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Parameter identification of a multi-stage, multi-load-demand experimental refrigeration plant

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ABSTRACT

Parameter estimation of a multi-stage, multi-load-demand refrigeration plant is addressed. It is shown that dominating system dynamics are those of heat exchangers, and their heat-transfer-related parameters affect system statics but barely influence system dynamics. A novel identification procedure focused on the heat exchangers is presented. It is based on non-measurable refrigerant phase-change zones, considering an overall heat transfer coefficient at each zone. Consistent values of all parameters are obtained considering only steady-state experimental data and some orders of magnitude found in the literature. The identified parameters are validated considering the two-stage, two-load-demand plant configuration.

1. Introduction

Cooling generation, including air conditioning and refrigeration systems, is used worldwide to remove heat from a space. Controlling room temperature is involved in as widely diverse areas as human comfort, food storage and transportation, and industrial processes (Rasmussen and Alleyne, 2006). A great deal of energy is required in such issues, in both developing and developed countries, as detailed in many studies in the literature, which characterise economical and environmental impact of refrigeration systems. For instance, statistical data show that air conditioners and refrigerators account for 28% of home energy consumption in the United States (RECS, 2009). Furthermore, supermarkets are one of the highest consumers in energy area, according to Baxter (2002); a typical one consumes yearly between 2 and 3 millions kWh, and around 50% of this energy is consumed in refrigeration processes. In case of office buildings, it has been estimated that the consumption due to HVAC (Heating, Ventilating, and Air Conditioning) systems is around 20–40% of total energy consumption at developed countries (Pérez-Lombard, Ortiz & Pout, 2008).

Among all types of cooling systems, electricity-based vapour compression cycles have a dominant position in current market. Due to pressing concern for energy shortage and global warming, greater efforts to reduce energy consumption and environmental impact of current vapour compression systems through system control and optimization are of practical significance. Some improvement has already been achieved, for instance, space heating and cooling (space conditioning) accounted for more than half of all residential energy consumption in USA for decades. Estimates from the most recent Residential Energy Consumption Survey show that 48% of energy consumption in USA homes in 2009 was for heating and cooling, down from 58% in 1993 (RECS, 2009). However, there is still more room for improvement.

This intended improvement involves, among others:

- Energy-efficiency-aware redesign of heat exchangers, in pursuit of improving their performance.
- Electronics and system control implementation, which enables to work with floating pressures in the cycle.
- Automatic fault detection and recovery capabilities.
- Use of optimization techniques which allow to continuously seek high efficiency, characterised in this area by the Coefficient of Performance (*COP*), regardless of external or uncontrollable conditions.
- Use of environmentally-friendly and harmless -in terms of their impact on the ozone layer- refrigerants.

These affordable guidelines require a deep knowledge of the process and modelling of such systems with required accuracy plays a central role, since many of the developed optimization techniques for vapour compression refrigeration cycles involve component and system modelling, at least static models. Moreover, availability of a purpose-built breadboard refrigeration plant which allows to test such optimization techniques, along with novel control strategies, is of the utmost importance to obtain real enhancements regarding energy efficiency and control performance. Some examples of experimental plants found

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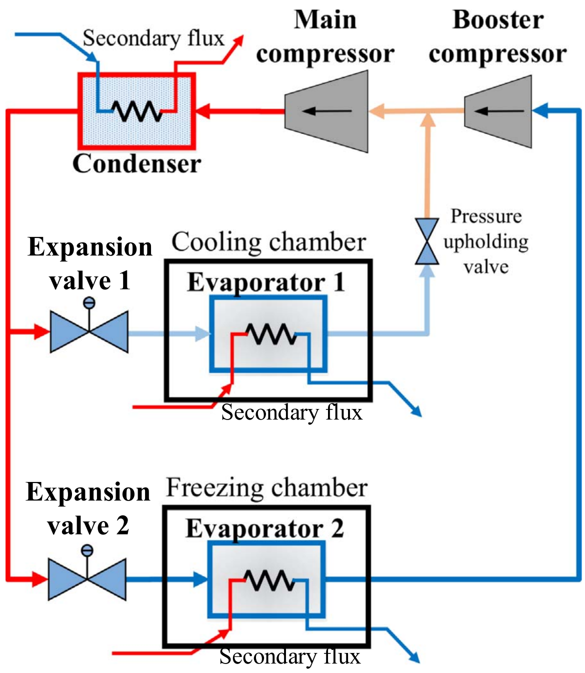

Fig. 1. Two-stage, two-load-demand refrigeration cycle.

in the literature are those described by Larsen (2005), Rasmussen, Musser and Alleyne (2005), and Schurt, Hermes and Trofino-Neto (2009), among others, but they are usually one-compression-stage refrigeration cycles, with one or more load demands.

Nevertheless, for instance at a supermarket, or simply at an ordinary domestic refrigerator, different service specifications usually coexist at the same system, for instance air conditioning, refrigeration, and freezing. Their temperature levels and cooling demands may vary, thus multi-compression-stage refrigeration cycles are useful to optimally satisfy all cooling demands.

