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Research Paper

Developing and validating a dynamic mathematical model of a three-evaporator air conditioning (TEAC) system

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HIGHLIGHTS

- A physics-based dynamic model of a three-evaporator air conditioning (TEAC) system was developed.
- The model was experimentally validated, with an acceptable modeling accuracy.
- It can help develop TEAC system controllers for improved indoor humidity.
- It can also help study a TEAC system's operational characteristics.

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ABSTRACT

The development of a physics-based dynamic model of a three-evaporator air conditioning (TEAC) system is reported. The TEAC model was built on sub-models of major system components in the TEAC system, including a compressor, an air-cooled condenser, three electronic expansion valves, three indoor units and indoor spaces. Unlike all other reported TEAC models, the TEAC model developed specifically took into account both sensible and latent heat balances on the airside of all indoor units.

The TEAC model was validated using a purpose-built TEAC experimental rig. Model predictions were found to be within ±6% of the measured values, suggesting that the model developed was capable of simulating both steady state and dynamic operation of a TEAC system with an acceptable modeling accuracy. Therefore, the TEAC model developed is expected to be very useful in studying the operating performances and developing novel controllers for TEAC systems, in particular the improved indoor relative humidity control using a TEAC system.

1. Introduction

For pursuing a high quality living and working environment with less energy consumption, multi-evaporator air-conditioning (MEAC) systems, which may also be called multi-split air conditioning systems or variable refrigerant flow/variable refrigerant volume (VRF/VRV) systems in the open literature, are widely used in small- to medium-scale buildings due to their advantages of high design flexibility, better indoor thermal comfort control and higher energy efficiency. Although MEAC systems worth many billions of dollars are sold worldwide, only a very limited number of compressor capacity control algorithms for an MEAC system can be identified in the open literature, and most of them, if not all, focus on temperature control only. Furthermore, there is a lack of validated dynamic mathematical MEAC simulation models, which may be used as platforms for developing advanced capacity controllers for MEAC systems for improved control accuracy and higher energy efficiency.

Although both a single-evaporator air conditioning (SEAC) system and an MEAC system are operated based on the same vapor compression cycle, there exist a number of noticeable differences between the two. Usually in an MEAC system, there are two or more indoor units (IU) installed in parallel without any pressure regulators, which results in strongly coupled operational parameters in each IU.

Over the past few decades, simulation study has become increasingly popular. Its applicability in design optimization and developing control strategies for refrigeration and air conditioning (RAC) installations has widely been accepted by the RAC industry. A large number of dynamic models for heat pumps/air conditioners are available. Various modeling approaches such as distributed-parameter modeling approach [1], lumped-parameter approach [2] and partial lumped-parameter approach [3] can be employed. It is, however, noted that almost all previous model development work reported for air conditioners focused on SEAC systems. In an MEAC

Abbreviations: DEAC, dual-evaporator air conditioning; EEV, electronic expansion valve; IS, indoor space; IU, indoor unit; LGU, load generating unit; MEAC, multi-evaporator air conditioning; RAC, refrigeration and air conditioning; RH, relative humidity, %; SEAC, single-evaporator air conditioning; TEAC, three-evaporator air conditioning; VRF, variable refrigerant flow; VRV, variable refrigerant volume.

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system, however, the multi-evaporators are connected in parallel, and the operating parameters in respective evaporators would influence one another. This would certainly increase the complexity and difficulty when modeling an MEAC system.

A number of previous studies on modeling MEAC systems can be identified in the open literature. Most existing MEAC models, however, dealt with a limited number of evaporators, with two being the most common number. Park et al. [4] solved a steady-state dual-evaporator air conditioning (DEAC) system model to analyze the cross-coupling effects between the two evaporators in the system. He and Asada [5] present a low-order model for a DEAC system which consisted of a feedback linearization part to compensate for the nonlinearity in the system dynamics. The model was applied to controller development for a DEAC system without validation. Pan et al. [6] carried out a modeling study on the effects of refrigerant pipeline length on the operational performance of a DEAC system. A generalized modeling approach for an MEAC system was proposed by Shah et al. [7]. The model validation on both an SEAC system and a DEAC system showed desired model responses. Zhu et al. [8] reported an MEAC model using TRNSYS simulation software. Two kinds of algorithms were provided, which proved to be suitable for modeling SEAC and MEAC systems, respectively. However, model validation was conducted based only on a DEAC system serving two indoor spaces (IS) having the same indoor thermal conditions. A DEAC model was developed and validated using the distributed-parameter modeling approach [9]. Using a two-phase fluid network approach, Shao et al. [10] and Shi et al. [11] developed a model to predict the performance of different complex refrigeration systems, including MEAC systems. Model validation was carried out by comparing model data with an MEAC system having two evaporators. Chen et al. [12] developed a simplified dynamic model for a TEAC system using the lumped-parameter modeling approach. However, no experimental validation for the model was conducted. System identification was used to obtain two linear, low-order models for both a TEAC [13] and a multi-type heat pump system [14]. However, system identification was not physical, but semi-empirically based, and a model so developed can be only applied to a specific system by which system parameters were identified.

