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Dynamic simulation of multi-unit air conditioners based on two-phase fluid network model

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A B S T R A C T

Multi-unit air conditioners (MUACs) are widely used in light commercial buildings and residential buildings due to their higher thermal comfort and energy efficiency. To investigate the transient characteristics of MUACs, a dynamic simulation model with the framework of two-phase fluid network is developed. The state-space forms are used to model the system and components, and the component submodels are embedded in the fluid network model, which makes it possible to update the system model and components submodels independently. In the model of state-space form, the differentials are obtained by taking the inverse of coefficient matrix, and then the state parameters are calculated by integrating the differentials with time. The simulation outputs are compared with the experimental data in the step changes of the compressor speed and electronic expansion valve openings. The comparison shows that the proposed model can catch the dynamic characteristics of MUACs with high accuracy. Therefore, it can be used as an effective tool to analyze the transient performance and optimize the control algorithm of MUACs.

1. Introduction

A multi-unit air conditioner (MUAC) is a system that can distribute cooling/heating capacity to different spaces, which consists of many indoor units (IDU) and at least one outdoor unit (ODU). Each IDU can operate according to the temperature and cooling/heating load of the space where it is installed, while the ODU can provide cooling/heating capacity to adapt to the total cooling/heating load of all IDUs. Featuring higher thermal comfort and lower energy consumption compared with the traditional air conditioners, multi-unit air conditioners with the variable capacity compressor and electronic expansion valve (EEV) are widely used in the light commercial buildings and residential buildings [1,2]. Therefore, research on the system performance analysis [3–8] and control optimization [9–11] of MUACs has become increasing attractive.

However, the performance of cooling/heating capacity and energy efficiency ratio (EER) of MUACs obtained by on-site measurements were much lower than their expectation [12,13]. Such differences are mainly caused by two reasons, one is the tube length and head difference among the IDUs and ODUs, and the other is that the control strategy and algorithm cannot make the system operate efficiently in varying working conditions and cooling/heating load.

In the first aspect, Hirao [14] found that the performance decreased by tube length and head difference of multi-unit air conditioners. With a steady-state simulation tool [15,16] and on-site measurement data, Shi [17] studied the influences of tube length and head difference on the performance and gave some guidelines on optimization of tube length and head difference between IDUs and ODUs [16,18].

In the second aspect, Choi [19] investigated the capacity modulation method by experiment and steady-state simulation. Lin [20–23] identified a dynamic model from the experimental data and optimized the control algorithm of multi-unit air conditioners. However, multi-unit air conditioners are much more complex than traditional air conditioning systems with only one IDU because of the interactions among the IDUs and ODUs [24,25]. Hence, experimental data and identified model from typical conditions are very limited to fully understand the transient characteristics and the interactions among the input and output parameters. The control algorithm gained from identified model cannot keep the multi-unit air conditioners operating at optimal state in varying conditions, moreover, it may lead to some abnormal operations, causing that not only the energy consumption increases significantly but also the EER drops to just 2.0 (kW k W^{-1}), which is only about 60% of the normal value [13,18].

