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Steady State Modeling of Advanced Vapor Compression Systems

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ABSTRACT

The use of heating, ventilation, air conditioning, and refrigeration (HVAC&R) systems is always increasing. This is because the HVACR systems are necessary for food production and ability to inhabit buildings that otherwise would be inhabitable. Thus, there is continued research focused on improving the efficiency and reducing the negative environmental impact of these systems. The basic vapor compression cycle (i.e., evaporator, condenser, expansion device and compressor), which is still the main underlying HVAC&R technology worldwide, has already reached its limits and researchers are investigating more creative and complex cycles to improve capacity and efficiency. This motivates the development of a generalized vapor compression system simulation platform. Steady state simulations require less time than transient simulations, and are used in system design optimization and cost minimization for given performance. 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 vapor compression system designs. This includes arbitrary system configurations, 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 a system engineer to quickly assemble and simulate a system where-in the component models and performance data comes from disparate sources. This allows different vapor compression systems design engineers, and manufacturers to use the solver without the need to expose the underlying component model complexities. We validate the solver using a residential air source heat pump system and the modeling results match the experimental results within 5% accuracy. Also, the solver shows an agreement within 10% accuracy with the experimental results of a vapor injection heat pump system with a flash tank.

1. INTRODUCTION

The use of vapor compression systems, whether on the commercial or residential scale, is continuously increasing. One reason for that is that vapor compression systems comprise the majority of the HVACR systems. According to the US Department of Energy (U.S. Department of Energy, 2010), heating, ventilation, and air conditioning (HVAC) account for 40%, and 33% of primary energy use in residential and commercial buildings, respectively. Thus, research is ongoing to improve the efficiency, and reduce the cost and environmental impact of the HVACR systems. In order to reach these targets, a large number of system designs need to be evaluated, either through simulation or building a prototype. The latter option is obviously expensive and time consuming. Hence, the development cost of vapor compression systems drops when using proper simulations tools as large number of prototypes can be evaluated without the need of manufacturing large number of prototypes (Negrão & Hermes, 2011). A proper simulation tool should combine three main factors: robustness, speed, and accuracy (Ding, 2007). A vapor compression system simulation tool comprises 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 in this paper, combines the component models together according to the relationship between component parameters. The aim is to obtain the steady state refrigerant state (e.g. pressure, enthalpy, temperature…etc.) while satisfying the energy and mass balance in the system.

There are many solvers that can be used for energy system simulation, such as vapor compression systems, that currently exist. These can be divided into two main categories with some solvers utilizing hybridizations of the two categories (Richardson, 2006). The first category is the general equation solvers. These solvers allows specifying the system in terms of its governing and component models' equations. The solver then solves these set of equations. Although this category allows for the simulation of any system, it requires a lot of efforts from the system designer. The second category of simulation packages is the advanced energy system solvers. These solvers are usually designed for a specific task (e.g. simulation of a heat pump model, solar power plant…etc.). This makes it easier to perform the desired simulations. However, it is usually limited with the specific system to which it is designed. This makes 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 typically fluid-related state information (Qiao, et al., 2010). The system solvers can also be divided in two main approaches in which the unknown variables are solved (Winkler, 2009): successive approach where a variable is solved before moving on to the next variable, and simultaneous approach which uses a non-linear equation solver to solve all the unknown variables simultaneously. The successive approach (Davis & Scott, 1976; Hiller & Glicksman, 1976; Ellison & Creswick, 1978; Tassou, et al., 1982; Domanski & Didion, 1983; Domanski & McLinden, 1992; Fischer & Rice, 1983; Robinson & Groll, 2000; Koury, et al., 2001; Joudi & Namik, 2003; Sarkar, et al., 2006; Fukushima, et al., 1977; de Lemos & Zaparoli, 1996; Zhao, et al., 2003; Rigola, et al., 2005; Santa & Garbai, 2013; Stefanuk, et al., 1992; Winkler, et al., 2008; Blanco, et al., 2012) 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. Thus, 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 (Almedia, et al., 1990; Belman, et al., 2009; Corberan, et al., 2002; Corberan, et al., 2000; Herbas, et al., 1993; Jin & Spitler, 2002; Hwang & Radermacher, 1998; Jolly, et al., 1990; Parise, 1986; Richardson, et al., 2002; Rossi, 1995; Richardson, et al., 2004; Shao, et al., 2008; Agrawal, et al., 2007; Bourdouxhe, et al., 1994; Browne & Bansal, 1998; Sanaye & Malekmohammadi, 2004; Paulus, et al., 1994), the number of unknown variables is higher than 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.

