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Optimal energy-efficient predictive controllers in automotive air-conditioning/refrigeration systems

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HIGHLIGHTS

- A discrete MPC is designed for the A/C-R system with a three-speed compressor.
- The control performance is studied under both normal and frosting conditions.
- Two designed hybrid controllers are more efficient under any heating load condition.
- A continuous MPC is made for the A/C-R system with continuously varying components.
- The controllers bring better performance and save up to 23% energy for A/C-R systems.

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ABSTRACT

This paper presents several robust model predictive controllers that improve the temperature performance and minimize energy consumption in an automotive air-conditioning/refrigeration (A/C-R) system with a three-speed and continuously-varying compressor. First, a simplified control-oriented model of the A/C-R system is briefly introduced. Accordingly, a discrete Model Predictive Controller (MPC) is designed based on the proposed model for an A/C-R system with a three-speed compressor. A proper terminal weight is chosen to guarantee its robustness under both regular and frost conditions. A case study is conducted under various heating load conditions. Two hybrid controllers are made, which combine the advantages of both the on/off controller and discrete MPC such that they will be more efficient under any ambient heating condition. In addition, a continuous MPC is developed for systems with continuous variable components. Finally, the experimental and simulation results of the new controllers and the conventional on/off controller are provided and compared to show that the proposed controllers can save up to 23% more energy.

1. Introduction

The continuously increasing demands on energy conservation and environmental protection have driven researchers to develop more efficient and "green" vehicles [1,2]. Recently, A/C-R systems have been widely used as the main auxiliary devices in vehicles. For example, A/C-R systems in food delivery trucks consume up to 25% of the vehicle's total fuel consumption. Efficiently operating A/C-R systems can significantly improve operating costs and the vehicle's effects on the environment [3,4]. Thus, making more efficient auxiliary devices such as A/C-R systems can bring many benefits to vehicle owners as well as the environment [5]. For any A/C-R system, a foremost step in achieving better performance and higher energy efficiency is a proper control strategy. However, in most conventional vehicles, the compressor speed is proportional to the engine speed instead of actively varying with the requirements of passengers or working conditions. This impedes the development of advanced controllers for A/C-R systems given that the controllers are usually applied to manipulate the speeds of the compressor and fans of heat exchangers. Recently, the onboard energy storage system (ESS) of anti-idling systems [6], hybrid electric vehicles (HEVs) [7] and electric vehicles (EV) [8,9] is capable of powering the A/C-R system independently such that the A/C-R system can be disconnected from the engines [10]. This indicates the feasibility of the electrification of the A/C-R system and the subsequent application of advanced controllers in vehicles. For the sake of accurate prediction, an accurate yet simple dynamic model of the whole A/C-R system is a prerequisite for the design of

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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
m	heat exchanger total mass
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
N	prediction and control horizontal length
P, Q, S	weight factor

any advanced controller. A simplified control-based model for all-purpose A/C-R systems that is validated by experimental data is provided [11]. Further based on the model, the controllers' development process is presented and followed by experimental validation and comparison work.

A literature review on the existing controllers including the MPC of A/C-R systems and the novelties of this paper is presented in the second section; next, the simplified model is briefly introduced. A brief introduction of the experimental system is provided in the following section. In addition, the development and implementation process of controllers are elaborated upon. Furthermore, the experimental results of both the discrete MPC and the conventional on/off controller are provided to demonstrate the energy-saving ability and the robustness of the proposed MPC. Moreover, a case study under varying heating load conditions is conducted by proposing the hybrid MPCs and the continuous MPC. In the last section, comments and future work are discussed.

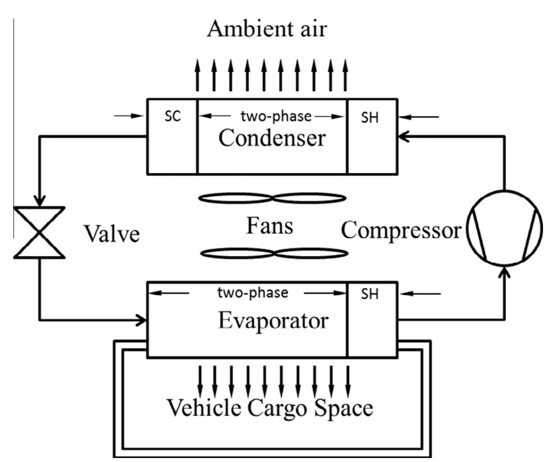

Fig. 1. Schematic diagram of an automotive A/C-R system with cargo.

2. Literature review

The A/C-R system generally consists of four main components: the compressor, evaporator, expansion valve, and the condenser, as shown in Fig. 1. One cycle is taken as an example for the demonstration of the whole working process of the A/C-R system. Let us begin with the high-pressure and low-temperature liquid refrigerant after it exits the condenser. It stays in the liquid phase before entering the expansion valve. Since the valve is usually assumed to be adiabatic, the enthalpy of the refrigerant at the inlet and outlet of the valve should be equal. In the evaporator, the low temperature and low-pressure two-phase refrigerant absorbs heat from the cargo space and exits from the superheat (SH) section in gas form to avoid damaging the compressor. The gas refrigerant is pressed when going through the compressor and exits the compressor with high temperature and high pressure. Finally, when it reaches the condenser, the superheated and over pressured gas refrigerant will go through the SH, two-phase and subcooling (SC) section when flowing through the condenser. Due to the extensive applications of A/C-R systems in different areas, many controllers have been developed in the literature.

Thanks to its simplicity, the on/off controller was initially applied. It could maintain the required temperature in a certain range by turning the whole system on or off. Instead, the on/off controller has many limitations. First, it is unable to regulate the temperature oscillation amplitudes in changing conditions including changing ambient temperatures or varying food temperatures. Secondly, frequent compressor activations (turning it on/off) can lead to excessive power consumption and cause the mechanical components to wear down over time. Above all, energy efficiency is not considered at all, and that is why [12,13] improved the original on/off controller's efficiency by introducing adaptive or optimization algorithms. However, due to the nature of the on/off controller, it is impossible to greatly enhance its performance. Recently, the application of variable-speed components into the