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Nomenclature

A	sectional area, (m^2)
a_1–a_9	coefficients of compressor mass flowrate
b0–b5	number of the branches
c_1–c_9	coefficients of compressor power input
C_p	specific heat, (kJ kg^{-1} °C^{-1})
C_v	flow coefficient of EEV
D_i	inner diameter, (m)
D_o	outer diameter, (m)
$\mathbf{f}_c$,$\mathbf{f}_e$	vectors of functions
F_1–F_3	coefficients in Traviss, Baron and Rohsenow equation
h	specific enthalpy, (kJ kg^{-1})
$\mathbf{H}_{I,N}$, $\mathbf{H}_{O,N}$, $\mathbf{H}_{I,B}$, $\mathbf{H}_{O,B}$	vectors of specific enthalpy
k_1–k_4	coefficients in heat transfer equation of air side
$\dot{m}$	refrigerant mass flowrate, (kg s^{-1})
$\dot{\mathbf{m}}_{I,N}$,$\dot{\mathbf{m}}_{O,N}$, $\dot{\mathbf{m}}_{I,B}$, $\dot{\mathbf{m}}_{O,B}$	vectors of the mass flowrate
n0–n2	number of the nodes
Nu	Nusselt number
P	pressure, (Pa)
P_c	condensing pressure, (Pa)
P_e	evaporating pressure, (Pa)
$\mathbf{P_N}$, $\mathbf{P}_{I,B}$, $\mathbf{P_{O,B}}$	vectors of the pressure
Pr	Prandtl number
$\mathbf{S}$, $\mathbf{S_I}$, $\mathbf{S_O}$	incidence matrixes
T	temperature, (°C)
T_a	air temperature, (°C)
T_c	condensing temperature, (°C)
T_d	compressor discharge temperature, (°C)
T_e	evaporating temperature, (°C)
T_r	refrigerant temperature, (°C)
T_{sc}	subcooling degree, (°C)
T_{sh}	superheating degree, (°C)
T_w	tube wall temperature, (°C)
t	time, (s)
u	velocity, (m s^{-1})
$\mathbf{u}_c$, $\mathbf{u}_e$	vectors of the input parameters
v_a	air volume, (m^3 h^{-1})
$\mathbf{x}_c$, $\mathbf{x}_e$	vectors of the state parameters
$\dot{\mathbf{x}}_c$, $\dot{\mathbf{x}}_e$	vectors of the differentials of the state parameters
z	length dimension, (m)
$\mathbf{Z_e}$, $\mathbf{Z}_c$	coefficient matrixes

Greek

α	heat transfer coefficient, (kW m^{-1} °C^{-1})
α_i	inner heat transfer coefficient, (kW m^{-1} °C^{-1})
α_o	outer heat transfer coefficient, (kW m^{-1} °C^{-1})
γ	void fraction of two-phase fluid
ρ	density, (kg m^{-3})
ω_{cp}	compressor frequency, (Hz)

Subscripts

A, B, C, D	indoor units
a	air
acc	accumulator
b0–b5	branches
c	condenser
c1	superheated region of the condenser
c2	two-phase region of the condenser
c3	subcooled region of the condenser
cf	saturated liquid in the condenser
cg	saturated gas in the condenser
ci	inlet of the condenser
co	outlet of the condenser
cp	compressor
dis	distributor
e	evaporator
e1	two-phase region of the evaporator
e2	superheated region of the evaporator
ef	saturated liquid in the evaporator
eg	saturated gas in the evaporator
ei	inlet of the evaporator
eo	outlet of the evaporator
f	saturated liquid
g	saturated gas
i, I	inner, inlet
n0–n2	nodes
o, O	outer, outlet, outdoor unit
r	refrigerant
v	electronic expansion valve (EEV)

Superscripts

*	at compressor rating condition
T	transpose of matrixes
−1	inverse of matrixes

Therefore, it is very urgent to provide an effective tool to study the transient characteristics and optimize the control algorithm to make the multi-unit air conditioners operate with higher thermal comfort and lower energy consumption. Based on the framework of two-phase fluid network, a dynamic simulation model is developed and validated with the available experimental data in this paper.

2. Two-phase fluid network model of multi-unit air conditioning system

Dynamic simulation models have been developed and applied to assist the research on transient performance analysis and control algorithm design of traditional air conditioner with only one IDU [26–28]. While in the multi-unit air conditioners, the increase of the number of IDUs leads to the complexity of the system structure and uncertainty of interactions among IDUs and ODU, which make it very difficult to design and optimize the control algorithm. Chen et al. [29] presented a dynamic simulation model of a multi-unit air conditioner with black-box method model of components. Shah et al. [30] developed a linearized dynamic model for a multi-evaporator system with moving boundary evaporator and condenser model, and the validation of single and dual-evaporator system showed desired responses. However, the above simulation models are physics-based model which is only for a specific air conditioner in cooling mode and it is difficult to apply it to other working modes and other systems. In our previous works [16,24], a steady-state model of multi-unit air conditioners with the framework of two-phase fluid network was developed, which can describe the complex systems with flexibility and variety. Therefore, a dynamic simulation model with the framework of two-phase fluid network is purposed in this study.

2.1. Two-phase fluid network model

As shown in Fig. 1, there are two typical multi-unit air conditioners, (a) parallel type, and (b) sequential type. In the parallel type of multi-unit air conditioners, each IDU connects to ODU directly, and the capacity and tube length of each IDU are similar, so the number of IDUs is limited, usually within 10, and the tube length cannot be very long. While in the sequential type of multi-unit air