A third 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 (Winkler, 2009). 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. However, only very few vapor compression system simulation packages implement this solution scheme.

To sum up, there are many steady state simulation solvers that exist in literature. However, 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. Also, 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 due to the proprietary equations and data used in the different components. Thus, 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 (DOE/ORNL, 2015; Winkler, et al., 2006). However, these tools lack one or more of the key 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. Also, this solver supports user-defined fluids, and user-defined convergence criteria.

2. OUTLINE OF THE NEW SOLVER

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. In the next part, we demonstrate the comprehensive solver outline for a basic vapor compression cycle with two condensers, shown in Fig.1. The unknown variables for this cycle are the pressure and enthalpy at each junction and the refrigerant mass flow rate fraction in the condensers. This makes a vector of a total of 9 unknown variables $[P_1\ P_2\ P_3\ P_4\ h_1\ h_2\ h_3\ h_4\ m_x]$. Based on the enthalpy marching solver (Winkler, et al., 2008), the enthalpy can be propagated from one component to the next (e.g. the enthalpy outlet of the compressor in the enthalpy inlet to the condenser). Therefore, the only unknown enthalpy is at the compressor inlet. These two considerations reduce the number of unknown variables to 5 variables $[P_1\ P_2\ P_4\ h_1\ m_x]$. 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, ejector …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. This means that 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 each pressure level containing a condenser (e.g. in the example cycle, this is one), at any condenser outlet (only one condenser outlet at the pressure level) 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 compressor, the solver formulates two residual equations at the compressor inlet. These two equations ($P_{1,i}$-$P_{1,i-1}$=0, $h_{1,i}$-$h_{1,i-1}$=0) compare the calculated compressor inlet pressure and enthalpy values after each iteration with the calculated values from the previous iteration. The solver uses an input inlet pressure guess value as the reference pressure at the first iteration. The suction enthalpy is based on the suction pressure and the desired superheat.
4. For every expansion device, the solver compares the input superheat value with the calculated enthalpy at the specified point at each iteration.

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), subcooling at any condenser outlet is an input convergence criteria.
2. For every compressor, the inlet and outlet pressures are two input guess values.

3. For every expansion device, a corresponding desired outlet condition (e.g. superheat value at any evaporator outlet along the same refrigerant path of the expansion device) is an input to the solver.

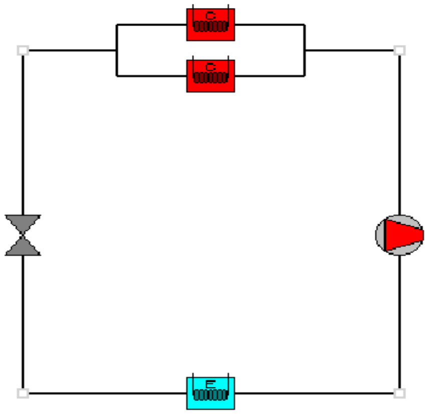

Figure 1: Basic vapor compression cycle with two condensers

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 proposed new 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 compressors, the suction and discharge pressures are known (either from the guess values or the previous iteration) and the suction 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 to run them one by one. For each component, if the upstream refrigerant state (i.e. inlet port state) is known, the solver runs the component model. However, if the inlet port state has not been calculated yet, the solver moves to the following component. As an example, in Fig. 1, after running the compressor, if the solver checks the evaporator, it will not run te evaporator as h_4 is not calculated yet. The solver will only be able to run the condensers since the refrigerant state at junction 2 is already calculated. The solver keeps repeating the same loop until it runs all the component models. It then calculates the residuals and passes the values to the non-linear equation solver to proceed to the following iteration. This keeps going until convergence occurs within the specified tolerance. Figure 2 shows the solver flowchart.

