Decentralized Active Disturbance Rejection Control for the Benchmark Refrigeration System

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Abstract: In this paper, decentralized linear active disturbance rejection control (LADRC) method is applied to the benchmark refrigeration system presented at the 3rd IFAC Conference on Advances in Proportional-Integral-Derivative Control (PID18). Two second-order LADRCs are tuned by trial and error without the knowledge of the benchmark refrigeration system. To overcome the saturation of the actuators, an anti-windup scheme for LADRC is adopted. Simulation results show that LADRC technique is simple to apply in practice and can achieve good performance compared with the given PID controllers for the benchmark system.

Keywords: linear active disturbance rejection control (LADRC), bandwidth method, the benchmark refrigeration system, anti-windup

1. INTRODUCTION

The refrigeration system, which is widely used in our daily life as well as in the industrial demands, consumes lots of energy. How to improve the energy efficiency and to reduce consumption has become an important issue. Generally components of the refrigeration system are connected through various pipes and valves, which have strong nonlinearity, large deadtime and strong coupling, resulting in modelling and control difficulties. Research has been done to control this process and to improve energy efficiency, such as decentralized PID (Salazar and Mendez, 2014), LQG control (Schurt *et al*., 2009), model predictive control (Alsaleem *et al*., 2017), and adaptive control (Rasmussen and Larsen, 2011).

A benchmark model of the refrigeration system is given at the 3rd IFAC Conference on Advances in PID Control (PID18). It gives an opportunity for researchers to test their recent developments in the design of PID controllers. Details about the dynamic model of the refrigeration system and the default controllers are provided in Benjarano *et al.* (2017).

PID control is the most used techniques in industrial processes, and its main advantage is the ease of implementation and tuning. To improve the performance of PID, Han (2009) proposed an active disturbance rejection control (ADRC) technique, which adopts an extended state observer (ESO) to estimate all the external disturbances and internal uncertainties in real time and compensate them in a nonlinear state feedback control law. According to Han's theory (Han, 2009), ADRCs have small overshoot, fast response speed, high accuracy, and strong disturbance-rejection capabilities. However, both the ESO and the state-feedback control law are nonlinear, causing the tuning of the parameters complicated and often dependent on experience. Gao (2003) used the concept of linearization and bandwidth and proposed a linear version of ADRC (LADRC), which greatly simplified the control structure and the tuning process. In LADRC the controller parameters are defined as the functions of two bandwidths: controller bandwidth ω_c and observer bandwidth ω_o, and analysis of the LADRC controlled system can be done via the internal model control method (Tan and Fu, 2016). Up to now LADRC has been successfully applied to the industrial motion control, power systems, machine processing and other fields (Zhang and Meng, 2010; Dong *et al*., 2012; Gao, 2013).

LADRC needs only to know the relative order and the high-frequency gain of the controlled plant instead of the complete model, thus it is quite useful in practice. In this paper, decentralized LADRC will be applied to the control of the benchmark refrigeration system. Two LADRCs are tuned to control the outputs separately. Simulation results show that LADRC can achieve good performance compared with the given PID controllers for the benchmark system.

The rest of the paper is organized as follows. A brief introduction to LADRC and its parameter tuning is presented in Section 2. Then LADRC design for the benchmark refrigeration system and the control performance indices are given in Section 3. Section 4 presents the qualitative and quantitative comparison of simulation results between the proposed decentralized LADRC and two benchmark PID controllers. Conclusions are given in Section 5.

2. ACTIVE DISTURBANCE REJECTION CONTROL

2.1 Structure of LADRC

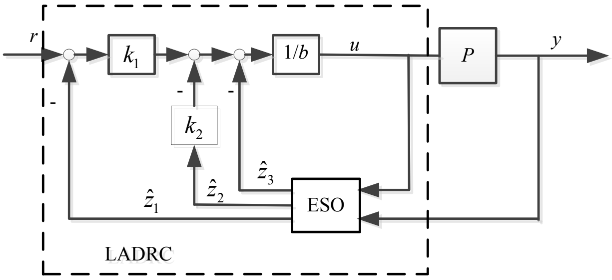

Fig. 1 Structure of LADRC

In this paper, second-order LADRC will be used since it has a compromise between simplicity in structure and effectiveness in control (Han, 2009). The structure of the second-order LADRC is shown in Fig. 1, which consists of an extended state observer (ESO) and a feedback control law. The plant is represented as P, the reference input is r, the plant output is y, and the plant input is u.

