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The Static Characteristic of the Evaporator Superheat Control Loop

D. Pršić +, A. Vičovac++ and V. Stojanović +

+ Department of Automatic Control, Fluid techniques and Robotics, University of Kragujevac, Faculty of Mechanical and Civil Engineering in Kraljevo, Dositejeva 19, 36000 Kraljevo, Serbia
Phone: (+381 36) 383 377, E-Mail: {prsic.d, stojanovic.v}@mfkv.kg.ac.rs

++ SM Engineering, Inc., Topličin Venac 21, 11000 Belgrade, Serbia
Phone: (+381 11) 263 8915, E-Mail: aleksandar@sm-inzenjering.rs

Abstract ***- One of two primary control loops of the vapour compression cycle-based system is the evaporator superheat control loop. Its function is to protect the components from damage and increase the energy efficiency of the system. The process part of the loop consists of the electronic expansion valve and the evaporator. The paper presents the static characteristic of the process part. The characteristic is determined experimentally on the water-to-water domestic heat pump installation. The input is the control signal of the valve, and the output is the evaporator superheat temperature. The static characteristic is static, multi-valued nonlinearity with hysteresis and saturation on one side. Using the approximation of nonlinearity by means of linear segments, the simulation results in obtaining the describing function of the static characteristic.***

Key words: ***evaporator, electronic expansion valve, evaporator superheat, static characteristic, describing function***

I. INTRODUCTION

Research aiming at increasing the energy efficiency of air conditioning and refrigeration (AC&R) systems is mostly carried out in three fields: working fluids, component design, and control systems design. There are two important reasons for the increasing application of the theory of control in AC&R systems. The first one is development of new algorithms of control which can solve complex dynamic problems encountered in such systems. The second one is the lower prices of sensors, actuators and computers, which allows practical realization of these algorithms. In addition to reducing energy consumption, control systems prolong the component/system lifetime by preventing undesirable transitional phenomena and harmful operating conditions.

The structure of the conventional vapour compression cycle (VCC)-based system is shown in Fig. 1. The system is composed of four basic components: two heat exchangers (condenser, evaporator), compressor and expansion device. Besides these basic ones, there are also other components whose function is to improve the performance and protect the system from damage.

For the same hardware configuration, different values of the coefficient of performance (COP) can be obtained depending on the operating parameters. The high potential of application of new algorithms of control lies right here. The goal is to maintain the optimum values of operating parameters giving the largest COP under variable environmental conditions, thermal loads, and desired set-points.

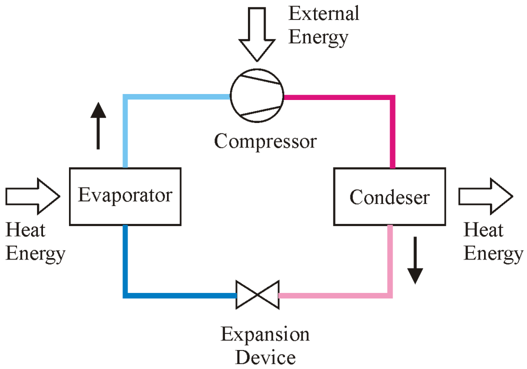


Fig. 1. VCC-based system

The two primary control objectives of a VCC-based system are to satisfy the desired load capacity by improving the system efficiency and safety. These two aims are realized through two control loops. Although there are different combinations of input-output variables, traditionally one loop (high level control) is used for the system capacity control and the second one (inner loop) for the evaporator superheat (ES) control. This paper deals with the second loop.

Evaporator superheat is one of the key indicators of efficiency and robust operation of the system. The amount of heat taken from the heat source is directly proportional to the temperature of the working fluid at the outlet of the evaporator. The goal is to lower the temperature (superheat level) as much as possible. On the other hand, in order to protect the compressor, it is necessary for the working fluid to evaporate completely before entering the compressor, i.e. to have as high superheat level as possible. Our task is to find and maintain the optimum value of ES, which represents the compromise between these two extremes. Although ES can be controlled with the compressor speed [1], the electronic expansion valve (EEV) is primarily used for the control of superheat. By changing the flow area at the valve, the flow of the working fluid, i.e. the degree of filling the evaporator is changed, too. The use of these valves instead of conventional expansion devices allows greater flexibility and much higher performances for a wide range of system operating conditions.

Independently of the type of capacity control, the control of superheat represents a serious challenge for designers. The reasons are the presence of nonlinearity and variability of operating conditions [2]. The problem is additionally complicated because of cross coupling between the control loops. The capacity control influences superheat control and vice versa. That connection can result in undesirable performances or even in the instability of the system [3].

