Applied Thermal Engineering 87 (2015) 779–787

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Modeling air conditioning system with storage evaporator for vehicle energy management

Quansheng Zhang*, Marcello Canova [1]

Center for Automotive Research, The Ohio State University, 930 Kinnear Road, Columbus, OH 43212, United States

HIGHLIGHTS

- Control-oriented modeling of storage evaporator.
- Demonstrate the benefits through simulations in Matlab/Simulink.
- Benchmark solution of optimization problem using dynamic programming.
- Preliminary application of hybrid optimal control problem.

ARTICLE INFO

Article history:
Received 24 January 2015
Accepted 2 May 2015
Available online 28 May 2015

Keywords:
Air conditioning system
Storage evaporator
Phase change material
Dynamic programming
Hybrid optimal control

ABSTRACT

Automotive Air Conditioning (A/C) system significantly affects fuel consumption and emission. Thus, Phase Change Material (PCM) is exploited in an innovative storage evaporator to improve the A/C system performance. Due to hybrid features introduced by mode switching when PCM changes its status between liquid and solid, the task of control-oriented modeling is particularly challenging. Upon the energy-based model built, an optimal control problem of an advanced A/C system with a storage evaporator is formulated as to find an optimal clutch command sequence balancing fuel consumption, cabin comfort and drivability constraints. In the scope of vehicle energy management, Dynamic Programming (DP) algorithm usually serves as a tool of obtaining benchmark optimal solution, against which results from other optimal algorithms are compared. However, a direct application of DP algorithm to the optimal control problem faces unexpected difficulty, because the discretization of state space is not feasible for an irregular multi-dimensional subspace formed by the multi-mode model. Alternatively, hybrid optimal control theory is pursued and a preliminary study is conducted to illustrate its promising application.

1. Introduction

Automotive A/C system has profound effects on the vehicle fuel economy. The majority of A/C system is still heuristically controlled and operates in an inefficient way. An analysis conducted in NREL [1] showed that the use of systems is equivalent to 5.5% of the domestic light duty vehicle fuel consumption. Two directions are mainly pursued in order to reduce fuel consumption of A/C system, namely model-based optimization and control design as well as hardware upgrades. The mass migration and heat transfer inside refrigerant loop is usually modeled using energy-based method [2], and its energy management is a typical a multi-objective optimization problem balancing fuel consumption, cooling requirement and mechanical weariness [3]. In Refs. [4–8], the optimal compressor clutch sequence is found using online implementable model predictive control (MPC) method. Recently, storage evaporator [9] is introduced to improve A/C system performance, because it increases thermal inertia and expands energy storage capability when the PCM changes its status between liquid and solid.

PCM has been widely applied in industrial areas, such as solar power plants, electronic devices, and transport [10,11]. Depending on the specific application, different models have been developed to characterize the heat transfer and phase change dynamics. Generally, these models belong to two categories, namely distributed-parameter model and lumped-parameter model. In Refs. [12–14], the PCM is treated using a one dimensional heat transfer model, a partial differential equation with boundary conditions specified. In Refs. [15], a simplified dynamic model is developed for predicting

* Corresponding author. Department of Mechanical and Aerospace Engineering, The Ohio State University, United States; Research and Innovation Center (RIC) in Ford, Dearborn, United States.

E-mail address: zhang.777@osu.edu (Q. Zhang).

[1] Department of Mechanical and Aerospace Engineering, The Ohio State University, United States.

http://dx.doi.org/10.1016/j.applthermaleng.2015.05.003
1359-4311/

the energy impact due to the addition of the PCM. Usually, these models are tailored for performance analysis at design stage, helping the designers determine appropriate geometric parameters or material types. However, little attention has been paid to the optimal operation of the PCM after the design stage.

This paper is aimed to apply optimal control theory automotive A/C system with storage evaporator. This work is challenging as it requires the modeling of phase change dynamics and choosing of appropriate control methods. The A/C loop dynamics changes significantly over PCM status, such as completely frozen, freezing/melting and completely melt. In other words, hybrid system dynamics exists and should be captured by the control-oriented model developed. The hybrid feature also affects the optimization process, as optimization algorithms applicable only in continuous domain might fail. Therefore, hybrid optimal control theory specifically developed for hybrid system is pursued herein. Different versions of Hybrid Minimum Principle (HMP) exist. A general version of the HMP is presented by Sussmann [16] based on a set of needle variations and a Boltyanski approximation cone. Two version of HMPs are introduced by Riedinger et al. [17,18] and Shaikh and Caines [19] for hybrid systems with autonomous and controlled switching. Although the above HMPs have solid theoretical foundation, they have hardly been applied to a practical problem before, like the energy management of A/C system. Therefore, this paper is aimed to illustrate the benefit of storage evaporator and the potential application of hybrid optimal theory in the A/C system energy management.

