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Steady State Modeling of Advanced Vapor Compression Systems with Multiple Air and Refrigerant Loops

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Abstract

The use of heating, ventilation, air conditioning, and refrigeration (HVACR) systems is always increasing. Thus, there is continued research focused on improving the efficiency and reducing the negative environmental impact of these systems. The basic vapor compression cycle has already reached its limits. Hence, researchers are investigating more creative and complex cycles to improve the capacity and efficiency. Furthermore, there is increased effort towards finding lower GWP alternative refrigerants, some of which require novel system design to improve efficiency or maintain capacity. This motivates the development of a fast and robust simulation tool for steady analysis of complex vapor compression systems. This paper presents a comprehensive vapor compression system steady state solver which has several novel features compared to the existing solvers. Firstly, this solver is capable of simulating large number of different designs of vapor compression systems. This includes arbitrary system configurations, multiple air and refrigerant paths, and user defined refrigerants. The solver uses a component-based solution scheme in which the component models are treated as black box objects. This allows different vapor compression systems design engineers, and manufacturers to use the solver without the need to expose any possible confidential component data. The solver is validated using a residential heat pump system, a vapor injection flash tank system, and a CO_2 two-stage refrigeration system and the preliminary modeling results match the experimental results within 5%, 10%, and 3% accuracy, respectively.

1. Introduction

The use of vapor compression systems is continuously increasing because vapor compression systems comprise the majority of the HVACR systems. The US Department of Energy [1] states that heating, ventilation, and air conditioning (HVAC) account for 40%, and 33% of primary energy use in residential and commercial buildings, respectively. Hence, a continuous need for improving the efficiency, and reducing the cost and environmental impact of these systems exists. In order to meet the aforementioned targets, large number of system designs must be evaluated, either through simulation or building a prototype. The latter option is apparently expensive and time consuming. Therefore, the development cost of vapor compression systems decreases when using proper simulations tools because large number of prototypes can be evaluated without manufacturing large number of prototypes [2]. A proper simulation tool must combine three main factors: robustness, speed, and accuracy [3]. A vapor compression system simulation tool includes two main parts; the component models, and the system solver. The component model can vary from empirical equations to detailed component equations. The system solver, which is the main focus of this paper, combines the component models according to the relationship between the

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component parameters. The aim is to obtain the steady state refrigerant state (e.g. pressure, enthalpy…etc.) while satisfying the energy and mass balance in the system.

There exists many solvers that can be used for energy system simulation, such as vapor compression systems, that currently exist. These solvers can be divided into two main categories: general equation solvers, and advanced energy system solvers, with some solvers utilizing hybridizations of the two categories [4]. The general equation solvers allows specifying the system in terms of its governing and component models' equations. The solver then solves these set of equations. Though this category allows for the simulation of any system, it requires many efforts from the system designer. The advanced energy system solvers are usually designed for a specific task (e.g. simulation of a heat pump model, solar power plant…etc.) which makes it easier to perform the desired simulations. Nevertheless, it is usually limited with the specific system to which it is designed making generalizations of the system very difficult if not impossible. Hybridizations of the two categories provide fixed systems with user defined component models. A reliable vapor compression system simulation solver should have the option to simulate user defined systems using user defined components. Although, such solver is highly required, it doesn't currently exist in literature.

The unknown variables in a vapor compression system solver are fluid-related state information [5]. The system solvers can also be divided in two main categories in which the unknown variables are solved [6]. The first category is the successive approach where a variable is solved before moving on to the next variable, whereas the second category is the simultaneous approach which uses a non-linear equation solver to solve all the unknown variables simultaneously. The successive approach [7-25] is fast and robust. However, as the system configuration gets more complicated, this approach needs more than one nested loop to perform the system level iterations. Hence, this approach becomes less convenient (i.e. it gets more difficult to determine the proper and efficient solution scheme) to use as the system configuration becomes more complex (e.g. more components, more splits and merges, multi-stage cycles…etc.). This is due to the fact that for a small modification to the system configuration, major code changes, if not a new solution scheme, are required. In the simultaneous approach [26-43], the number of unknown variables is higher than (at least double) in the successive approach for the same system configuration. This is because all the unknown variables are independent and are solved for simultaneously. Although this approach provides higher flexibility for the modeled system configuration, it has higher computational cost than the successive approach. Also, for this approach, unlike the successive approach, the sequence of running the different component models in the system is not important. Thus, a new solver is required that combines the robustness and speed efficiency of the successive approach while maintaining the flexibility of the simultaneous approach.

