European Journal of Control 26 (2015) 53–62

Contents lists available at ScienceDirect

European Journal of Control

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

Controllability analysis and robust control of a one-stage refrigeration system ☆

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ARTICLE INFO

Article history:
Received 23 January 2015
Received in revised form
2 June 2015
Accepted 31 August 2015
Recommended by M. Kano
Available online 25 September 2015

Keywords:
Refrigeration system
Vapour compression cycle
Controllability analysis
Robust control
H_∞ Mixed Sensitivity Problem

ABSTRACT

This paper describes the controllability analysis and the design of a multivariable robust controller for a one-stage refrigeration cycle, which is the most used system for cooling issues and whose energy management and control are key factors. The controlled variables are the superheating degree of refrigerant at the evaporator outlet and the outlet temperature of evaporator secondary flux, whereas the control variables are the electronic expansion valve opening and the compressor speed. The system is considered therefore as a MIMO one. Up to eight different operating points are identified in order to design the multivariable H_∞ controller based on the $S/KS/T$ Mixed Sensitivity Problem. Simulation results comparing this controller to a decentralised PID and to a multivariable predictive one are shown, proving a better performance of the robust controller as well as accomplishment with the controllability analysis conclusions.

1. Introduction

Vapour compression systems, see Fig. 1, are the most used method worldwide for cooling generation, with applications in domestic, commercial and industrial refrigeration or air conditioning [20]. Refrigeration implies a high percentage of energetic consumption and its economical and environmental impact is well characterised. For instance, supermarkets are one of the highest consumers in the energy sector. A typical supermarket consumes yearly between 2 and 3 millions kWh [2], and around 50% of this energy is consumed in refrigeration processes. In the 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 [19]. Because of the rising shortage of different energy sources, its economy turns into a more and more urgent issue to deal with, and in this process the actual performance of the controller plays a central role.

As shown in Fig. 1, a refrigeration cycle consists of a variable-speed compressor, an electronic expansion valve (*EEV*) and two heat exchangers (evaporator and condenser). In a refrigeration process heat is absorbed at the evaporator (specifically from the secondary flux) by evaporating a flow of liquid refrigerant at low pressure and temperature, and heat is exchanged with the secondary flux at the condenser. The main control objective is to hold the temperature of the cold room at its desired value, which can be reflected in a reference for the outlet temperature of evaporator secondary flux ($T_{out,sec,e}$). As two manipulated variables (the compressor speed N and the valve opening A_v) are available, a secondary control objective is affordable: the generation of the requested cooling capacity with as high as possible Coefficient of Performance (*COP*) is intended. High energy efficiency is generally achieved if a significant amount of liquid filling in the evaporator is obtained at all compressor capacities, and the level of liquid filling is indirectly measured by the refrigerant superheating degree at evaporator outlet (*TSH*). Hence, in industry a set point or at least a constraint for minimum *TSH* is usually generated in order to ensure a high *COP*.

The difficulty in controlling this type of process lies in high thermal inertia, dead times, high coupling between system variables and strong nonlinearities. The most used linear control techniques which can be found in the literature are decentralised control [15,28,29]; decoupling multivariable control [26], LQG control [8,24,25]; model predictive control [6,21–23], and robust H_∞ control [11].

Marcinichen et al. [15] have studied a *SISO* dual strategy for N and A_v simultaneous control, specifically through PI controllers. The most used matching is to control *TSH* with A_v and $T_{out,sec,e}$

☆The authors would like to acknowledge Spanish Ministry of Economy and Competitiveness (Grant DPI2012-37580-C02-02) for funding this work.

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http://dx.doi.org/10.1016/j.ejcon.2015.08.001
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Nomenclature