Second-order LADRC assumes the controlled plant has the following model:

$$\ddot{y}(t) = b_0 u(t) + f(y,u,t) \tag{1}$$

where b_0 is the high-frequency gain of the plant, and f is a combination of the unknown dynamics and the external disturbances of the plant, and denoted as the *generalized disturbance*.

In the LADRC framework, ESO is the core concept which is used to estimate the generalized disturbance f in real time. Let

$$z_1 = y, z_2 = \dot{y}, z_3 = f \tag{2}$$

Assume that f is differentiable. Then an extended state-space realization of system (1) is

$$\begin{cases} \dot{z} = Az + Bu + E\dot{f} \\ y = Cz \end{cases} \tag{3}$$

where,

$$\begin{cases} A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ b_0 \\ 0 \end{bmatrix}, E = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \\ C = [1 \quad 0 \quad 0] \\ z = [z_1, z_2, z_3]^T \end{cases} \tag{4}$$

Design a full-order state-observer for (3), the input to the ESO includes the controller output u and the system output y, and the output of the ESO is $\hat{z} = [\hat{z}_1, \hat{z}_2, \hat{z}_3]$. The equation of the ESO is:

$$\dot{\hat{z}} = A\hat{z} + Bu + L_o(y - C\hat{z}) \Rightarrow \begin{cases} \dot{\hat{z}}_1 = \hat{z}_2 - \beta_1 \hat{z}_1 + \beta_1 y \\ \dot{\hat{z}}_2 = \hat{z}_3 - \beta_2 \hat{z}_1 + \beta_2 y + b_0 u \\ \dot{\hat{z}}_3 = -\beta_3 \hat{z}_1 + \beta_3 y \end{cases} \tag{5}$$

where L_o is the gain vector of the observer.

$$L_o = [\beta_1, \beta_2, \beta_3]^T \tag{6}$$

When $A_e - L_o C_e$ is asymptotically stable, $\hat{z}_1(t), \hat{z}_2(t)$ will appproximate $y(t)$ and its derivative, and $\hat{z}_3(t)$ will approximate the generalized disturbance f. The estimated generalized disturbance can be used in control to reject it as in the following state-feedback law:

$$\begin{aligned} u(t) &= \frac{k_1(r(t) - \hat{z}_1(t)) + k_2(\dot{r}(t) - \hat{z}_2(t)) - \hat{z}_3(t)}{b_0} \\ &=: K_o(\hat{r}(t) - \hat{z}(t)) \end{aligned} \tag{7}$$

where $r(t)$ is the reference signal, and

$$K_o = [k_1 \quad k_2 \quad 1] / b_0 \tag{8}$$

is the state-feedback control gain.

To sum up, a second-order LADRC is a combination of (5) and (7), and can be described in the following state space form:

$$\begin{cases} \dot{\hat{z}} = (A - L_o C)\hat{z} + Bu + L_o y \\ u = K_0(\hat{r} - \hat{z}) \end{cases} \tag{9}$$

2.2 Bandwidth Tuning of LADRC

From (9), it is shown that for a second-order LADRC there are two gains to tune: L_o, the observer gain for ESO, and K_o, the controller gain. In order to simplify the tuning process, Gao (2003) introduces the bandwidth concept, and the tuning of K_0 and L_o is reduced to the tuning of two parameters: ω_o, the observer bandwidth, and ω_c, the controller bandwidth.

