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Design Method of Steady State Detector for Multi-Evaporator Heat Pump System with Decomposition Analysis Technique

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ABSTRACT

Recent market trend of eco-friendly products let the manufacturers be ready for the high quality of maintenance technologies to assure the system's high efficiency during its entire life span. However, this post-manufacturing activities burden the manufacturer with high warranty cost. Therefore, in order to promote economical businesses, the manufacturers are developing various fault detection and diagnosis (FDD) technologies. This paper presents a general design methodology of the steady-state detector (SSD) which is the preemptive core logic of fault detection and diagnosis (FDD) module. The logic of moving window (MW) and decomposition analysis technique (DAT) is embedded in the SSD. Using the MW and DAT, the SSD can detect steady states independently for each component in a system. This independent detection of steady state in a component level provides different perspectives to understand the steady state of the heat pump system which has multiple indoor units.

1. INTRODUCTION

Recent air-conditioner and heat pump market wants the system that can contribute to energy savings and environment conservation. This so called eco-friendly products are advertised in the high performance as well as the high level of maintenance quality including warranty. By the various maintenance activities, heat pump system can assure its full design performance during its entire life span. To guarantee full performance during a long period of operation, the auto-maintenance function at a high level is being treated as an essential function of the system. However, these maintenance activities burden the manufacturers with a heavy warranty cost. Thus, in order to promote the economical maintenance activities, an effective way of the fault detection and diagnosis (FDD) functions should be researched.

The main flow of FDD research has been carried out in a steady-state approach (Grimmelious *et al.*, 1995; Stylianou and Nikanpour, 1996; Rossi and Braun, 1997; Kim *et al.*, 2006; Kim *et al.*, 2008), because operating characteristics in a steady state is relatively more credible and reproducible than in a transient state. When applying steady-state approach, a steady-state detector (SSD) should be developed in advance to develop FDD modules. Since the SSD identifies steady state or transient state of a system, it should be designed properly for the communication with the FDD main logics.

In this paper, a new type of SSD for multi-evaporator heat pump systems is reported using two kinds of data processing methods: moving window (MW) and decomposition analysis technique (DAT). By these methods, the SSD detects the steady state in a component level, so the steady state of each component can be decided separately. The approach which detects the steady state in a component level provides different perspectives to understand the steady state in a heat pump system.

2. DATA PROCESSING LOGIC

2.1 Moving Window for Steady State Detection

A pre-defined moving window (MW) is applied, as illustrated in Fig. 1 (Li, 2004; Kim *et al.*, 2008). A pre-defined time interval is established depending on which parameters are sampled at regular intervals. The pre-defined time interval generates an array of system parameters that are continuously updated and held in memory. Suppose that at any instant k , the average of latest n samples of a data sequence, x_i , is given by

$$\bar{x}_k = \frac{1}{n} \sum_{i=k-n+1}^k x_i \quad (1)$$

A difference between two averages of the latest n samples at the current time, k , and at the previous time instant, $k-1$, is represented by

$$\bar{x}_k - \bar{x}_{k-1} = \frac{1}{n} \left[\sum_{i=k-n+1}^k x_i - \sum_{i=k-n}^{k-1} x_i \right] = \frac{1}{n} (x_k - x_{k-n}) \quad (2)$$

With Eq. (2), the average at each k -th instant is based on the most recent set of n values. A MW variance and deviation is defined in Eq. (3) and Eq. (4), respectively.

$$v_k = v_{k-1} + \frac{1}{n} (x_k^2 - x_{k-n}^2) - (\bar{x}_k^2 - \bar{x}_{k-1}^2) \quad (3)$$

$$\sigma_k = \sqrt{v_k} \quad (4)$$

2.2 Decomposition Analysis Technique for Steady State Detection

In the field of energy economics, the decomposition analysis technique (DAT) has been recognized as the useful data-processing methodology to compare relative contribution of the different factors affecting the changes in energy consumption (Sun, 1998). In this context, the DAT can be useful methodology to compare the effect of performance deviation in the each component which is interconnected by tubes in a heat pump system. We used a four-effect-model using the evaporator outlet temperature for each i -th multi-evaporator ($T_{E,i}$), condenser outlet temperature (T_{CD}), compressor outlet temperature (T_{CO}), and compressor inlet temperature (T_{CI}). Using the above four main parameter sets in a heat pump system, we built a model according to Eq. (5).

