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TOOLS FOR EVALUATING AIR FLOW NETWORK OF DUAL DUCT DOUBLE FAN SYSTEMS

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ABSTRACT

Dynamic system simulation tools are needed for developing advanced control, operation, and fault detection and diagnosis techniques for heating, ventilation, and air conditioning (HVAC) systems. There has been a lack of dynamic simulation tool development focusing on dual duct systems. The work here summarizes an effort to develop and validate a dynamic simulation model that is able to simulate fault free and faulty operational data for the air flow network in a dual duct double fan system. The challenges and solutions of simulating such dual duct dual fan air flow networks are discussed. A systematic validation procedure is developed to validate the model, which shows good agreement between simulated outputs and experimental data generated from a small commercial building in a laboratory facility.

INTRODUCTION

In a dual duct system, hot and cold air flows are separately carried by two parallel duct systems. The hot deck is equipped with a heating coil and the cold deck is equipped with a cooling coil. The two decks run in a parallel configuration throughout the building. In a terminal unit, the proper proportions of hot and cold air streams are modulated by cold air and hot air dampers before proceeding downstream to the space. The simultaneous availability of hot and cold air enriches the flexibility of this system to handle zones with widely varying loads. Meanwhile, energy could be saved by utilizing outside air directly as hot air or cold air in different seasons. The dual duct systems may be designed as constant air volume (CAV) or variable air volume (VAV). In a CAV dual duct system, the supply air flow rate through the supply fan and to each zone is constant. However, the flow rates through the cold and hot decks vary depending on the requirements to satisfy the individual zone load. In a VAV dual duct system, the supply air flow rate through the supply fan is not constant and is dependent on the zone temperature control and ventilation needs. Similar to single duct VAV terminal units, VAV dual duct terminal units can also be categorized as pressure-dependent or pressure-independent units. More details about how dual duct systems are controlled can be found in (Kreider et al. 2002).

Over the past three decades, various computer software applications have been developed to simulate dynamic interactions between a building's envelope, its internal loads, its ambient conditions, and its HVAC systems, but very little attention has been devoted to dual duct systems. Salsbury et al. (2000) discussed the potential of simulation as a performance validation tool to evaluate a dual duct single fan system installed in an office in San Francisco. But there has been no prior work specifically about dynamic simulation and model validation for dual duct systems. The development of advanced control, operation, and automated fault detection and diagnosis techniques requires reliable simulation tools, therefore there is a need to develop a simulation tool that is capable of simulating realistic fault free and faulty operational data for dual duct systems.

The work documented here models the air flow network of a pressure-independent VAV dual duct double fan system serving four zones that have various orientations. This model will later be extended to include thermal and control aspects of the system and to include other common dual duct configurations. In comparison with single duct systems, dual duct systems present unique challenges, especially regarding air flow simulations. Since the cold and hot air flow network are strongly coupled, how to simulate them simultaneously and robustly is a key obstacle. Here, the focus is to model the constituent components of a dual duct system in terms of their governing equations, as well as the arrangement of these equations to achieve a stable and efficient simulation.

The HVACSIM+ software (Park et al, 1985) developed by the U.S. National Institute of Standards and

Technology (NIST) is used in this study. It employs a unique hierarchical computation approach. Individual simulation elements (called "units") are firstly grouped by the user into "blocks" for a simultaneous solution. Blocks are then similarly grouped into "superblocks" for simultaneous solution. Each superblock is a numerically independent subsystem of the overall simulation; its time evolution and internal solutions are propagated independently of other superblocks. Each individual unit is an instance of a specifically serialized equipment or device "TYPE" (written all caps, to distinguish from the common use of the word), requiring the user to link inputs and outputs between all units and assign unit parameters. A subroutine solves the resulting sets of nonlinear algebraic and differential equations to determine system state at each time step (DeSimone, 1996). This hierarchical approach makes even complex simulations solvable. HVACSIM+ has been experimentally validated and improved (Dexter et al., 1987), and proven appropriate for faulty and fault-free modeling for HVAC systems (Bushby et al. 2001, Dexter, 1995, Peitsman et al. 1997, Li and Wen, 2010, Li et al. 2010).