For instance, a two-compression-stage, two-load-demand refrigeration system is represented in Fig. 1. It consists of two electronic expansion valves (*EEV*), two variable-speed compressors, and three heat exchangers (two evaporators and one condenser), in addition to a pressure upholding valve. Heat is transferred from the respective secondary flux to the refrigerant at both evaporators, taking advantage of its low pressure and temperature, and then the refrigerant flow is compressed in two stages, using the main compressor and the booster one. Later, heat is rejected to the secondary flux at the condenser by condensing the superheated refrigerant. Since there are different temperature requirements at the freezing and cooling chambers, an auxiliary valve is required in order to hold up the pressure difference between the Evaporator 1 output and the discharge of the booster compressor. Likewise, the expansion valves hold the pressure difference up between the condenser and each evaporator.

An experimental refrigeration plant which can be configured to work with up to two compression stages and up to two load demands is located at the Department of System Engineering and Automation of University of Seville (Bejarano, Alfaya, Ortega & Rubio, 2015b). New optimization and model-based control strategies are expected to be applied to this experimental facility, in order to test their performance and reliability.

As previously stated, many of the developed optimization techniques in the literature require component and system modelling. Modelling of vapour compression refrigeration systems is widely studied in the literature (Rasmussen, 2012). Diverse approaches have been presented, from very complicated models to simpler ones oriented to control design. Even though there are some discussions on the modelling of compressors and expansion valves, the main work in this area is still focused on the development of heat exchanger models, since their dynamics are shown to be about one order of magnitude slower than those of compressors and expansion valves. This is the reason why the latter elements are usually statically modelled.

Most of works related to heat exchanger dynamic modelling can be classified according to their formulation as *finite volume* or *moving boundary* models. In both methodologies the heat exchanger is discretised into a certain amount of control volumes, whose average or *lumped* parameters are calculated.

The *finite volume* approach involves applying mass, energy, and momentum balances of the refrigerant and secondary flux, and the material of which the heat exchanger is made, considering an arbitrary number of equally-sized control volumes. A numerical solution of a set of differential equations discretised into a finite difference form must be calculated (MacArthur, Meixel & Shen, 1983; MacArthur, 1984; Jia, Tso, Jolly & Wong, 1999). Very detailed information about system statics and dynamics is obtained, but the inherent tradeoff between accuracy and computational cost arises, since increasing the discretisation also adds new variables to compute.

In the *moving boundary* approach the heat exchanger is divided into a few control volumes corresponding to each refrigerant phase: superheated vapour, two-phase flow, and subcooled liquid (if necessary). This approach represents correctly system dynamics and it has a certain flexibility for adaptation to heat exchangers of different physical configuration (Grald and MacArthur, 1992; He, 1996; Rasmussen, Musser & Alleyne, 2005; Liang, Shao, Tain & Yang, 2010). Moreover, its computational cost is more affordable (Pangborn, Alleyne & Wu, 2015), and it could be implemented in real-time applications which might make use of a heat exchanger dynamic model for control or optimization purposes.

Furthermore, black-box models can be found in the literature, where any variable defining the cooling power is to be predicted from the manipulated variables. For instance, Bittanti and Piroddi propose a neural network approach to identification of a heat exchanger (Bittanti and Piroddi, 1997), while Romero *et al.* propose a simplified black-box model to predict accurately the chilled water temperature dynamic response of a vapour compression chiller, where the Box-Jenkins structure gets the best fit to experimental results (Romero, Navarro-Esbrí & Belman-Flores, 2011). This modelling approach is suitable for control purposes, but only the identified output variables can be controlled. Moreover, optimization requires a more detailed model to achieve significant improvements in energy efficiency.

Taking into account that the developed model is intended to be used within model-based optimization and control strategies, the *moving boundary* approach is used for the heat exchangers, while all other elements are statically modelled. As previously commented, the *moving boundary* approach is a first-principle methodology, therefore the parameters of each heat exchanger model must be estimated. Some authors who make use of this approach propose the use of correlations to calculate the heat-transfer-related parameters (Liang, Shao, Tain & Yang, 2010; Li and Alleyne, 2010), using a white-box model approach. However, we consider that the steady-state parameter identification based on experimental data plays a key role in such systems to propose model-based optimization and control techniques, since calculating the heat transfer coefficients based only on correlations (when available for the refrigerant and the type of heat exchanger at the specific facility) might lead to modelling errors which may be greater than the generated when identifying these coefficients according to real data. Most of correlations are used for heat exchanger design and not for real-time simulation, and not all flow conditions (laminar or turbulent regime) are usually considered for all fluids and types of heat exchanger. Moreover, having an estimation of heat transfer coefficients according to experimental data and therefore closer to real values than those provided by correlations enables to compute in simulation a more accurate estimation of the length of the different heat exchanger zones. Those non-measurable variables, among others, determine the