For the ESO, the characteristic equation of A-L_oC is:

$$|sI - (A - L_o C)| = s^3 + \beta_1 s^2 + \beta_2 s + \beta_3 \tag{10}$$

For the sake of simplicity, all poles of the observer are placed in -ω_o, then:

$$s^3 + \beta_1 s^2 + \beta_2 s + \beta_3 = (s + \omega_o)^3 \tag{11}$$

which implies

$$\beta_1 = 3\omega_o, \beta_2 = 3\omega_o^2, \beta_3 = \omega_o^3 \tag{12}$$

Thus, ω_o becomes the only parameter of ESO and it is denoted as the bandwidth of the observer.

If the generalized disturbance f is estimated and compensated accurately, the controlled system is reduced to a second-order integral system. The characteristic equation of the feedback control system is:

$$|sI - (A - BK_0)| = s(s^2 + k_2 s + k_1) \tag{13}$$

Similarly, all poles can be placed in $-\omega_c$ (except the origin), then the parameters of the controller gain vector can be obtained as

$$k_1 = \omega_c^2, k_2 = 2\omega_c \tag{14}$$

Thus, the controller bandwidth ω_c becomes the only parameter to be tuned in the state feedback control law.

Remark: LADRC is easy and effective, especially when the order of LADCR is equal to the relative order of the process and the value of b_0 is accurate (Huang and Xue, 2014). But in the industrial practice, the exact relative degree of a process may be difficult to determine. Lower order LADRC is preferred with implementation and maintenance considered.

In this paper, second-order LADRC will be applied to the benchmark refrigeration system. Since we have no information about the relative order of the system and the gain b_0, we will treat b_0 as an additional tuning parameter.

In summary, LADRC is a general-purpose controller that has a fixed structure independent of the plant. It is easy to implement and has three parameters to tune. Besides, there is no need to add an integrator in the controller, because LADRC itself has the integral behaviour. So LADRC is a good candidate to improve the performance of PID controllers in practice.

3. APPLICATION TO THE BENCHMARK SYSTEM

3.1 The Benchmark Refrigeration System

The benchmark refrigeration system is shown in Fig.2 (Bejarano et al., 2017).

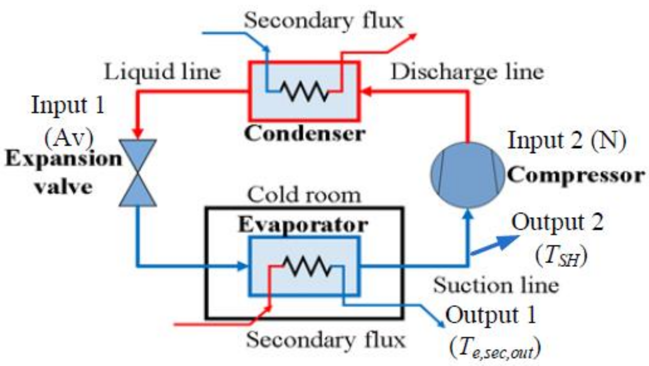

Fig.2 Benchmark refrigeration system

Table 1 Variable ranges and initial operating point

Variables		Range	Operating point	Units
Input variables	A_v	[10-100]	≈50	%
	N	[30-50]	≈40	Hz
Disturbances	$T_{c,sec,in}$	[27-33]	30	°C
	$\dot{m}_{c,sec}$	[125-175]	150	g s^{-1}
	$P_{c,sec,in}$	—	1	bar
	$T_{e,sec,in}$	[-22 - -18]	-20	°C
	$\dot{m}_{e,sec}$	[55-75]	64.5	g s^{-1}
	$P_{e,sec,in}$	—	1	bar
	T_{surr}	[20-30]	25	°C
Output variables	$T_{e,sec,out}$	—	≈-22.15	°C
	T_{SH}	—	≈14.65	°C

The system mainly consists of condenser, compressor, evaporator and expansion valve. The objective of this cycle is to remove heat at the evaporator from its secondary flux and reject heat at the condenser by transferring it to the condenser secondary flux. It is a multivariable system with two variables (the outlet temperature of the evaporator secondary flux $T_{e,sec,out}$ and the degree of superheating T_{SH}) to be controlled by manipulating two variables (the compressor speed N and the expansion valve opening A_v). The other variables are regarded as disturbances.