In this paper, the test facility in which validation data are produced is described first. Details about the model including new TYPEs that are needed in the model are introduced in the following section. It is then followed by model validation procedures and results.

DUAL DUCT SYSTEM AND BUILDING DESCRIPTION AT TEST FACILITY

Experiments have been conducted at Iowa Energy Center Energy Resource Station (ERS) on a full scale dual duct system in three different seasons to generate operational data used in validation of the developed model for this study. The ERS has been described in at least three earlier studies (Norford et al. 2000, Castro et al. 2003, Li et al. 2010). The major feature of this test facility is two identical HVAC systems (A and B systems). However, significant modifications have been made to the two identical single duct AHU systems (AHU-A and B) to convert them from two single duct systems as previously described to one dual duct double fan system with one return duct. More specifically, the following major changes have been made: 1) The two existing and identical single duct AHUs (AHU-A and B) were connected by a duct (bridge), so that the mixing box and return duct of the AHU-B were used as the dual duct mixing box and return duct; 2) In AHU-A, the duct work before the bridge connection was completely blocked. The downstream (after the connecting bridge) components of AHU-A, including a heating coil, a cooling coil (not used), and a supply fan, were used in the dual duct system; 3) In the four test rooms that were used in this study, pressure independent dual duct terminal units were installed. After these changes, AHU-A and B were respectively serving as the hot deck and cold deck of the new dual duct system. Instrumentation used in this study consisted of humidity, pressure, temperature and air flow sensors as well as electric power meters to monitor the system. Figure 1 demonstrates the new dual duct double fan system and the four test rooms.

AIR FLOW MODEL OF DUAL DUCT SYSTEM IN HVACSIM+

This section presents the development of an air flow network model in HVACSIM+ for the above described dual duct system. As suggested in the previous studies (Norford et al. 2000, Castro et al. 2003, Li and Wen 2010), when simulating a comprehensive HVAC and building system in HVACSIM+, all of the constitutive processes represented by them can be divided among multiple constituent TYPEs. Each TYPE separately expresses one category of process states that is both physically and numerically independent from-or at most, coupled only weakly to- any other category of the process states in the system.

Generally in modeling HVAC systems five distinct categories of states -(1) sensor, (2) actuator, (3) control logic, (4) fluid (i.e., mass flow and pressure), and (5) thermal (temperature and humidity)- must be modeled independently. The representative TYPEs of the same state category are grouped as a network to create a superblock. Each superblock is an independent subsystem within which the system of governing equations of one state category is solved simultaneously. This approach was used to develop the dual duct system model. In this study, only the development of the air flow network (superblock) has been described.

Figure 2 represents the developed air flow network of the studied dual duct system. In this Figure, each box represents an UNIT to which a TYPE has been assigned. The description and the TYPE that each UNIT uses have been provided within the UNIT box. The inputs and outputs of each UNIT have also been specified. In Figure 2, mass flow rates, pressures, and control signals are respectively presented by m, p and C. Notice that a separated modeled control network (not shown here) will eventually provide all of the control inputs. Since the focus of this study is only the air flow network, the control signals are considered as boundary signals and provided by the experimental data. After the air flow network is fully validated, other networks will be developed and connected with the air flow network.

Most of the TYPEs that have been used in this dual duct air flow network are the existing TYPEs provided by the HVACSIM+ component library and have been used in previous studies. Three new TYPES, i.e., TYPEs 535, 536 and 538 have been developed to simulate the air flow rate and pressure in dual duct terminal units. TYPE 535 determines hot, cold, and total air flow rates at the two inlets and one outlet, when pressures at these inlets and outlet are given. TYPE 536 determines air flow rate for hot deck inlet, total air flow rate for outlet, and cold deck inlet pressure, when hot deck inlet pressure, outlet pressure, and cold deck inlet air flow rate are given. Similarly, TYPE 538 determines air flow rate for cold deck inlet, total air flow rate for outlet, and hot deck inlet pressure, when cold deck inlet pressure, outlet pressure, and hot deck inlet air flow rate are given. These different TYPEs are used for different test room configurations. Dominant equations of TYPE 535, which is used as dual duct terminal unit for South-B room (refer to Figure 2), are presented in Equations (1) to (3).