Latin symbols

A_v	expansion valve opening (%)
COP	coefficient of performance (dimensionless)
D	scaling matrix
f	heat exchanger forcing function
$\hat{E}_{OP}(s)$	multiplicative output uncertainty transfer matrix
$G(s)$	system transfer matrix
$\hat{G}(s)$	scaled system transfer matrix
$\hat{G}_{OP}(s)$	operating point scaled transfer matrix
$GP(s)$	generalised plant for the $S/KS/T$ Problem
h	specific enthalpy (J kg)
$K(s)$	controller transfer matrix
$\hat{K}(s)$	scaled controller transfer matrix
k	static gain
$\dot{m}$	mass flow (kg s)
N	compressor speed (rpm)
OP	operating point
P	pressure (Pa)
PO	percentage overshoot (%)
$S_0(s)$	output sensitivity transfer matrix
T	temperature (K)
TSH	superheating degree (K)
$T_0(s)$	output complementary sensitivity transfer matrix
$T_{z\omega}(s)$	generalised plant closed-loop transfer matrix
t_r	rise time (s)
t_s	settling time (s)
u	input vector
$\boldsymbol{u}$	generalised plant control vector
$\boldsymbol{v}$	generalised plant measured vector
W	weight on the MPC objective function
$W_{KS}(s)$	control sensitivity weighting matrix
$W_S(s)$	output sensitivity weighting matrix
$W_T(s)$	output complementary sensitivity weighting matrix
x	heat exchanger state vector
Z	heat exchanger coefficient matrix
z	transfer function zero
$\boldsymbol{z}$	generalised plant error vector

Greek symbols

α	output sensitivity weighting matrix parameter (dimensionless)
β	output sensitivity weighting matrix parameter (dimensionless)
γ	ratio between $\boldsymbol{z}$ and $\boldsymbol{\omega}$ (dimensionless)
$\overline{\gamma}$	mean void fraction (dimensionless)
ζ	normalised zone length (dimensionless)
κ	design parameter (dimensionless)
σ	singular value (dimensionless)
τ	time constant (s)
ω	frequency (rad s)
ω_B	crossover frequency with −3 dB of output sensitivity function (rad s)
ω_{cr}	achievable control bandwidth (rad s)
ω_T	crossover frequency of output complementary sensitivity weight (rad s)
$\boldsymbol{\omega}$	exogenous signal vector

Subscripts

c	condenser
$diag$	diagonal
e	evaporator
err	tracking error
f	fast
in	inlet
max	maximum
min	minimum
out	outlet
RHP	right-half plane
s	slow
sc	subcooled zone
sec	secondary flux
sh	superheated zone
tp	two-phase zone
u	input
w	wall
z	zero

through *N*. Wang et al. [29] implement a hybrid PID-Neural Network controller, where the neural network tunes PID parameters online. Meanwhile, Underwood [28] proposes a decoupling control strategy where PID controllers are jointly tuned through optimisation techniques.

Regarding the robust control strategy, Larsen and Holm [11] design a *MIMO* H_∞ controller which solves the S/KS problem. Here the authors bear in mind that, for the system they consider, the coupling between the outlet temperature of evaporator secondary flux and the valve opening is weak. The reduced order controller is compared to a *SISO* H_∞ controller, obtained through the easing of the closed-loop system bandwidth. However, regarding the S/KS problem, only uncertainties along the frequency are considered.

Being aware of the complexity of the process, it could be appropriate to implement a controller which could cope with the coupling and uncertainties that may exist when modelling these systems linearly, due to the strong nonlinearities. These uncertainties should be studied not only along the frequency, but also at different operating points which could be reached. According to this, the development of a robust controller seems suitable. This paper proposes one in particular: a multivariable centralised H_∞ controller, based on the $S/KS/T$ Mixed Sensitivity Problem. Firstly, in order to describe the fundamental dynamic behaviour of the system, multivariable linear models are identified at several operating points by means of step response, selecting one of them as nominal model, which minimises the uncertainty region.

Secondly, a controllability analysis of the nominal linear model is carried out to show some constraints in its performance. Finally a systematic methodology for designing the weighting matrices of

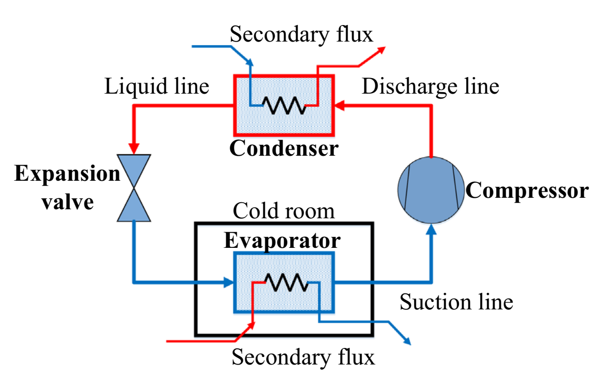

Fig. 1. Vapour compression system.