The paper is organized as follows. Section 2 models the A/C system dynamics using a lumped-parameter approach and resulted system equations are in descriptor form. Section 3 compares the performances between storage evaporator and conventional evaporator, and identifies the benefits of enhanced thermal inertia. Section 4 fits the problem of optimal control of A/C system into the field of vehicle energy management, and tests two common optimization algorithms for a specific driving scenario. A conclusion is given in Section 5.

2. Modeling A/C system with storage evaporator

As shown in Fig. 1, the A/C system of a passenger car is generally based on a simple vapor compression cycle realized through a fixed-displacement rotary piston compressor, a condenser with a fan, an evaporator with a blower, and a thermal expansion valve. The compressor is clutched on/off to remove heat from the air flowing through the evaporator and reject heat into the air flowing through the condenser, determined by the blower and fan rotation speed, respectively.

In an innovative A/C loop, the conventional evaporator is replaced with a storage evaporator with PCM added [9]. Physically, PCM in the outer tube is assembled around an inner tube which the refrigerant flows through. When the compressor is turned on, the refrigerant evaporates to solidify PCM that further cools down air flowing through fins; when the compressor stops, the PCM starts to melt to prevent the air temperature rising up quickly until it is completely melted.

In addition to the refrigerant phase change between vapor and liquid, another phase change happens in the storage evaporator is the PCM melting or freezing between liquid and solid. Both dynamics need to be captured in order to fully characterize the dynamics of the storage evaporator. In order to develop a supervisory controller, it is necessary to build suitable control-oriented A/C models balancing model accuracy and simulation time. Therefore, an energy-based model for the A/C system with storage evaporator is developed herein with major assumptions introduced sequentially to reduce the model complexity, since the computation burdens of optimization algorithms later developed strongly rely on the total number of states within the A/C model.

2.1. Lumped-parameter modeling approach

The methodology of building a high-fidelity A/C model is generally classified into two categories, namely finite-volume method and moving-boundary method [31]. However, the total number of system states in both cases are much more than the level that can be tolerated by those optimization algorithms commonly adopted in vehicle energy management. The main drawback of both methods is that the physical properties are treated as distributed parameters, meaning that a group of thermodynamic variables are required to characterize the thermo-fluid dynamics inside individual control volume. Instead, a lumped-parameter modeling approach is adopted to facilitate future optimization algorithms development.

Assumption I. *The temperature spatial distribution of refrigerant, wall and PCM is uniform along the tube length direction*.

Hence, the condenser is modeled as a lumped thermal mass with two control volumes representing, respectively, the volume occupied by the refrigerant flowing in the tubes and the metal mass (walls). Similarly, the evaporator consists of four control volumes, two of which are closely related to PCM dynamics. Considering the schematic of a storage evaporator with refrigerant flowing in the inner tube and PCM stored in the outer tube, as shown in Fig. 2, the spatially averaged PCM temperature T_{pcm} and exterior wall temperature T_{ewo} are determined by the heat transfer rates between refrigerant, PCM and air.

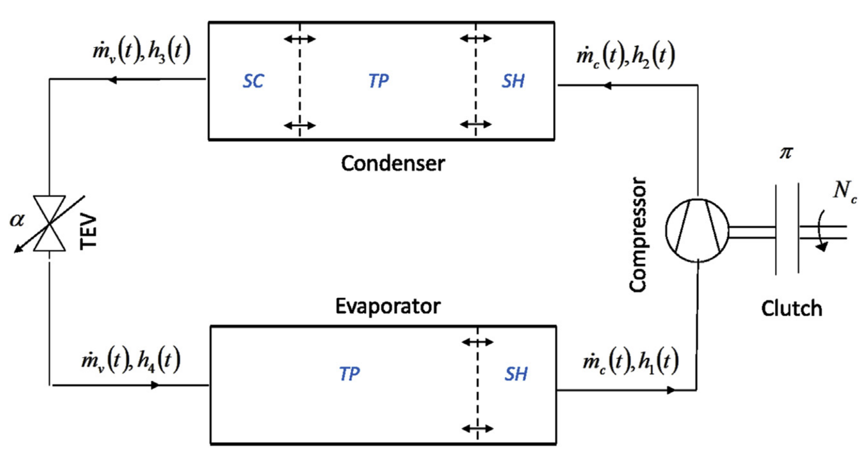

Fig. 1. Conventional A/C loop with refrigerant phase change.