$$m_8 = \sqrt{\frac{P_{13}-P_{23}}{R_{hot\ damper}}} \tag{1}$$

$$m_{16} = \sqrt{\frac{P_{21}-P_{23}}{R_{cold\ damper}}} \tag{2}$$

$$m_{18} = m_8 + m_{16} \tag{3}$$

m_8, m_{16} and m_{18} as well as P_{13}, P_{21} and P_{23} have been illustrated in Figure 2. Furthermore, $R_{hot\ damper}$ and $R_{cold\ damper}$ are the pressure resistances of hot and cold dampers, respectively. The governing equations of TYPE 536 and 538 are similar. For example, the dominant equations for TYPE 536, which is used as terminal unit for West-A room, are presented in Equations (4) to (6).

$$m_6 = \sqrt{\frac{P_{11}-P_{22}}{R_{hot\ damper}}} \tag{4}$$

$$P_{20} = P_{22} + R_{cold\ damper} m_{15}^2 \tag{5}$$

$$m_{17} = m_6 + m_{15} \tag{6}$$

m_6, m_{15} and m_{17} as well as P_{11}, P_{20} and P_{22} have been illustrated in Figure 2. Equations for TYPE 538 are not presented here for brevity.

In the developed air flow network model, pressures and flow rates in different units are determined by solving the system of governing mass-pressure equations. Because the dual duct air flow network has two separate air flow paths (hot and cold) that are strongly coupled, it is subject to convergence issues. The arrangement of UNITs as well as the equation formats within a UNIT need to be carefully considered to avoid convergence problems. Different UNIT arrangements and equations formats were tried and discarded before those shown in Figure 2 were found effective. One unique TYPE specifically used for the dual duct air flow network is the main duct splitter unit TYPE 345. The equations used in this TYPE are summarized here:

$$m_4 = \frac{R_{HD} m_2 \mp \sqrt{R_{HD}\ R_{CD}\ m_2^2 - (R_{HD}-R_{CD})(P_4-P_5)}}{(R_{HD}-R_{CD})} \tag{7}$$

$$m_3 = m_2 - m_4 \tag{8}$$

$$P_3 = P_4 + R_{HD} \mathrm{m}_3^2 - R_{inlet} \mathrm{m}_2^2 \tag{9}$$

m_2, m_3 and m_4 as well as P_3, P_4 and P_5 have been illustrated in Figure 2. Furthermore, R_{HD}, R_{CD} and R_{inlet} are the pressure resistances of the junction dividing the flow between hot and cold decks.

The TYPE 345 splitter equations are different from those of TYPE 346, commonly used in single duct simulations. For comparison, the equations for TYPE 346 are provided as Equations (10) to (12).

$$\mathrm{m}_{\text{main outlet}} = \mathrm{m}_{\text{inlet}} - \mathrm{m}_{\text{branch}} \tag{10}$$

$$P_{inlet} = P_{main\ outlet} + R_{main\ outlet} \mathrm{m}_{main\ outlet}^2 + R_{inlet} \mathrm{m}_{\text{inlet}}^2 \tag{11}$$

$$P_{\text{branch}} = P_{main\ outlet} + R_{main\ outlet} \mathrm{m}_{main\ outlet}^2 - R_{branch} \mathrm{m}_{\text{branch}}^2 \tag{12}$$

Considering the first splitter after the supply fan in the hot deck (the top deck) m_{inlet} and P_{inlet} are m_3 and P_7, $m_{main\ outlet}$ and $P_{main\ outlet}$ are m_5 and P_{10} and m_{branch} and P_{branch} are m_6 and P_{11}. Parameters R_{inlet}, $R_{main\ outlet}$ and R_{branch} are the respective pressure resistances.

The use of TYPE 345 as the main duct splitter was found to be critical to receive robust and converging performance of dual duct air flow network simulations.