The parameters used in the paper are shown in Table 1 including variable ranges and the initial operating point. The Coefficient of Performance (COP) is used as quality steady-state performance variable. Details of this process can be found on the following website:

http://www.dia.uned.es/fmorilla/benchmarkPID2018/

3.2 Design and Tuning of LADRC

In this paper, a decentralized LADRC structure is adopted for the benchmark refrigeration system. The loop pairing is the same as the given default controller in Bejarano et al. (2017). The coupling between the two outputs, unmodeled dynamics, and various disturbances are treated as the *generalized disturbance*, which will be estimated by a second-order ESO and rejected with a state-feedback control law.

Just as PID controllers, an LADRC has three parameters to tune: ω_o, the observer bandwidth, ω_c, the controller bandwidth, and b_0, the high-frequency gain of the plant. Generally, the larger the bandwidths are, the better the disturbance rejection performance. Once the two bandwidths are fixed, $1/b_0$ determines the gain of the LADRC, thus the smaller b_0 is, the better the disturbance rejection performance. Since only a simulation model for the benchmark system is given, we just tune the three parameters by trial and error for LADRC design.

Because of the physical limitation of the refrigeration system, the inputs to the system are often saturated, as shown in Table 1. Saturation will affect the performance of the designed control system and even lead to instability. Since the original LADRC is designed without considering the input constraints, we need to apply a compensating technique to avoid the controller saturation. In this paper, an observer-based anti-windup scheme (Zhou and Tan, 2014) is adopted to deal with this problem (Fig.3). The input u to the ESO is replaced by the actual input $\hat{u}$ of the plant in the scheme, thus correct states can be estimated.

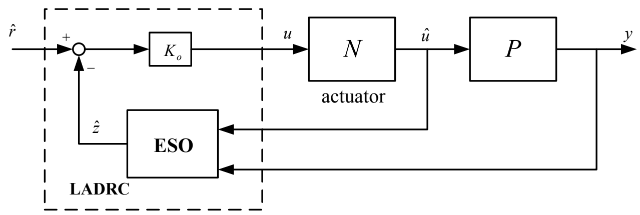

Fig.3 Anti-windup scheme for LADRC

The final decentralized LADRC structure with anti-windup scheme for the benchmark system is shown in Fig.4. The parameters of the two LADRCs are tuned as

$$b_{01}=1,\ \omega_{c1}=5,\ \omega_{o1}=10,\ b_{o2}=1,\ \omega_{c2}=4,\ \omega_{o2}=3 \qquad (15)$$

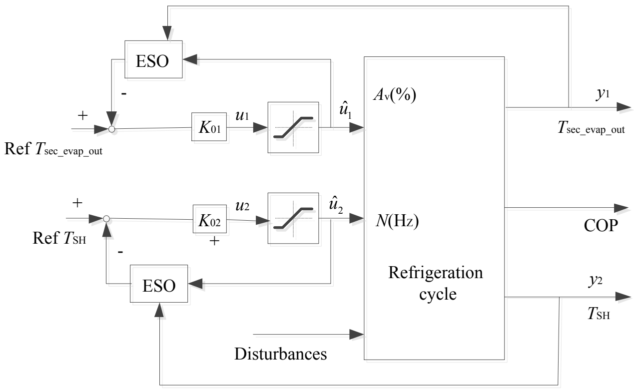

Fig. 4 Decentralized LADRC for the benchmark system

4. SIMULATION RESULTS

In this section, the decentralized LADRC is tested for the benchmark refrigeration system. The simulation results will be compared quantitatively and qualitatively with the given two PID controllers reported in Bejarano *et al.* (2017).