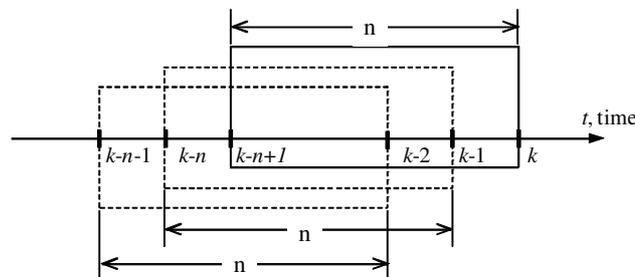


Figure 1: Moving window of n data points at k -th time

$$P = \frac{T_{E,i,t}}{T_{CD,t}} \times \frac{T_{CD,t}}{T_{CO,t}} \times \frac{T_{CO,t}}{T_{CI,t}} \times T_{CI,t} = E_{i,t} \times CD_t \times CO_t \times CI_t \quad (5)$$

Differentiating Eq. (5), the model of a form in Eq. (6) can be derived with complete DAT principle.

$$\Delta P = E_{\text{effect}} + CD_{\text{effect}} + CO_{\text{effect}} + CI_{\text{effect}} \quad (6)$$

3. DEVELOPMENT OF THE SSD

3.1 Experimental Setup and SSD

The SSD and FDD logic should be optimized for a target system. In this paper, as illustrated in Fig. 2, a multi-evaporator heat pump system using R410A as a refrigerant was selected as the target system which has 20 kW cooling capacity. The inverter compressor is a scroll compressor. The facility was built in a basic R410A air conditioning and heat pump system without any typical control logics to enhance the system performance. T-type thermocouples measured the temperature of inlet and outlet of the each component in a system.

3.2 Setting thresholds

The thresholds must be selected to both minimize non-steady state data and maximize steady state data. Excessive large thresholds allow faster and broader data collection but carry a risk of including false declaration of steady state. Thus, the optimized thresholds for each SSD in a specific system should be determined by laboratorial experiments.

To determine the thresholds in SSD for the target system, the 360 data scans in an hour were collected after the system has enough stabilizing time. We assumed a Gaussian distribution of the measured system parameters while the system was stable. The MW size was 300 seconds, and the threshold was $\pm 3\sigma$ of standard deviation for each component.

4. TEST WITH START-UP TRANSIENT SITUATION

The test with start-up transient situation was carried out to verify the developed SSD for the target system. The major purpose of using SSD is to declare the steady state of the system which shows stable operating characteristics.