AIR FLOW NETWORK MODEL VALIDATION

Validation of the dual duct air flow network model was accomplished by a two level approach: at the component level model, and at the system level model. At each level of validation, the model parameters or structures were adjusted to achieve good agreement between simulated and experimental data.

For each UNIT, the values for the parameters needed to be determined. These parameter values were determined either through manufacturer's catalog data or a component test (especially for critical components). However, for the duct work, the pressure resistances of –the converging and diverging junctions in supply and return ducts were calculated based on a loss coefficient method (Pita 2002). Many of the components in this dual duct system, such as the mixing box, heating/cooling coils, and the return fan, were the same components used in the ASHRAE 1312 research project (Li, et al., 2010). Therefore, parameters obtained from ASHRAE 1312 project were kept the same for these components.

Although the supply fans used in this dual duct system were the same as the ones (AHU-A and -B) used in the ASHRAE 1312 project, significant differences were found between the fan data generated from the ASHRAE 1312 project and this study, mostly due to the duct work modifications and different operating conditions. Therefore, new parameters were generated from experimental data (June 9th 2013 and Oct 3rd 2013 for cold deck and June 9th 2013 and Nov 12th 2013 for hot deck) for the two supply fans. The procedures used in determining the new fan parameters were similar to those described by (Li, et al., 2010) and are not repeated here.

A new component test was performed for the dual duct terminal unit hot and cold dampers. The pressure drop across the dampers was calculated by Equation (13)

$$\Delta P = K_\theta \frac{\rho v^2}{2} \tag{13}$$

Where ΔP is the pressure drop across damper (Pa or psf) ρ is air density (kg/m^3 or lbm/ft^3), v is mean air velocity (m/s or fpm), and K_θ is the loss coefficient. $log_e K_\theta$ is a function of damper position and represented by a three region model, namely, a dead band, a linear, and a polynomial region. More detailed damper equations have been provided in prior work (Li and Wen, 2010).

During damper component testing, damper positions were systematically adjusted from 0% to 100% open with 10% increments for cold and hot dampers in the South-B room dual duct terminal unit. The pressure drop across the dampers and resulting discharge air flow rate were measured after the system reached steady state. Experimental data generated from this component test were then used to determine hot and cold dampers' loss coefficient (K_θ) and then pressure resistances at various damper positions.

As Figure 3 indicates, when damper opening is between 50 and 60 % open, the relationship between damper resistance and damper opening is quite different from other damper positions. Considering that 50-60% open is a very commonly used damper position range, it was important to model this range well. Therefore, several models were generated based on the component test data for each damper. The changes between different models included starting and ending damper positions for each region and/or model parameters. The goal was to develop a model with good overall R^2 and also small modeling error between 50 and 60% damper positions. In the end, the models represented by red square symbols on Figure 3 were selected.

After the component level validation, system level validation was performed. Variables examined for system level validation included hot and cold deck supply air flow rates and return air flow rate as well as their values for each zone. In order to validate the air flow network model independently from other networks, control signals (mixing box dampers, terminal units hot and cold dampers, supply and return fan speeds) were provided directly from experimental data as boundary conditions. The system level validation is further designed to include two steps. The first step was to validate a subsystem starting from the hot and cold supply deck splitters all the way down to the rooms (before any flow merging). This step validated the hot and cold air supply decks, including the majority of modifications of the air flow network model. Satisfactory results from this first step ensured the accuracy of new parameters and new TYPEs. Subsequently, the entire air flow network validation was performed.

In order to perform the first step of validation, hot and cold deck air flow rates (m3 and m4 in Figure 2) along with corresponding damper positions for each zone, were obtained from experimental data to be boundary conditions. Experimental data from a normal test day in summer (June 9th, 2013) were used for sub-system level validation. The comparison of experimental data and simulation results (not shown here) demonstrated that the pressure resistances calculated for the new splitters and the fitted model for hot and cold dampers in VAV terminal units simulated the distribution of air flow among various rooms satisfactorily. There were slight discrepancies between the simulated hot and cold air flow rates and the real data due to the fact that component tests for damper model validation were only performed in the South-B room.