Fig. 5-11 show the simulation results of comparative performance of the decentralized LADRC and two PID controllers. The simulations start from the operation point A_v≈48.79%, N≈36.45Hz, and other initial values are given in Table 1. It can be observed that the decentralized LADRC can achieve better performance than the two given PID controllers with fast tracking and strong disturbance rejection capabilities. The quantitative results of two tests are presented in Table 2, and the performance indices evaluated in the comparison show that LADRC achieves tighter control than PID controllers, with the control effort of LADRC is close to PID controllers. From the combined index, the overall performance of the proposed LADRC is better.

Table 2 Performance Indexes for different controllers *C*=LADRC, *C*₁=decentralized PID; *C*₂=Multivariable PID

Indexes	C_1 vs C	C_2 vs C
$RIAE_1(C,C_i)$	0.1387	0.3951
$RIAE_2(C,C_i)$	0.2622	0.5881
$RITAE_1(C,C_i,t_{c1},t_{s1})$	0.388	0.241
$RITAE_2(C,C_i,t_{c2},t_{s2})$	0.0889	0.4858
$RITAE_2(C,C_i,t_{c3},t_{s3})$	0.1855	0.5805
$RITAE_2(C,C_i,t_{c4},t_{s4})$	0.0156	0.122
$RIAVU_1(C,C_i)$	1.1003	0.9751
$RIAVU_2(C,C_i)$	1.0092	0.7346
$J(C,C_i)$	0.2726	0.4182

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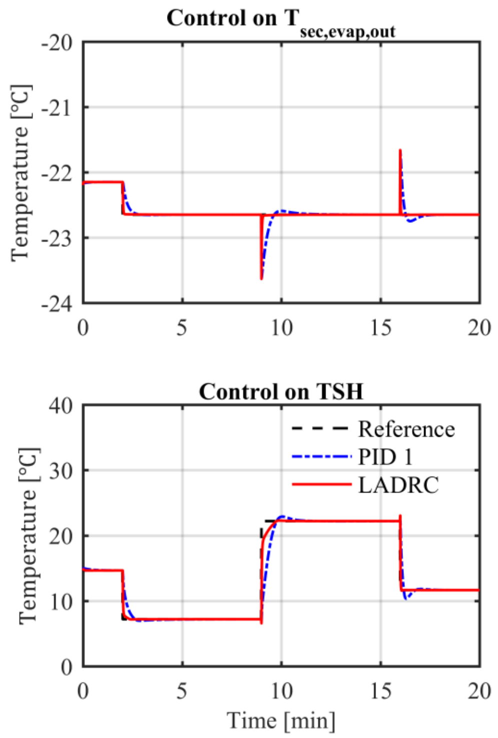