Therefore, as discussed, most studies related to modeling MEAC systems are based on DEAC systems, with experimental validation [6–10]. Although limited TEAC system models have also been developed, they were either simulation based without experimental validation [5,12] or based on system identification [13,14], not physically based.

Furthermore, simulation studies for MEAC systems primarily focused on the operational characteristics of their refrigerant side, such as refrigerant flow distribution and evaporating pressures, without much attention paid to the detailed airside characteristics of the simultaneous air cooling and dehumidification in each IU of the MEAC systems. This may appear understandable since most current research efforts focus on using MEAC system to control indoor air dry-bulb temperature only [8,12–14], but not indoor air humidity.

Consequently, an experimentally validated physics-based dynamic model for a TEAC system, which can be applied to all TEAC systems and help develop strategies for simultaneous indoor air temperature and humidity control, by taking into account the air side characteristics in each of its IU, should be developed.

In this paper, the development of such a dynamic TEAC model is reported. Firstly, the development for the TEAC system is presented by detailing the sub-models for each of system components. Secondly, details of the experimental validations of the TEAC model developed are presented.

2. Dynamic modeling of the TEAC system

A partial-lumped parameter dynamic model for a TEAC system, specially taking into consideration both the sensible and latent heat balances on the airside of all IUs, has been developed. The model was built on sub-models for individual components in the TEAC system and was implemented using MATLAB programming environment.

A schematic diagram of the TEAC system modeled is shown in Fig. 1. The major system components included a variable speed rotary compressor, an air-cooled condenser, and three IUs each having an electronic expansion valves (EEV) and an evaporator. Refrigerant R22 was used as the working substance of the TEAC system.

When modeling, the DX evaporator was divided into two regions, i.e., a two-phase and a superheated region (SH); and the air-cooled condenser into three regions, i.e., a desuperheating region (DS), a two-phase region and a sub-cooled region (SB). Since a good representation of heat exchangers was required, the two-phase region was further divided into a liquid (L) and a vapor zone (V). A conceptual model of the TEAC system is shown in Fig. 2. In this paper, when presenting the sub-models, reference is made to Fig. 2 for symbols representing the zones and subscripts indicating the actual locations in the TEAC system. For the nomenclatures used in Fig. 2, V indicates the space volume and Q the heat transfer of each region/zone, respectively. For the sub-scripts following V or Q, e indicates an evaporator and c an air-cooled condenser, respectively; r indicates the refrigerant side, a the air side and m the metal of each region, respectively; and $\_i(i = 1, 2, 3)$ represents the ith evaporator. For example, the refrigerant side of the two phase region of Evaporator 1 is separated into two zones, i.e., a liquid zone, which is represented by $V_{er1\_1}(\mathrm{L})$, and a vapor zone, which is represented by $V_{er2\_1}(\mathrm{V})$. The zone representing the metal tube wall of the two-phase region of Evaporator 1 is denoted by V_{em1_1}, and the amount of heat released by the air in the airside zone V_{ea1_1} by Q_{ea1_1}.

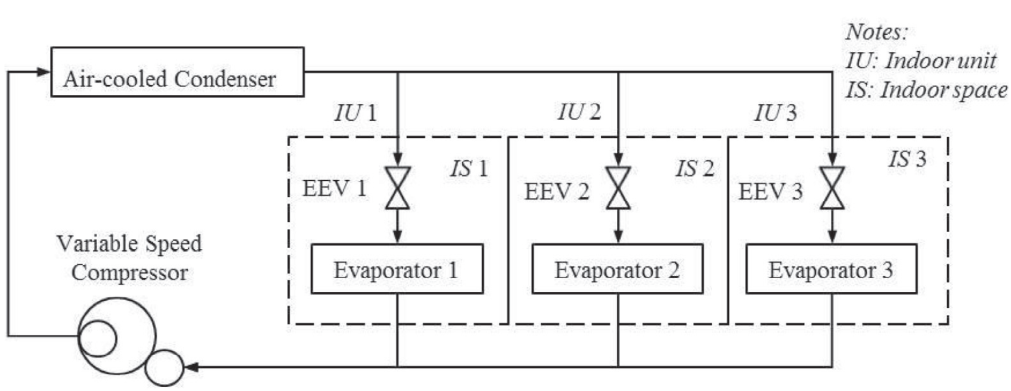

Fig. 1. Schematics of the TEAC system modeled.