Lastly, the entire air flow model was validated using data from three seasons (June 9th 2013, Oct 3rd 2013, Oct 7th 2013, November 12th 2013 and November 25th 2013). For the summer test days, the outdoor air damper was fully closed and the system was in 100% recirculation mode. For the winter and fall seasons, the outdoor air damper position was mostly maintained at a minimum position (45%). But when outdoor air temperature was below 60 °F, the outdoor air damper was controlled by an economizer mode.

Figure 4 displays the simulation results for the summer test case (June 9th 2013 data). In this Figure, navy blue and red lines respectively represent experimental data and model predicted results and green lines represent the control signal that was provided to the model from experimental data. The first three graphs illustrate hot and cold deck supply air and total return air flow rates. Each pair of the following graphs respectively display hot and cold air flow rate to the West-A, South-B, South-A and East-B rooms. In general, model predicted results are in close agreement with operational data. The difference between experimental and model predicted hot air supply flow rate is on average within 78 CFM (0.0368 m^3/s) and this difference for cold air supply flow rate is on average within 57 CFM (0.0269 m^3/s). The biggest discrepancy between the model predicted results and experimental data is the 200 CFM (0.094 m^3/s) for cold air and 117 CFM (0.055 m^3/s) for hot air supply flow rates. As Figure 4 displays, the East-B room cold air flow rate simulation shows the highest discrepancy when damper positions are greater than 60%. Results from other seasons have very similar trends to those shown in Figure 4 and, for brevity, are not presented. For other seasons, the difference between experimental and model predicted hot air supply flow rate is on average within 150 CFM (0.07 m3/s) and this difference for cold air supply flow rate is on average within 250 CFM (0.12 m3/s). The amount of discrepancy between the model and experiment for outdoor air is around 200 CFM (0.094 m3/s), which is about 14 percent of the outdoor air flow rate.

CONCLUSION AND SUMMARY

In this work, a dynamic numerical model of the air flow state of a dual duct double fan system has been developed and validated. Three new components models (TYPE) representing the air flow state of VAV dual duct terminal units have been created for inclusion in the component library of the HVACSIM+ simulation package. A model structure for the air flow states of dual duct systems that will result in robust dynamic simulations is introduced. Validation of the air flow model was in two steps, starting with component level validation, followed by system level validation. Validation of air flow subsystems including hot and cold deck splitters and ductwork all the way to rooms laid the groundwork for the entire air flow model validation. Full system experimental data from three seasons were used to validate the entire air flow network model. The developed model shows satisfactory simulation results when compared with experimental measurements. Other networks, such as sensor, control, and thermal networks, need to be developed and validated by following similar processes in order to develop a complete model for dual duct dual fan systems.