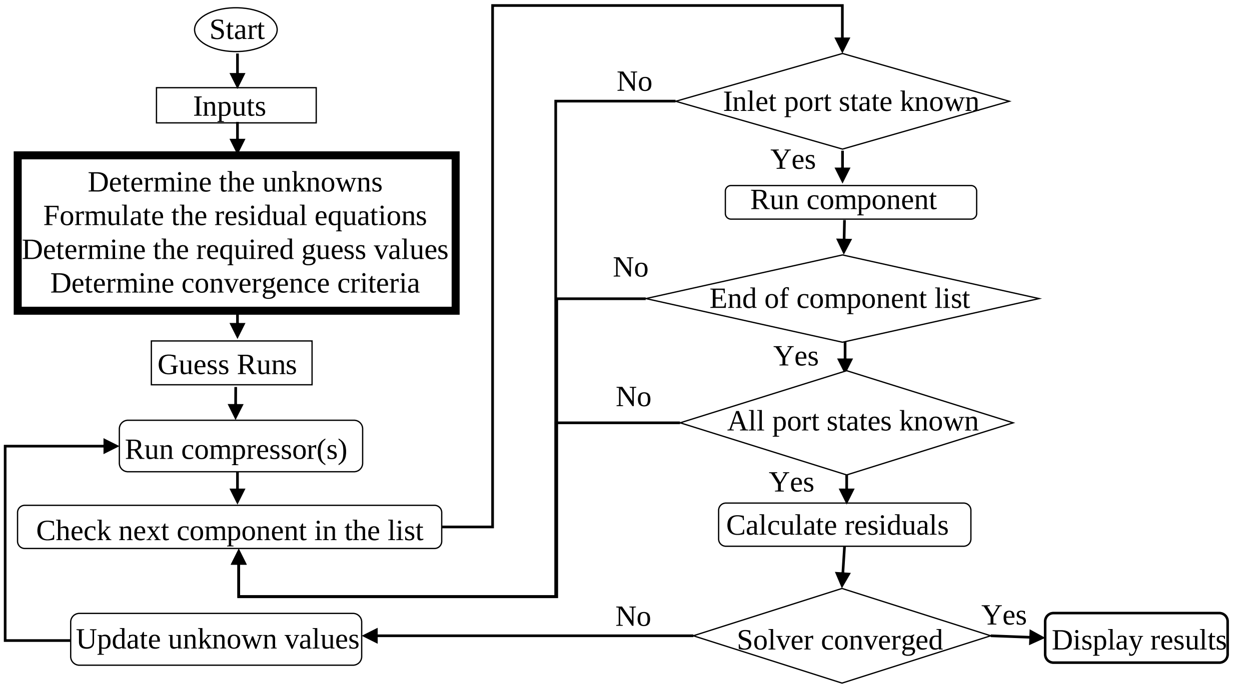

Figure 2: Solver flowchart

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. (Alabdulkarem, et al., 2013). 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 (Jiang, et al., 2006). 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 Fig. 3. It is worth noting that the same validation study was previously done using the enthalpy marching solver and results showed the same agreement (Alabdulkarem, et al., 2015).

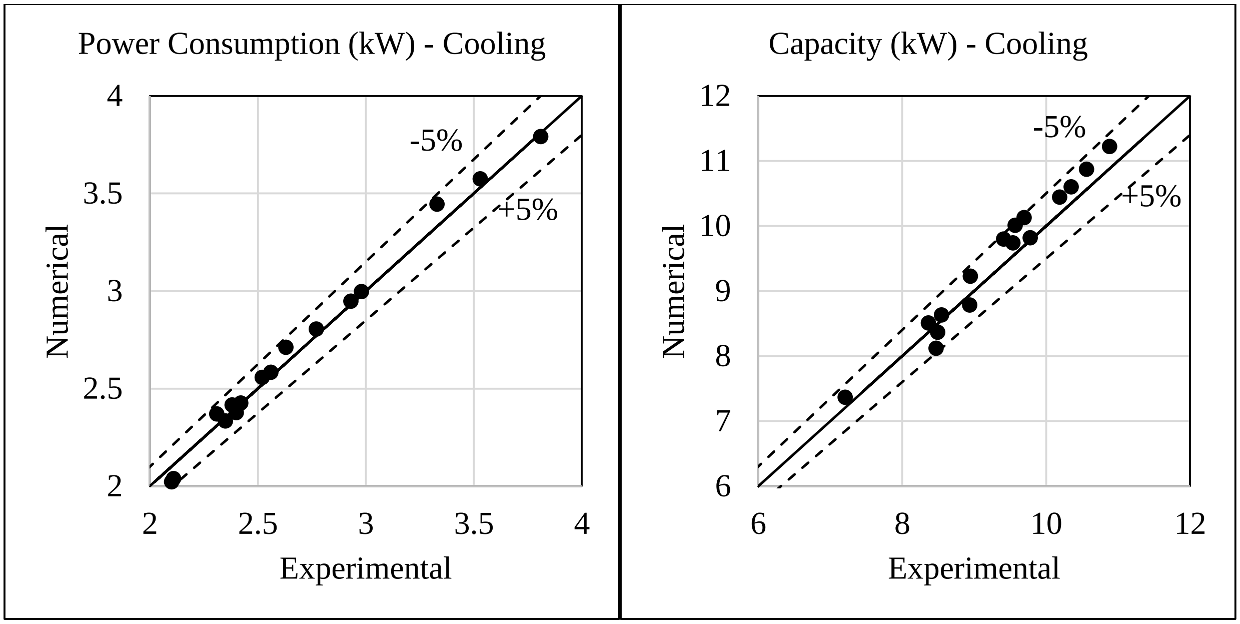

Figure 3: ASHP validation

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 (Xu, et al., 2013). 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 (Jiang, et al., 2006). 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 5 shows the cycle schematic. The modeling results match the experimental results within 10% accuracy as shown in Fig. 4.