The third common method of categorizing the system solvers is based on the relation between the system solver and component models. The system solvers are then categorized into two main schemes: the global scheme and the component-based scheme [6]. In the global scheme, the equations used in the component models are typically hard coded within the system solver. This helps improve the robustness of the solver since the solver is directly evaluating all the mathematical equations. Also, general equations solvers can be used to solve the generated set of equations. However, the obvious drawback of this scheme is its inflexibility. Adding new components or changing part of the system configuration needs a lot of effort. This is because the set of equations and solution variables are not dynamically formulated based on the system configuration. In the component-based solution scheme, the system solver is decoupled from the component models. In other words, the system solver treats the component models as black-box objects interacting with one another through a series of ports and junctions. In order to create a generic vapor compression system simulation tool that can handle arbitrary system configurations, a component-based solution scheme is needed. Nonetheless, only very few vapor compression system simulation packages implement this solution scheme.

In summary, although many steady state simulation solvers exist in literature, these solvers either implement the fast and robust successive approach which has limited flexibility to system configuration, or the flexible simultaneous approach which suffers from speed and robustness problems. Most of these solvers require the equations used in the component models to be hardcoded and/or exposed to the system solver. This limits the widespread use of these tools among the vapor compression system manufacturers. Therefore, some existing solvers use the component-based solution scheme where the different components are defined as refrigeration system components, and are modeled as black box objects interacting with one another through a series of ports and junctions [44, 45]. Nevertheless, those tools lack one or more of the important features: a user friendly

interface, the ease of incorporating new component models in the system, the flexibility to create new arbitrary cycles, and the capability to perform further analysis on the system (e.g. optimization, sensitivity, or parametric analysis). Therefore, this paper presents a comprehensive vapor compression system steady state solver that can simulate advanced vapor compression systems with multiple air and refrigerant fluid paths. Also, this solver supports user-defined fluids, and user-defined convergence criteria.

2. Outline of the new solver

2.1. Arbitrary Cycle Solver Outline

The new solver falls under the successive solution scheme category of solvers. However, the solver uses highly flexible data structures to overcome the flexibility problem associated with this type of system solvers. The solver outline consists of three main steps:

1. Determining the unknown variables and formulating the residual equations
2. Determining the number of required initial guess values and convergence criteria
3. Running the non-linear equation solver

The most challenging steps in this outline are the first two steps. These steps makes the solver gain its flexibility to simulate arbitrary system configurations. Thus, these two steps are the main focus in the new solver.

Before moving on to the solving scheme, we need to derive a general method to be used by the solver to determine the unknown variables in any arbitrary system configuration. The solver applies the following rules to determine the number of unknown variables:

1. For every pressure based component (compressor, pump …etc.), the inlet pressure and enthalpy, and the outlet pressure are unknown.
2. For each refrigerant flow split, the solver adds a number of unknown variables equal to the number of additional split branches (i.e. number of additional unknowns = number of branches -1).
3. For each expansion device, the outlet pressure is an unknown.

Then, a non-linear equation solver is used to solve the residual equations to obtain the value of the unknown variables. Hence, we need a set of residual equations corresponding to the number of unknown variables. The solver uses the following rules in the first step to formulate the residual equations:

1. For the high side (i.e. discharge) pressure, the residual equation is based on an input system constraint (e.g. system subcooling at condenser outlet, or discharge pressure for a transcritical system).
2. For every refrigerant flow merge, the pressure levels from each branch are equal to one another. This provides a number of residual equations equal to the number of additional split branches (i.e. number of residual equations = number of branches -1).
3. For every pressure based component, the solver formulates two residual equations at the component inlet. These two equations ($P_{1,i}$-$P_{1,guess,i}$=0, $h_{1,i}$-$h_{1,guess,i}$=0) compare the calculated pressure based component inlet (guess) pressure and enthalpy values after each iteration with the calculated values from the outlet of the upstream component (i.e. junction pressure based on the outlet of the upstream components). The solver uses inlet pressure guess value as the reference pressure at the first iteration.
4. For every expansion device, the solver compares the enthalpy calculated based on the specified convergence criteria (e.g. superheat value) with the enthalpy calculated at the specified port at each iteration. This provides a number of residual equations equal to the number of unknown outlet pressures for each of the expansion devices in the cycle.

