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An energy-saving set-point optimizer with a sliding mode controller for automotive air-conditioning/refrigeration systems

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HIGHLIGHTS

- A novel two-layer energy-saving controller for automotive A/C-R system is developed.
- A set-point optimizer at the outer loop is designed based on the steady state model.
- A sliding mode controller in the inner loop is built.
- Extensively experiments studies show that about 9% energy can be saving by this controller.

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ABSTRACT

This paper presents an energy-saving controller for automotive air-conditioning/refrigeration (A/C-R) systems. With their extensive application in homes, industry, and vehicles, A/C-R systems are consuming considerable amounts of energy. The proposed controller consists of two different time-scale layers. The outer or the slow time-scale layer called a set-point optimizer is used to find the set points related to energy efficiency by using the steady state model; whereas, the inner or the fast time-scale layer is used to track the obtained set points. In the inner loop, thanks to its robustness, a sliding mode controller (SMC) is utilized to track the set point of the cargo temperature. The currently used on/off controller is presented and employed as a basis for comparison to the proposed controller. More importantly, the real experimental results under several disturbed scenarios are analysed to demonstrate how the proposed controller can improve performance while reducing the energy consumption by 9% comparing with the on/off controller. The controller is suitable for any type of A/C-R system even though it is applied to an automotive A/C-R system in this paper.

1. Introduction

With the extensive application of A/C-R systems in residence, industry, and vehicles, a huge amount of energy is being consumed [1]. Meanwhile, the continuous growth in the demand for energy conservation and environment protection is prompting researchers to design green devices with greater efficiency. As is known, efficient operation of A/C-R systems can reduce operating costs as well as adverse effects on the environment, and an important step in making such systems work efficiently is adopting a proper control strategy [2,3]. Therefore, efforts are made to elaborate upon the development process of the proposed controller as well as the real experimental and comparison work to the conventional on/off the controller. The analysis indicates that the proposed controller is promising and it can reduce energy consumption by an average of 9% while enhancing the controller performance without adding more computational effort.

This paper first briefly reviews the existing controllers used in A/C-R systems, followed by the introduction of a simplified model using the moving boundary and lumped parameter method. Then, the experimental system is briefly explained. In addition, the experimental results from both controllers are compared and analysed to show the benefits and advantages of the proposed controller. The last section discusses comments and future work.

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Nomenclature

A_v	opening area of expansion valve
$A_c(A_e)$	cross-sectional area of condenser (evaporator) tube
$A_{oc}(A_{oe})$	exterior area of the condenser (evaporator)
$\alpha_{ic}(\alpha_{ie})$	equivalent refrigerant-side heat transfer coefficient in two-phase region
$\alpha_{oc}(\alpha_{oe})$	air-side heat transfer coefficient
$\alpha_{icsh}(\alpha_{iesh})$	refrigerant-side heat transfer coefficient in superheat region
C_p	specific heat of the heat exchangers
C_v	discharge coefficient of expansion valve
C_{air}	specific heat of the ambient air
$D_{ic}(D_{ie})$	heat exchanger tube internal diameter
$h_{ge}(h_{gc})$	enthalpy of vapor refrigerant
$h_{ic}(h_{ie})$	enthalpy of refrigerant at the inlet of heat exchanger
h_{is}	isentropic of refrigerant in compressor
$h_{lc}(h_{le})$	enthalpy of liquid refrigerant
$h_{lgc}(h_{lge})$	latent enthalpy of refrigerant
h_{oc}	enthalpy at the outlet of condenser
$l_c(l_e)$	length of two-phase section in two heat exchangers
$\dot{m}_v$	refrigerant mass flow rate through the expansion valve
$\dot{m}_{comp}$	refrigerant mass flow rate through the compressor
m_{pipe}	total refrigerant mass in the pipes
N_{comp}	compressor speed
N_{cond}	condenser fan control input
N_{evap}	evaporator fan control input
$P_c(P_e)$	pressure of two heat exchangers
ρ_v	density of refrigerant through the valve
ρ_{ref}	density of refrigerant
$\rho_{lc}(\rho_{le})$	density of liquid refrigerant
$\rho_{gc}(\rho_{ge})$	density of vapor refrigerant
$\rho_{shc}(\rho_{she})$	density of refrigerant in superheat section
T_{amb}	ambient temperature
$T_{wfc}(T_{wfe})$	equivalent temperature of tube wall & fin
$T_{rc}(T_{re})$	saturation temperature of refrigerant
$T_{ac}(T_{ae})$	air temperature around the heat exchanger
T_{sh}	superheat
T_{ic}	refrigerant temperature at the inlet of condenser
T_{cargo}	temperature of cargo
T_{cargo_init}	initial temperature of cargo
V_d	volumetric displacement of compressor
η_{vol}	volumetric efficiency of compressor
η_a	adiabatic efficiency of compressor
$\bar{\gamma}_c(\bar{\gamma}_e)$	mean void fraction of two-phase section
λ, k, ϕ	controller parameters