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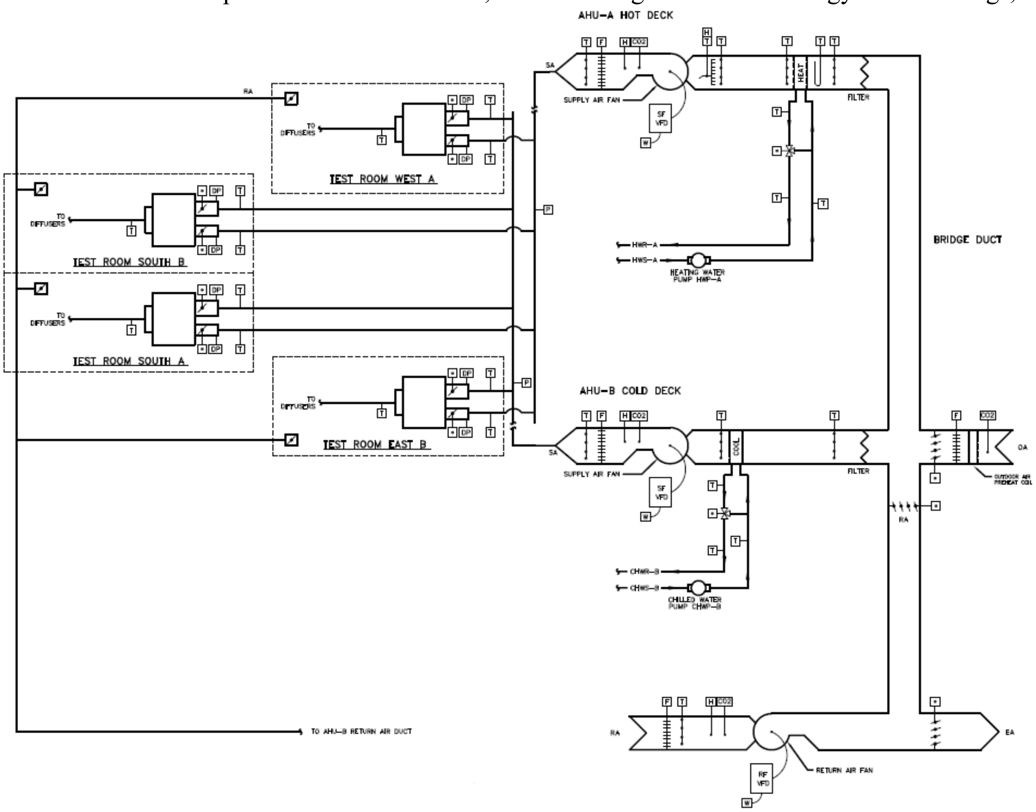

Figure 1 Schematic of dual duct test double fan system at ERS serving four perimeter zones