Also, the non-linear equation solver needs initial guess values as a starting point for some of the unknown variables. The solver uses the following rules to determine the number of required guess values, and convergence criteria in the second step:

1. For each pressure level containing a condenser (e.g. in the example cycle = 1), one convergence criteria (e.g. subcooling at any condenser outlet for subcritical cycle, gas cooler outlet pressure for transcritical cycle) is a required input to the solver.
2. For every compressor, the inlet and outlet pressures are two input guess values to the solver.
3. For every expansion device, a corresponding convergence criteria along the same refrigerant path of the expansion device (e.g. evaporator outlet superheat) is an input to the solver.

Applying the previous steps to any system configuration, the solver determines the number of required guess values, and formulates the residual equations. The solver then assigns the default residual equations based on the input convergence criteria. Finally, the solver might require additional (i.e. missing or unspecified) residual equations.

At every iteration, we need to run all the component models. As mentioned previously, at this point many of the existing tools are not flexible enough as the sequence of executing the components is important and typically hardcoded. In the comprehensive solver, one of the key steps is to run all the pressure based components (e.g. compressors) at the beginning of each iteration. This is because for all the pressure based components, the suction and discharge pressures are known (either from the guess values or the previous iteration) and the inlet enthalpy is calculated (based on the input suction superheat, or the previous iteration). Once the solver runs all the pressure based components, it loops through all the other components in the components list to run them one by one by. For each component in the list, if the upstream refrigerant state (i.e. inlet port state) is known, the solver runs the component model. The solver then checks this component as run. How[illegible] of the inlet port state has not been calculated yet, the solver moves to the following component. Th[illegible] the same loop until it runs all the component models. It then calculates the residuals and p[illegible]s to the non-linear equation solver to proceed to the following iteration. This keeps going until convergence occurs within the specified tolerance. Figure 1 shows the solver flowchart.

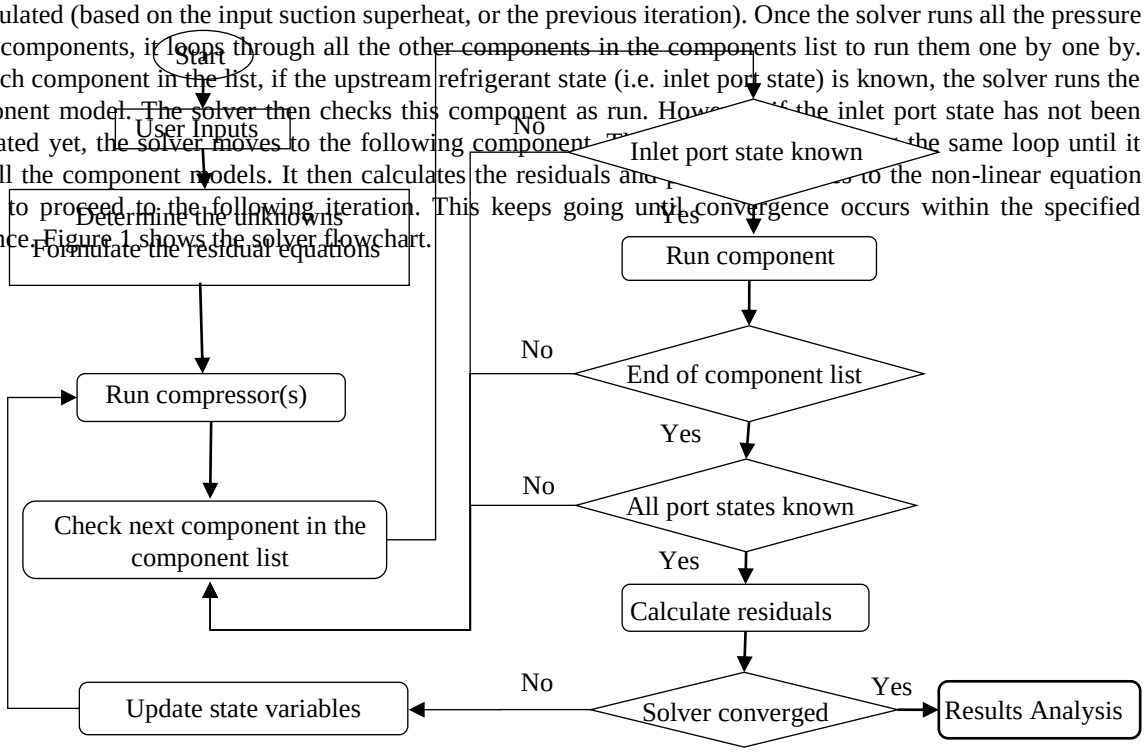


Figure 1: Solver flowchart

A random cycle generator is also developed using this solver. This cycle generator generates a basic four component cycle with additional pipes and components in series and parallel. This cycle generator confirms that the solver can successfully solve cycles with more than 500 components including up to 99 compressors (the

maximum limit for each component type). It is worth noting that the solver assigns the unknown variables and residual equations based on the ports of the components rather than the junctions in the cycle.