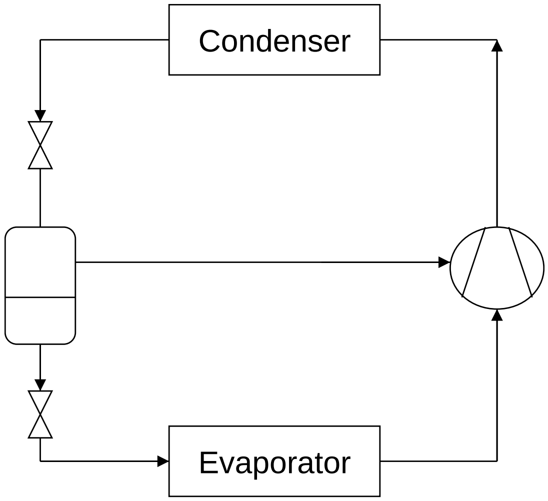

Figure 4: Vapor injection cycle schematic

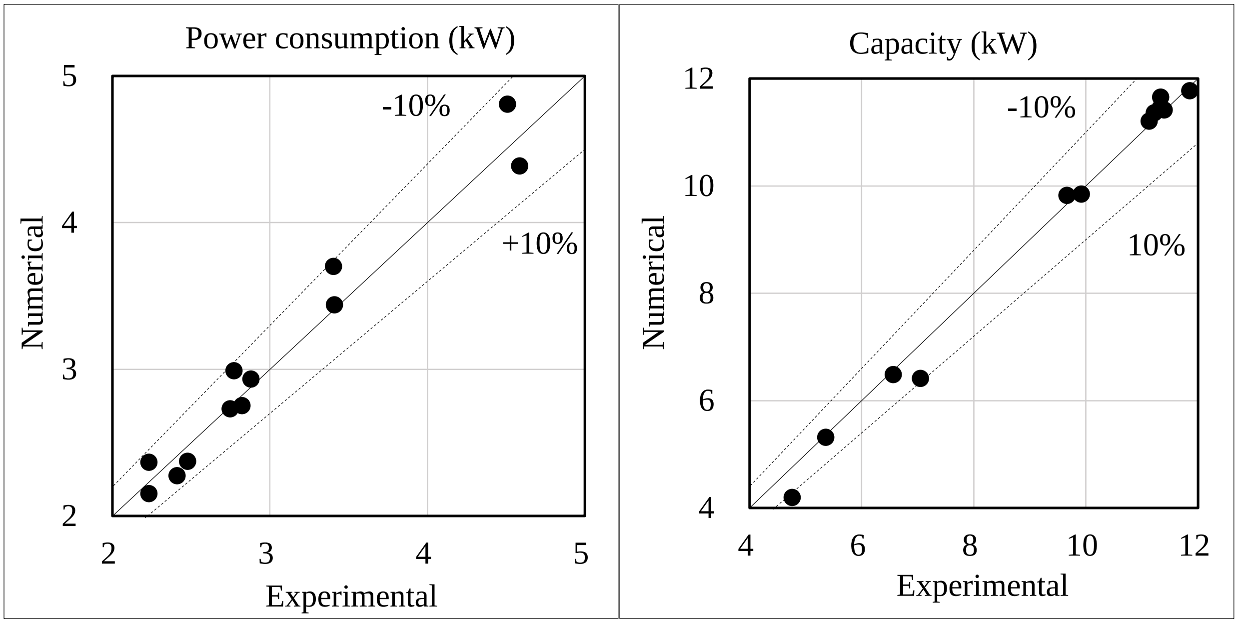

Figure 5: Flash tank cycle validation

4. CONCLUSION

This paper presents a new component-model based steady state vapor compression systems solver. This solver falls under the successive solution scheme category of solvers. Nevertheless, it uses highly flexible data structures to overcome the flexibility problem associated with this category of system solvers. Thus, this solver can handle arbitrary system configurations without compromising modeling speed or robustness. Moreover, this solver supports user-defined fluids, and user-defined convergence criteria. The solver outline is demonstrated for a basic vapor compression cycle with two condensers. The solver is also validated using a residential ASHP, and vapor injection heat pump systems and the modeling results match the experimental results within 5%, and 10% accuracy, respectively.

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