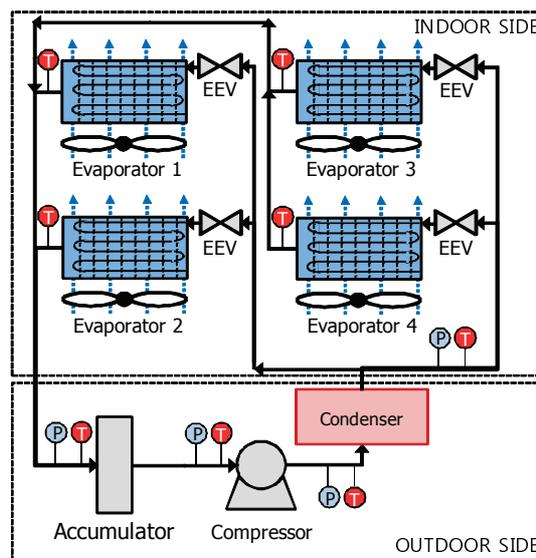


Figure 2: Schematic diagram of experimental setup

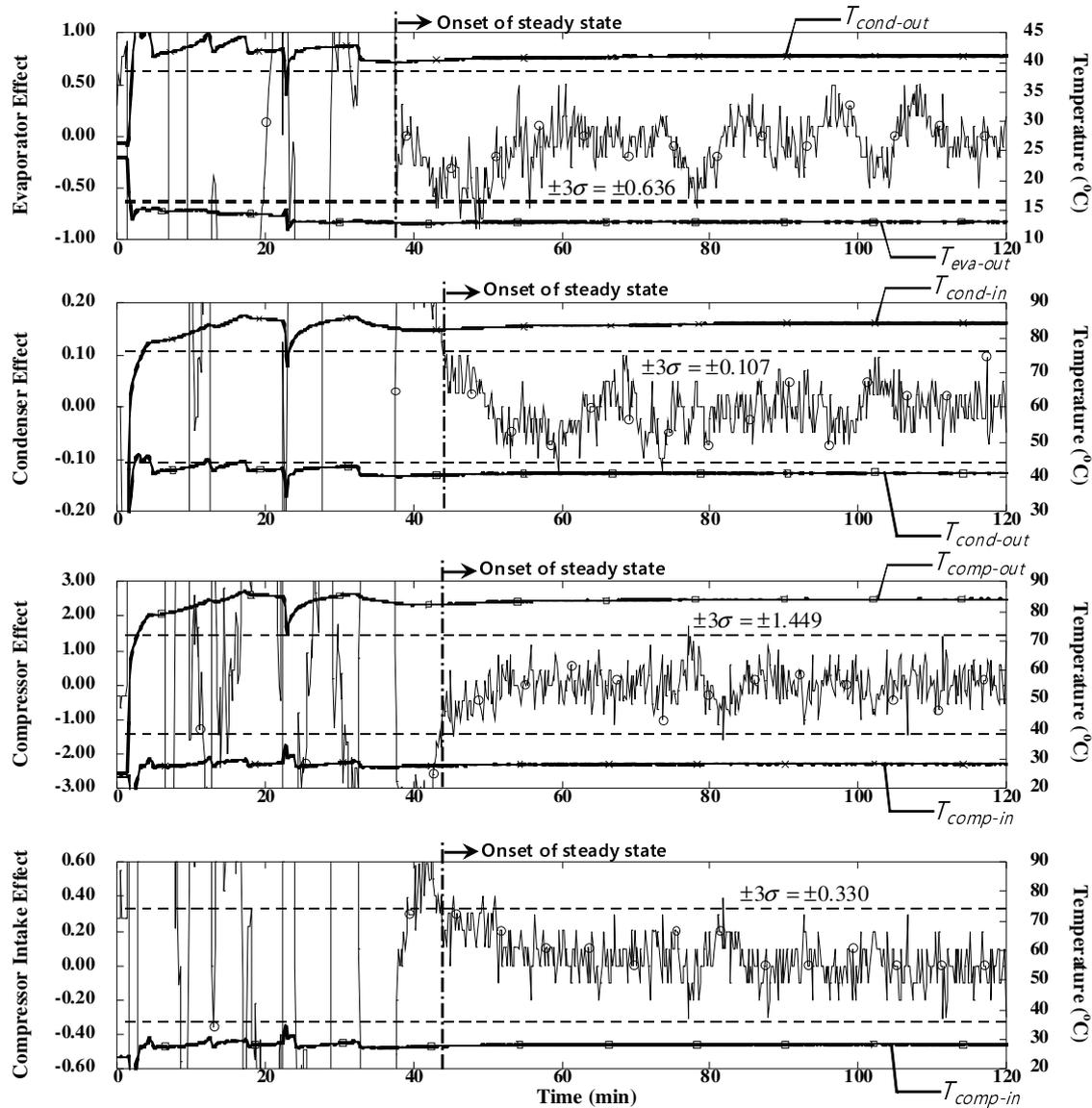


Figure 3: Onset of steady state during start-up transient test: (a) evaporator effect, (b) condenser effect, (c) compressor effect, and (d) compressor intake effect

The stable operating characteristics are represented by several figures. One of them can be the stable running of temperature profile. The stability of pressure changes also can be a candidate for the operating characteristic to show the system being in steady state. Recent researches are concerning the degree of super heat (DSH) and degree of super cooling (DSC) to judge the steady state in a system. DSH and DSC are also very good candidates to judge the steady state in a heat pump system, because the DSH and DSC are combined concept of pressure and temperature.

Like DSH and DSC, the raw temperature and pressure data is required to be re-processed, because the well designed re-processed data is essential to judge the steady state of the system reasonably and clearly, and to design cost-effective FDD modules being equipped for the target system. By the DAT and MW, we processed the raw temperature data to the proper data types for the electronic SSD modules that can judge whether the system is in steady state.

The DAT and MW let the detector to declare the steady state in a component level as well as in a system level. Because the DAT re-allocate the coupled effect of transient shooting which propagates by tubing from one component to the other component, it gives theoretical base that the entire system's steady state can be declared when the three major unit's (evaporator unit, condenser unit, compressor unit) steady state being declared.

Figure 3 displays variation of the four effect terms in the post-startup period with $\pm 3\sigma$ thresholds superimposed. The vertical dash-dot lines, extending to Fig. 3, indicate the onset of a steady state for each component. In Fig.3, although the sporadic quasi-steady state is observed, when all the effect terms are enclosed in each $\pm 3\sigma$ region is the time of declaring the target system's steady state.

In the case of Fig. 3, the SSD declares the system's steady state in 43 minutes after the system is turned on. However, the SSD that observes the 'evaporator effect' declares the steady state of evaporator in 38 minutes after the system is turned on. The SSD of other components like condenser and compressor also shows slightly difference of declaring the steady state for each component. It indicates that the each component's reaching time to the steady state is slightly different, but their overall reaching time to the steady state is generally simultaneous. As a successive research, we clarified that there is a 'leading component' and 'determination component' which is the core component in a system reaching to the steady state.

5. CONCLUSION

The methodology was presented for developing a steady-state detector for R410A multi-evaporator air-conditioner based on a MW and DAT using four fundamental temperature data. The thresholds band of the selected parameters was set at $\pm 3\sigma$ reflecting their fluctuations during steady state operation.

It is found that the time to reach the steady state for each component is different. Thus, there is the determination component which reaches to the steady state finally. It determines the overall system's steady-state. To declare the overall system's steady state, the developer of SSD should consider and clarify what the determination component is in a system.

NOMENCLATURE

t	time (min)
T	temperature ($^{\circ}\text{C}$)
E	evaporator
CD	condenser
CO	compressor out
DAT	decomposition analysis technique
FDD	fault detection and diagnosis
i	feature index, evaporator index
MW	moving window
n	number of data samples in a moving window
SSD	steady-state detector
v	variance
x	measured data
\bar{x}	moving window average of measured data
σ	standard deviation about the mean value
Δ	difference

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