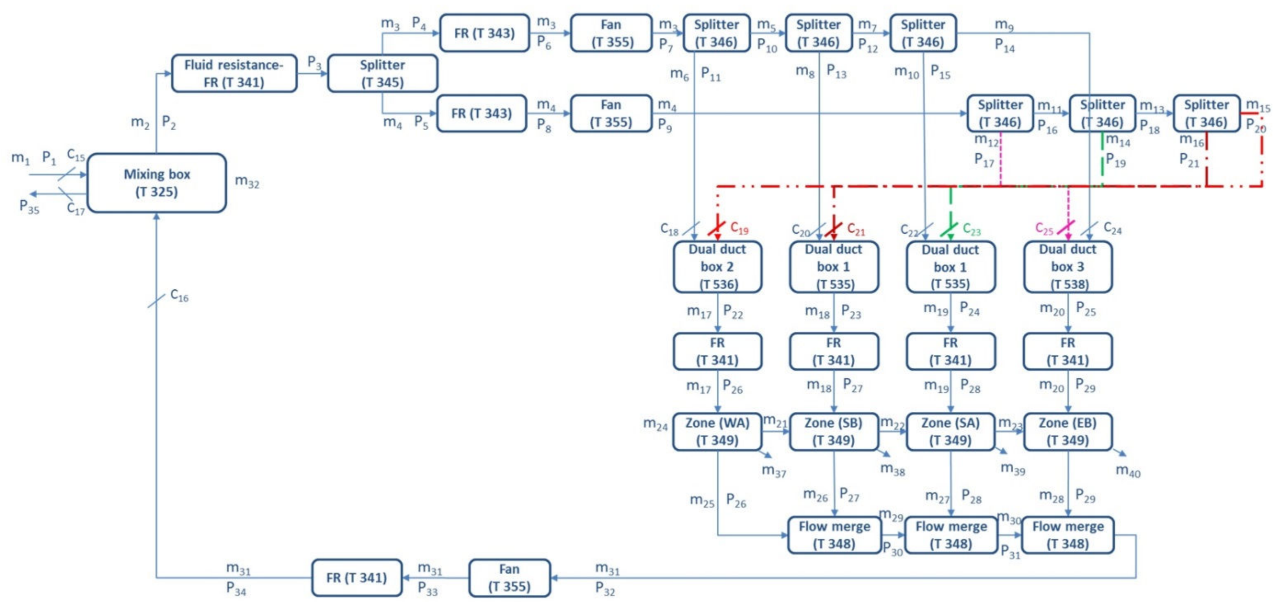

Figure 2 Air flow model of ERS dual duct double fan system in HVACSIM+

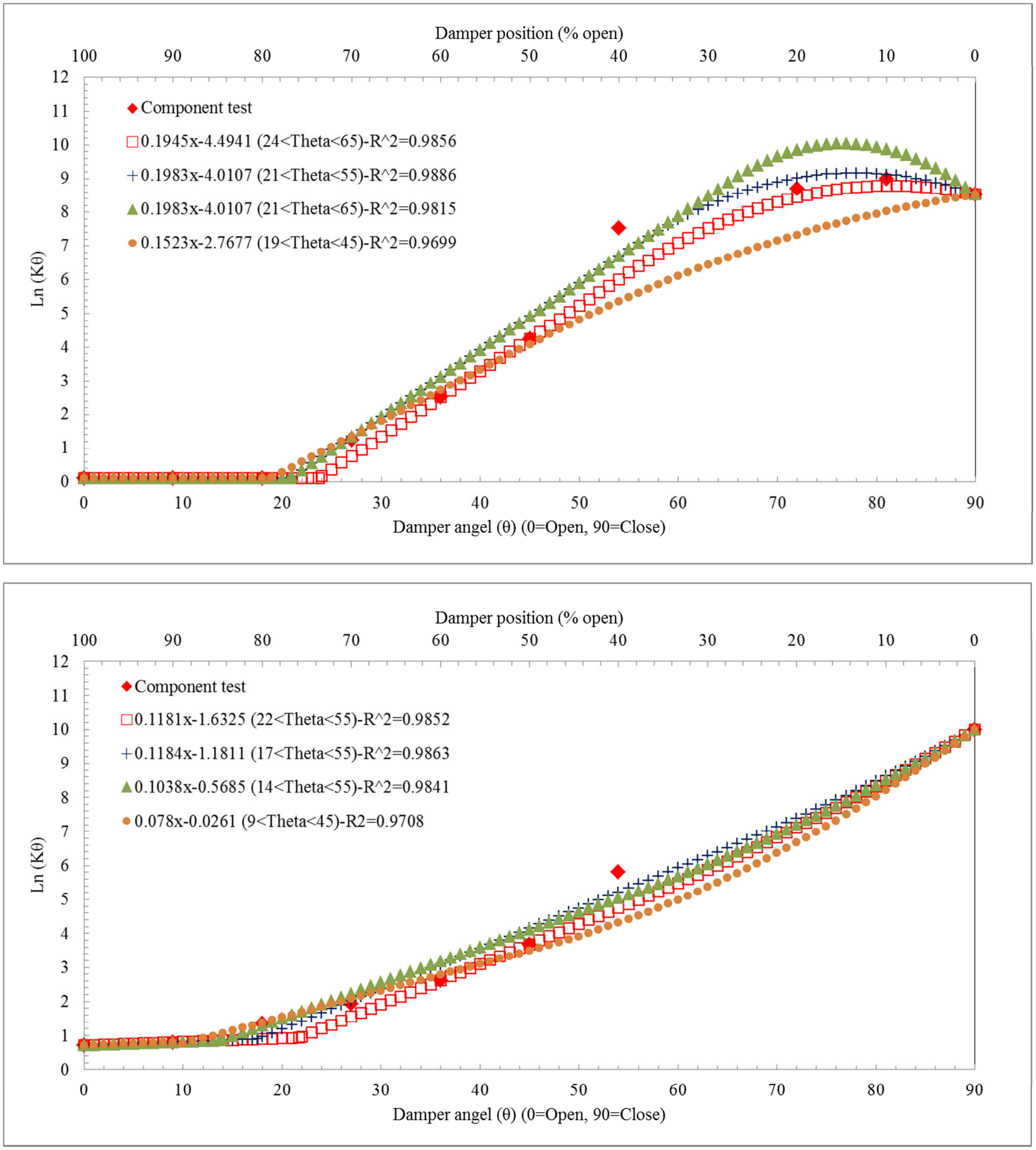

Figure 3 Hot (top) and cold (bottom) damper models in dual duct terminal unit

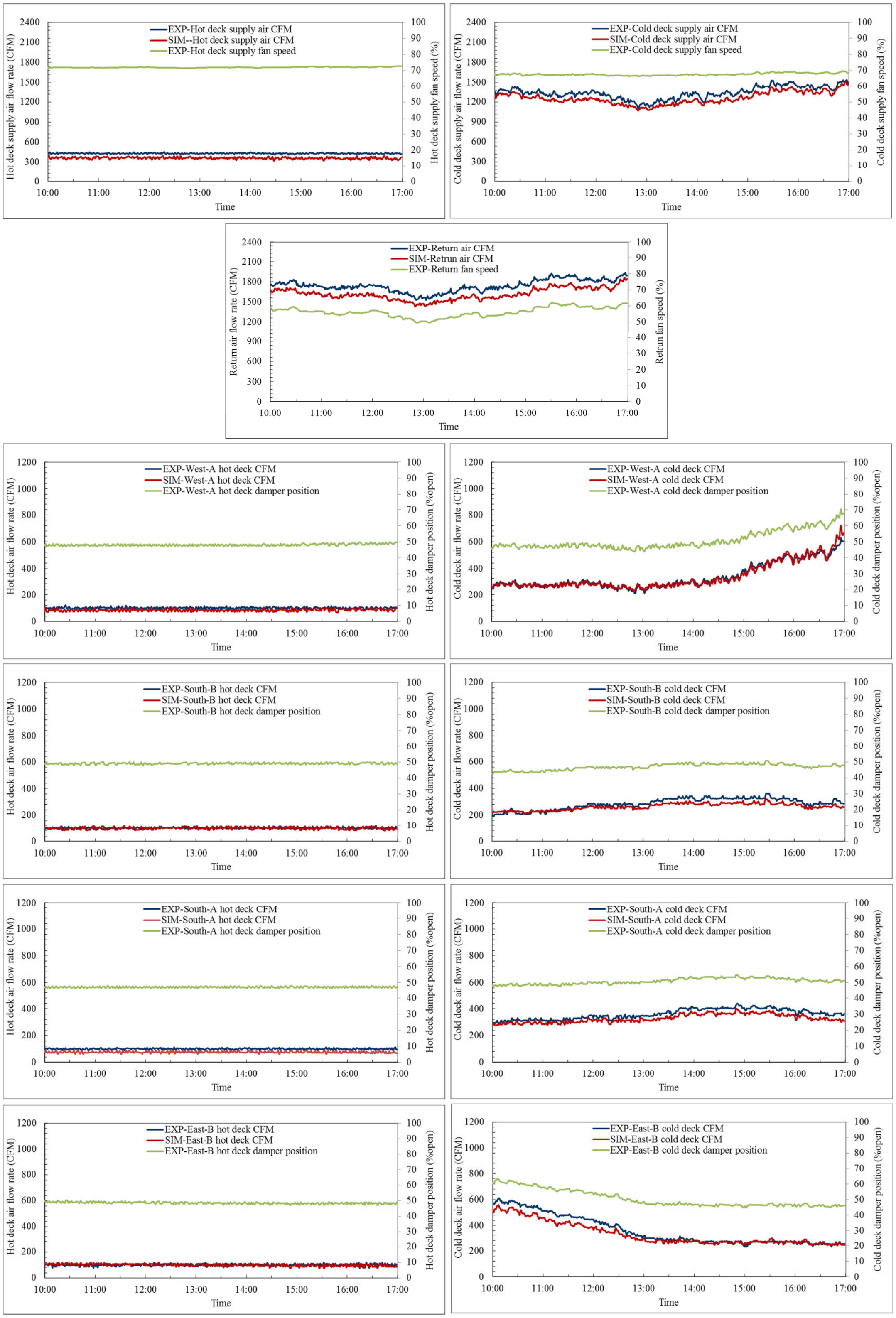

Figure 4 Dual duct system air flow network simulation result comparison with the real operational data