2.2. Multi-fluid Solver

The solver outlined in section 2.1 can handle user defined cycles with one fluid in the system. However, many vapor compression systems utilize more than one refrigerant. Thus, the multi-fluid solver can handle more than one refrigerant in the system. This solver is based on the arbitrary cycle solver. The solver determines the unknown variables, and residual equations for each of the refrigerant loops similar to the arbitrary cycle solver. However, when running the non-linear equation solver and the component models, the same outline as the one shown in Figure 1 is used. That is, for a cascade cycle for example, the two compressors are run at the beginning of the solver runs. The cascade heat exchanger (HX) runs as the last component in the cycle since it requires that the two inlet port states are determined beforehand.

3. Validations

3.1. Residential Air Source Heat Pump (ASHP) System

In this section, an ASHP system is validated against experimental data in the AHRI low GWP AREP report by Alabdulkarem et al. [46]. The compressor model is a ten-coefficient (AHRI-540-2004 Standard) model with power and mass flow rate adjustment factors. The condenser and evaporator component models use a finite volume heat exchanger simulation tool [47]. The expansion device's inlet subcooling and suction superheat are the convergence criteria. These criteria values are set to be equal to the experimental values for the corresponding testing conditions and refrigerant. The modeling results match the experimental results within 5% accuracy as shown in Figure 2. It is worth noting that the same validation study was previously done using the enthalpy marching solver and results showed the same agreement [48].

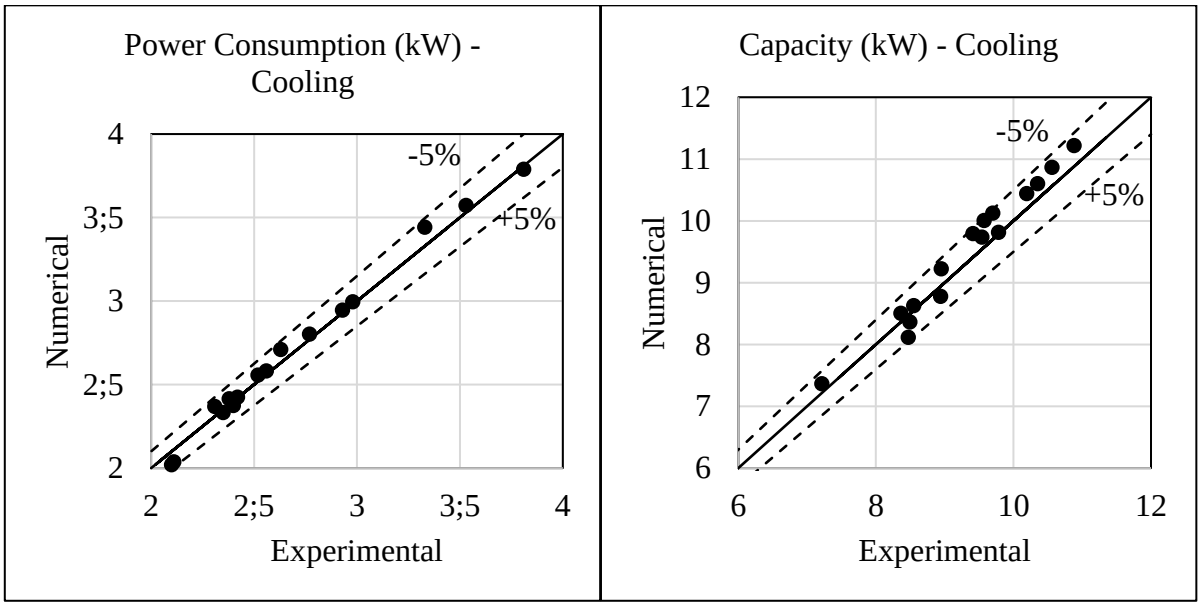


Figure 2: ASHP validation

3.2. Vapor Injection Heat Pump System with a Flash Tank

In this section, a vapor injection heat pump system with a flash tank is validated against experimental data by Xu [49]. The compressor model is a two stage compressor with an intermediate suction port. The condenser and evaporator component models use a finite volume heat exchanger simulation tool [47]. The expansion device's inlet subcooling and suction superheat are the convergence criteria. These criteria values are set to be equal to the

experimental values for the corresponding testing conditions and refrigerant. Figure 3 shows the cycle schematic. The modeling results match the experimental results within 10% accuracy as shown in Figure 4.