Fig. 5 Comparison of the controlled variables: C_1 vs C

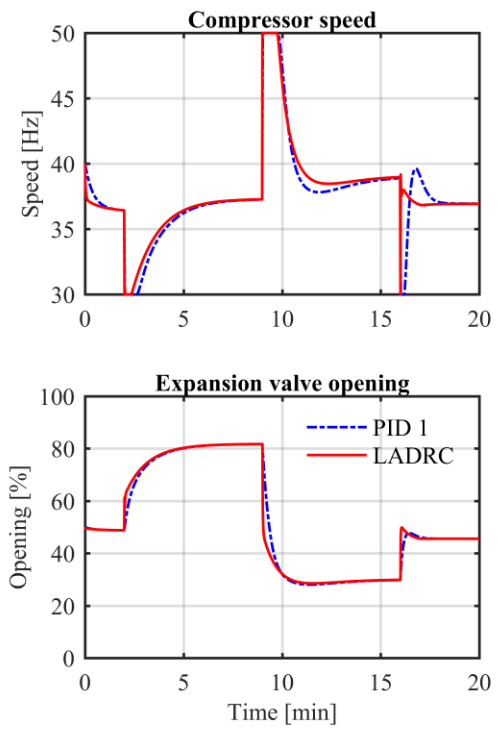

Fig. 6 Comparison of the manipulated variables: C_1 vs C

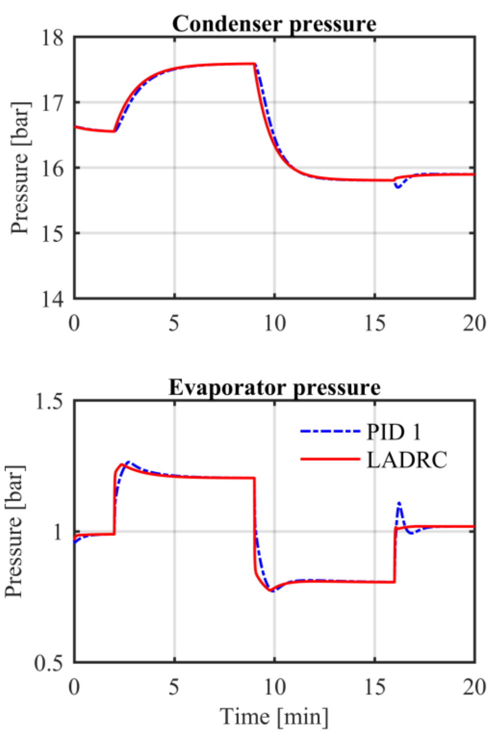

Fig.7 Comparison of the evaporation and condensation pressures: C_1 vs C

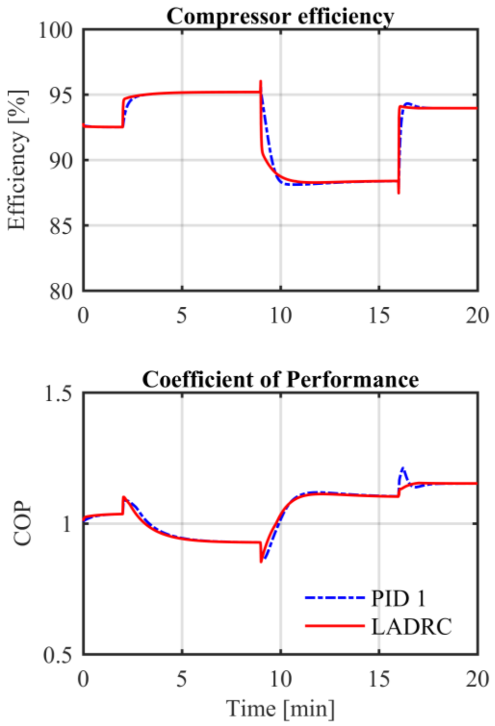

Fig.8 Comparison of the compressor efficiency and coefficient of performance: C_1 vs C

