a/1234ze(E)	12/5/83	106.3	223.4
R-444B	R-32/152a/1234ze(E)	41.5/10/48.5	95.7	204.2
R-445A	R-744/134a/1234ze(E)	6/9/85	106.1	222.9
R-446A	R-32/1234ze(E)/600	68/29/3	86.1	186.9
R-447A	R-32/125/1234ze(E)	68/3.5/28.5	85.3	185.5
R-447B	R-32/125/1234ze(E)	68/8/24	78.9	174.1
R-448A	R-32/125/1234yf/134a/1234ze(E)	26/26/20/21/7	82.7	180.8
R-449A	R-32/125/1234yf/134a	24.3/24.7/25.3/25.7	82.1	179.7
R-449B	R-32/125/1234yf/134a	25/24/23/27	82.2	180.0
R-449C	R-32/125/1234yf/134a	20/20/31/29	86.8	188.3
R-450A	R-134a/1234ze(E)	42/58	104.5	220.0
R-451A	R-1234yf/134a	89.8/10.2	94.4	201.9
R-451B	R-1234yf/134a	88.8/11.2	94.3	201.8
R-452A	R-32/125/1234yf	11/59/30	75.1	167.1
R-452B	R-32/125/1234yf	67/7/26	77.1	170.8
R-452C	R-32/125/1234yf	12.5/61/26.5	74.1	165.3
R-453A	R-32/125/134a/600/601a	20/20/53.8/0.6/0.6	88.0	190.3
R-454A	R-32/1234yf	35/65	81.7	179.1
R-454B	R-32/1234yf	69/31	78.1	172.6
R-454C	R-32/1234yf	21.5/78.5	79.3	174.7
R-455A	R-744/32/1234yf	3/21.5/75.5	85.6	186.1
R-456A	R-32/134a/1234ze(E)	6/45/49	102.7	216.8
R-457A	R-32/1234yf/152a	18/70/12	91.3	196.3
R-458A	R-32/125/134a/227ea/236fa	20.5/4/61.4/13.5/0.6	91.5	196.8
R-459A	R-32/1234yf/1234ze(E)	68/26/6	79.6	175.3
R-459B	R-32/1234yf/1234ze(E)	21/69/10	87.5	189.4
R-460A	R-32/125/134a/1234ze(E)	12/52/14/22	83.6	182.5
R-460B	R-32/125/134a/1234ze(E)	28/25/20/27	88.1	190.5
R-500	R-12/152a	73.8/26.2	102.1	215.7
R-501	R-22/12	75/25	95.9	204.5
R-502	R-22/115	48.8/51.2	81.5	178.7
R-503	R-23/13	40.1/59.9	18.3	64.1
R-504	R-32/115	48.2/51.8	62.2	144.0
R-507A	R-125/143a	50/50	70.6	159.1
R-508A	R-23/116	39/61	10.2	50.3
R-508B	R-23/116	46/54	11.2	52.2
R-509A	R-22/218	44/56	68.5	155.2
R-510A	DME/600a	88/12	125.7	258.2
R-511A	R-290/DME	95/5	97.0	206.6
R-512A	R-134a/152a	5/95	112.8	235.1
R-513A	R-1234yf/134a	56/44	94.9	202.8
R-513B	R-1234yf/134a	58.5/41.5	94.8	202.6
R-515A	R-1234ze(E)/227ea	88/12	108.2	226.7

The user can add new mixtures to CYCLE_D-HX by either defining new blends (Figure 2) or by placing new mixture files into the 'mixtures' folder. The mixture file must be compatible with REFPROP. The added mixtures will appear in the selection list when the program runs (if the list window is already opened, close and reopen it to get the list refreshed).

The 'mixtures' folder is located in C:\Users\[UserID]\AppData\Local\CYCLE_D_HX\CYCLE_D-HX 2.0\1.0.0.0. This path may be hidden according to the Windows setting. To get the path visible, on 'Windows Search' type 'Folder Options', open the 'Folder Options' window, select the 'View' tab, under 'Hidden files and folders' check 'Show hidden files, folders and drives'.

Appendix C

COMPRESSOR MAPS

C.1 Compressor Map Formats

CYCLE_D-HX uses three types of compressor maps for representing the compressor performance. Their format is given below.

Compressor map # 1 (based on the ANSI/AHRI Standard 540 (AHRI, 2015))

$$X = B1 + B2 \cdot T_s + B3 \cdot T_d + B4 \cdot T_s^2 + B5 \cdot T_s \cdot T_d + B6 \cdot T_d^2 + B7 \cdot T_s^3 + B8 \cdot T_d \cdot T_s^2 + B9 \cdot T_s \cdot T_d^2 + B10 \cdot T_d^3$$

where:

B1-B10	=	correlation coefficients
T_s	=	compressor suction dew-point temperature, °C (°F)
T_d	=	compressor discharge dew-point temperature, °C (°F)
X	=	represents (as designated): refrigerant mass flow rate, kg/s (lb/h) or power input W, (W)

Compressor map # 2 (pressure-based correlation)

$$X = B1 + B2 \cdot P_d + B3 \cdot P_s + B4 \cdot P_d^{0.9} + B5 \cdot P_s^{0.89} + B6 \cdot P_s \cdot P_d$$

where:

B1-B6	=	correlation coefficients
P_s	=	suction pressure, kPa (psia)
P_d	=	discharge pressure, kPa (psia)
X	=	represents (as designated): cooling capacity, W (Btu/h) or power input W

Compressor map # 3 (modified temperature-based correlation)

$$X = B1 + B2 \cdot T_d + B3 \cdot T_d^2 + B4 \cdot T_s + B5 \cdot T_s \cdot T_d + B6 \cdot T_s \cdot T_d^2 + B7 \cdot T_s^2 + B8 \cdot T_d \cdot T_s^2 + B9 \cdot T_s^2 \cdot T_d^2$$

where:

B1-B9	=	correlation coefficients
T_s	=	compressor suction dew-point temperature, °C (°F)
T_d	=	compressor discharge dew-point temperature, °C (°F)
X	=	represents (as designated): cooling capacity, W (Btu/h) or power input kW

C.2 Preparing a New Compressor Map

In the **Cycle Specifications** tab (Figure 12), click the **Switch to Maps** button located in the compressor input data box, and then click the **Create New** button (shown in Figure 15), which after which a **Compressor Data** widow will appear for inputting compressor map data (Figure C1).

Figure C1. **Compressor Data** window for entering compressor map coefficients (ANSI/AHRI Standard 540-2015 map selected)

The **Compressor Data** window has radio buttons for selecting one of the three compressor maps and their units. The units selected in the window are applicable to the compressor map output, coefficients and temperature unit for which the coefficients were developed. This unit selection does not override the units the user selected outside of this window for the input data and output of simulation results.

The refrigerant selection in this window will override the prior selection of the refrigerant within the **Refrigerant** tab (Figure 2). The refrigerants available for selection in this window are those available within the **Refrigerant** tab as **Single-Compound Fluid** or **Predefined Blend**. If the compressor uses a blend that is not available, the user needs to define this blend first using the **Define New Blend** (Figure 2) button before inputting compressor coefficients.

Appendix D

NOMENCLATURE USED FOR REPORTING SIMULATION RESULTS

This appendix presents the symbol convention used for simulation results in the order they are displayed. Self-explanatory output is omitted here. Note that the set of simulation results varies somewhat between simulation options.

D.1 Thermodynamic Cycle Results

T = temperature
P = pressure
h = specific enthalpy
v = specific volume
s = specific entropy
XQ = mass-based quality
Work = compressor motor energy consumption per unit mass of circulated refrigerant
   Work = $(h(3)-h(2))/ \eta_{comp\ motor}$
   where $\eta_{comp\ motor}$ = compressor motor efficiency (fraction)
Qevap = specific evaporator capacity
Qcond = specific condenser capacity
COPc = coefficient of performance in the cooling mode
COPh = coefficient of performance in the heating mode
Two-phase glide, evaporator = temperature difference between saturated vapor and evaporator inlet
Two-phase glide, condenser = temperature difference between saturated vapor and saturated liquid
Condenser superheat = temperature difference between condenser inlet and saturated vapor
P(3)/P(2) = compression pressure ratio
Volumetric capacity, cooling = Qevap/v(2)
Volumetric capacity, heating = Qcond/v(2)

D.2 Compressor and System Results

Total power = sum of powers of compressor, indoor fan, outdoor fan, and controls
COPc,sys = (system cooling capacity)/(total power)
COPh,sys = (system heating capacity)/(total power)

Appendix E

UNITS, CHECKS AND WARNINGS

There are several built-in checks and warnings in CYCLE_D-HX. Efforts have been made in developing the program to make the checks self-explanatory. Presented below are: (1) an explanation of consistency in units and (2) some examples of run time checks and warnings.

Systems of Units

Users may select either I-P or SI units.

  I-P Units: By selecting 'I-P units,' **temperatures** are entered in °**F.**

  SI Units: By selecting 'SI units,' **temperatures** are entered in °**C** (**SI – Celsius** option) or **K** (**SI – Kelvin** option).

  Common Bases: In both systems, mass composition and efficiency values are entered as decimals not greater than unity. **(Note, decimals, *not* percentages)**

Checks and Warnings

The following are examples of checks and warnings built into the CYCLE_D-HX system:

1. In selecting the number of refrigerants in a new mixture, the number must be from 2 to 5.

2. If the sum of refrigerant mass (or mole) fractions is greater than unity, an error message is issued.

3. Compressor isentropic efficiency values must be greater than or equal to 0.05 and less than or equal to unity.

4. Compressor volumetric efficiency values must be greater than or equal to 0.05 and less than or equal to unity.

5. Compressor motor efficiency values must be greater than or equal to 0.05 and less than or equal to unity.

6. The bubble-point temperature (or pressure) of refrigerant in the condenser must be greater than the dew-point temperature (or pressure) of refrigerant in the evaporator.

7. The evaporator HTF inlet temperature must be greater than the HTF outlet temperature.

8. The condenser HTF outlet temperature must be greater than the HTF inlet temperature.

9. The intermediate pressures for the two-stage economizer cycle, the two-stage compression with intercooling cycle, and the three-stage economizer cycle must fall between the evaporator and condenser pressures.

10. For the three-stage economizer cycle, the intermediate pressure of the low-pressure stage must be below the intermediate pressure of the high-pressure stage.

Appendix F

CONTACTS

For questions regarding availability of CYCLE_D-HX or questions pertaining to its use, contact:

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