2. Literature review

The vapor compression cycle or the A/C-R system is usually composed of four major components, namely, the compressor, evaporator, expansion valve, and condenser, which are connected end to end as shown in Fig. 1.

A/C-R systems are used extensively in different fields. Researchers have conducted many studies on their controller development with different perspectives, which can be summarized as (1) proper air temperature and humidity of the specific area; (2) improvement of system steady-state performance as well as robustness; (3) reduction of energy consumption [4].

The on/off controller was first applied thanks to its simplicity as well as ease of application. It can keep the temperature within a certain range via switching the whole system on or off. Nevertheless, it is incapable of controlling the temperature oscillation amplitudes according to varying working conditions, such as, the ambient temperature and varying temperature set points. Moreover, frequent on/off activations can cause excessive power consumption and wear of mechanical components over time [4]. But above all, energy efficiency is ignored completely in on/off controllers, which is also the reason that Leva et al. [5], Li et al. [6] and Kang et al. [7] improved on/off controllers by adding adaptive, optimization or intelligent algorithms. However, such nature of on/off controllers make greater enhancement difficult.

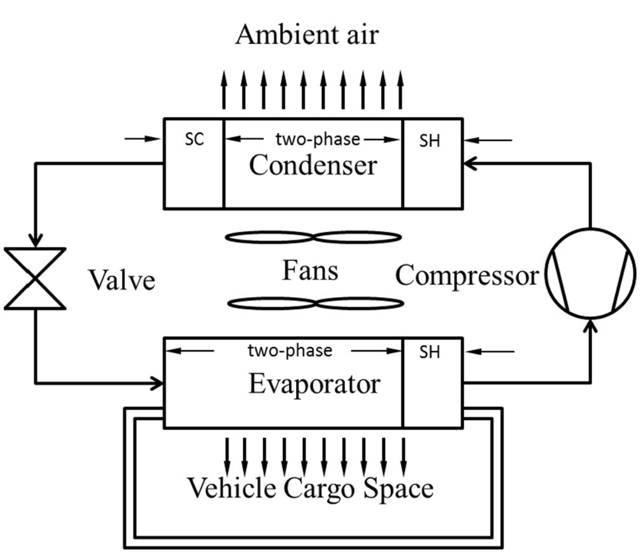

Fig. 1. Schematic diagram of A/C-R system.

As anti-idling technologies [8,9] and hybrid [10] or pure electric vehicles [11] become more and more popular, the electrification technology of automotive A/C-R systems will depart the compressor from the engine such that the compressor is able to actively change its speed instead of passively following the engine's speed. This will prompt researchers to design more advanced controllers instead of still trying to adapt on/off controllers to high energy efficiency and performance requirements. The current controllers used in A/C-R systems other than the on/off one can be classified into three types: the classic feedback controller, intelligent controller, and the advanced controller [4] or the classical control, soft controller and hard controller [12]. As the most popular conventional feedback controller, the PI controller has been used for a long time. A relevant instance is the temperature-compressor control and superheat-expansion valve [13]. This continuous feedback controller could indeed alleviate mechanical wear of the compressor. Nevertheless, due to the nonlinear and MIMO nature of A/C-R systems, it is difficult to tune controller parameters. Anders et al. in [14] came up with a method to decouple the controllers. This conventional feedback control strategy takes energy efficiency into consideration indirectly by controlling superheat in the evaporator [15].

Artificial intelligent control techniques such as the artificial neural network (ANN), fuzzy logic control, and expert system, etc., are proposed to deal with uncertainties or nonlinearities in the development processes of A/C-R controllers. In many cases, these AI techniques are combined with the A/C-R system control [4,16]. However, literature [17] mentions their limitations, which include overtraining, extrapolation, network optimization, and lack of optimality, all of which impede their development.