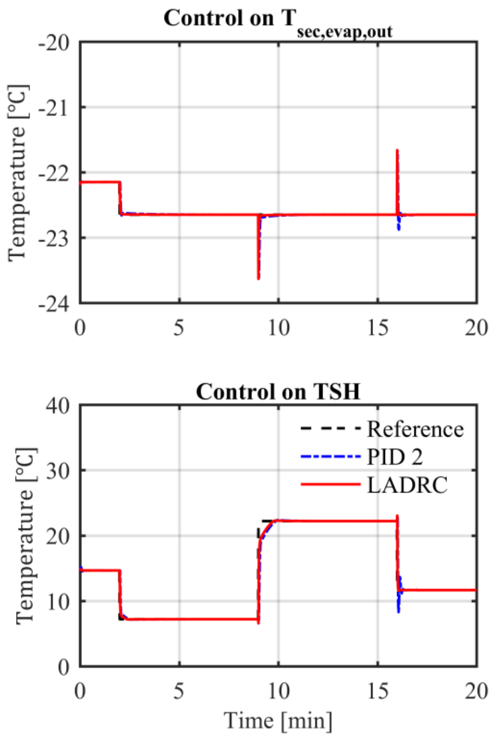

Fig.9 Comparison of the controlled variables: C_2 vs C

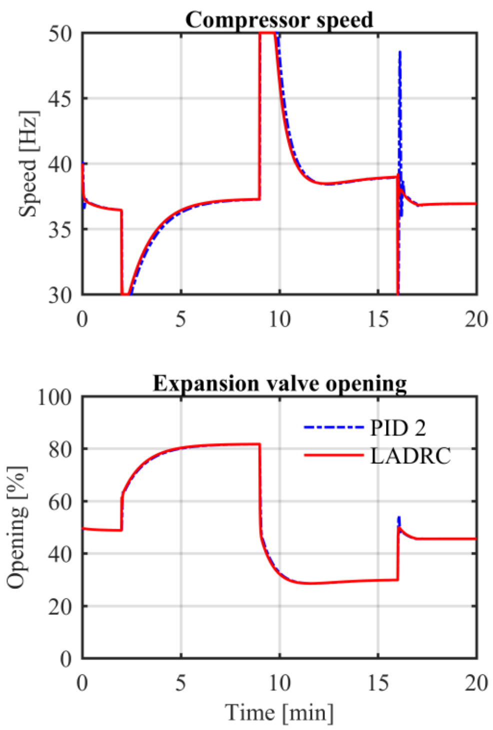

Fig.10 Comparison of the manipulated variables: C_2 vs C

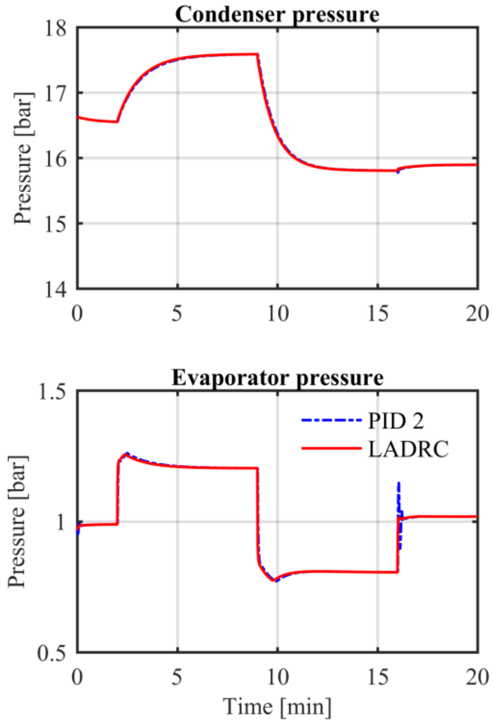

Fig.11 Comparison of the evaporation and condensation pressures: C_2 vs C

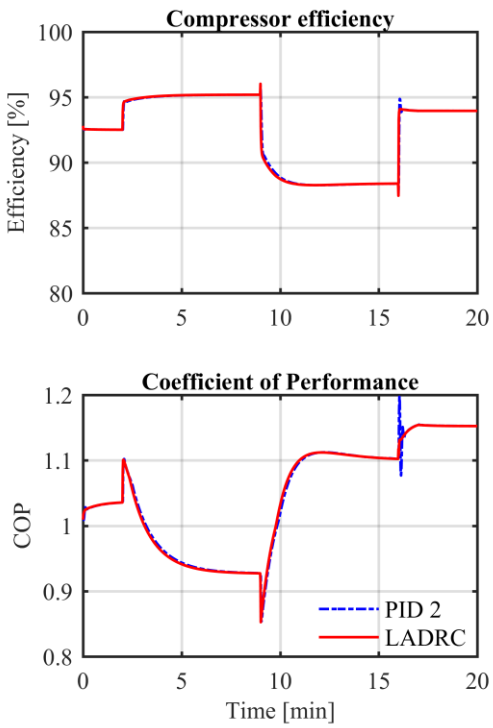

Fig.12 Comparison of the compressor efficiency and coefficient of performance: C_2 vs C

5. CONCLUSIONS

Decentralized LADRC was applied to the benchmark refrigeration system. Two second-order LADRCs were tuned manually without knowing the model of the benchmark system. Simulation results show that decentralized LADRC can obtain better performance in tracking and disturbance rejection abilities than the two benchmark PID controllers.

ACKNOWLEDGMENT

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