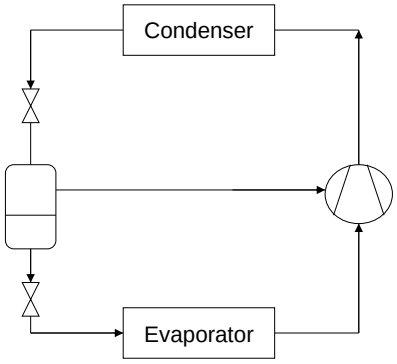


Figure 3: Vapor injection cycle schematic

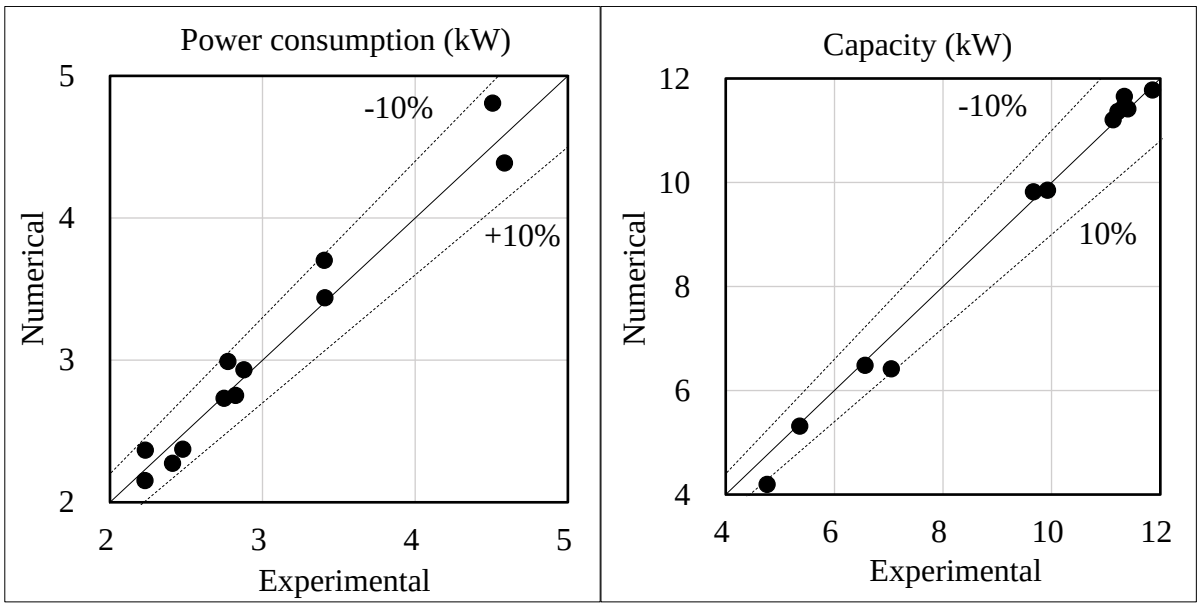


Figure 4: Flash tank cycle validation

3.3. CO_2 Two-Stage Refrigeration System with Mechanical Subcooler

In this section, a CO_2 two-stage refrigeration system with mechanical subcooler, shown in Figure 5, is validated against experimental data. The CO_2 gas cooler component model is based on a finite volume HX model [47] while the subcooler HX, medium temperature (MT) and low temperature (LT) evaporators use a finite volume plate HX model [50, 51]. The R134a subcooler is not simulated in the system model and the inlet glycol operating condition is based on the experimental data. The LT compressor model is a ten-coefficient (AHRI-540-2004 Standard [52]) model with a power adjustment factor of 0.87 while the MT compressor is defined using the volumetric and isentropic efficiencies, the displacement volume and RPM. This system has 11 unknown variables and corresponding residual equations. This system requires setting 4 different convergence criteria in the system. The selected criteria are the discharge pressure for transcritical operating conditions (outlet GC/condenser quality for subcritical operating conditions) at point 1, expansion valve outlet quality at point 14, and superheat at the outlet of each of the two evaporators. These convergence criteria values are set to be equal to the experimental values

for the corresponding testing conditions. The validation results for the COP, power consumption and total system capacity are shown in Figure 6. The predictions are within 3% of the experimental data.

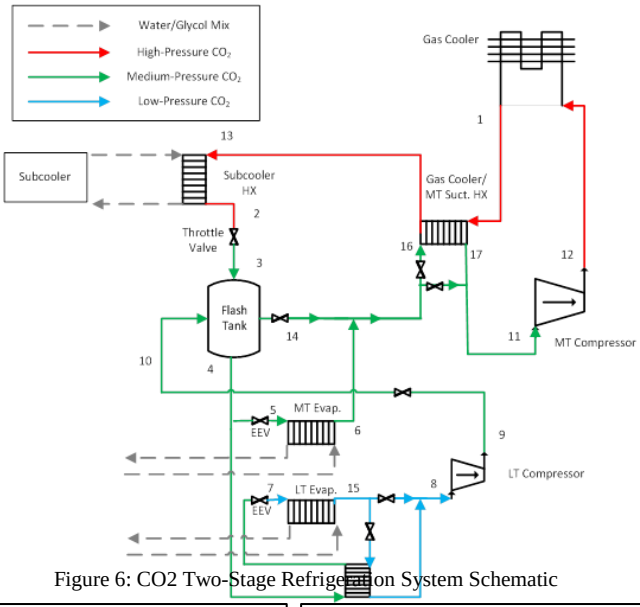


Figure 6: CO2 Two-Stage Refrigeration System Schematic

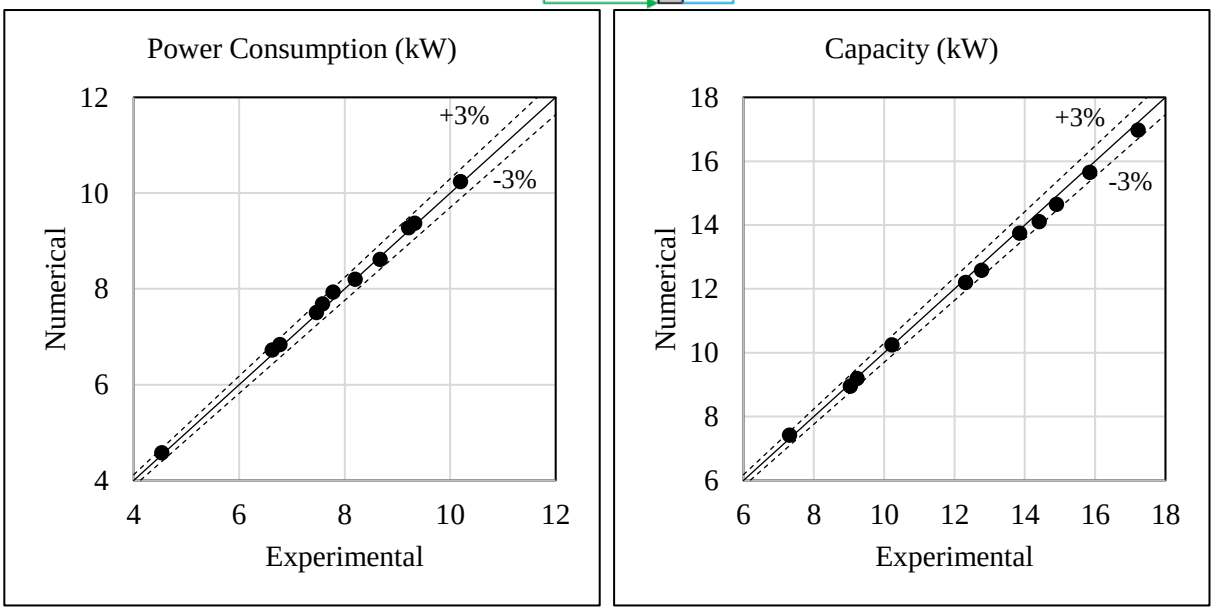


Figure 5: CO2 Two-Stage Refrigeration System Validation

4. Conclusion

This paper presents a new component-model based steady state vapor compression systems solver is developed. This solver can handle arbitrary system configurations with large number of components (more than 500), multiple refrigerants without compromising modeling speed or robustness. Moreover, this solver supports user-defined fluids, and user-defined convergence criteria. The solver is validated using a residential ASHP, a vapor injection heat pump, and CO_2 two-stage refrigeration system systems and the modeling results match the experimental results within 5%, 10%, and 3% accuracy, respectively.

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