The nonlinearity occurs both because of the nonlinear nature of the components which are built in the system and because of nonlinear changes of state of the working fluid. The nonlinearity is particularly pronounced in systems with a wide operating range and multiple operating points, where the nonlinearity cannot be ignored. In order to solve the problem of design and high-precision tracking control of those systems, it is necessary to have a better understanding of their nonlinear characteristics.

II. EVAPORATOR SUPERHEAT CONTROL

The role of the expansion valve in a VCC system is dual: it reduces the pressure of the working fluid before it enters the evaporator and modulates its flow. Two aims are accomplished by the change of flow: the compressor is protected from damage and the system efficiency is increased. In both cases, the controlled variable is the evaporator superheat temperature.

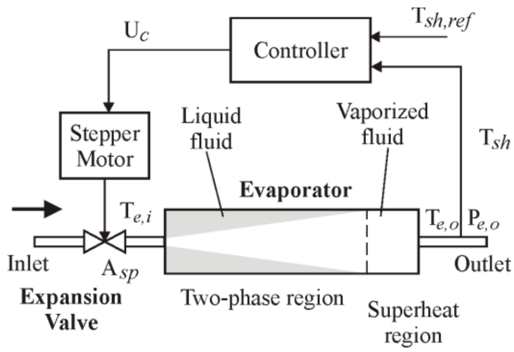
Superheat is defined as the temperature difference between actual temperature of the working fluid and saturation temperature at the evaporator outlet. In this case, two sensors at the evaporator outlet are used for measuring superheat: the pressure sensor, which is used to determine the saturation temperature, and the temperature sensor, which is used to determine the actual temperature. According to the second definition, superheat is the temperature difference of the working fluid between the outlet and the inlet of the evaporator [4, 5]. It is assumed that the pressure drop in the evaporator is negligibly small. Then two temperature sensors are used for measuring superheat, one at the inlet and the other at the outlet of the evaporator. Also, there is a third method where only one temperature sensor is used for measuring ES [1, 6], but it produces less accurate results.

The conventional approach is used in this paper. The first method is used for determination of superheat temperature because it gives the most accurate results in defining the static characteristic.

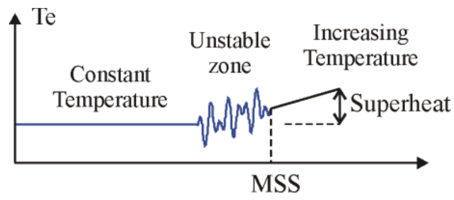
The schematic representation of the installation for ES regulation is shown in Fig. 2a.

The working fluid enters the evaporator in the two-phase state. While passing through the evaporator, it absorbs heat from the environment and boils. At the evaporator outlet, the working should be 100% vaporized and in a superheated state.

The level of superheat is determined based on the difference:



a) Control loop



b) Temperature profile

Fig. 2 Evaporator superheat

$$T_{sh} = T_{e,o} - T_e(P_{e,o}) \quad (1)$$

The actual temperature at the evaporator outlet (T_{eo}) is determined by direct measuring. The evaporation temperature (T_e) is determined indirectly, by measuring the outlet pressure ($P_{e,o}$). Based on the difference between the actual and reference values of superheat ($T_{sh,ref}$), the control signal U_c is formed in the controller. Proportionally to it, the flow area of the expansion valve (A_{sp}), i.e. the mass flow rate of the working fluid through the evaporator is changed.

Figure 2b shows the temperature profile (TP) of the working fluid through the evaporator at a given capacity [7, 8]. Three regions can be noticed on the profile. In the first part, the temperature is constant because all absorbed heat is used for boiling of the liquid phase of the working fluid. After a complete passing to the vapour phase, there is an increase in temperature because the absorbed heat is used for heating. Between these two extreme regions, there is a transitional zone with unstable fluctuations. The zone after which the fluctuations stop and where the increase in temperature is stable is called the minimum stable superheat (MSS) point. At this point, all of the refrigerant has finished evaporating and the evaporator is fully utilized. The highest efficiency for the given thermal load is accomplished at MSS. The aim of control is to keep the MSS point as close to the evaporator outlet as possible. If there is an increase in the thermal load, there is an increase in the superheat temperature (T_{sh}), the MSS point is moved to the left, and the width of the region of the constant temperature (Fig. 2b) is reduced. It results in the decrease in the system efficiency because less heat is absorbed from the environment. The control variable U_c should open the valve and increase the flow of the working fluid so that the MSS point could return to the initial position. Similarly, if there is a drop of thermal load, the internal mechanism of self-regulation is activated again. Then the MSS point is moved to the right, and the width of the region of the constant temperature is increased. Although the system efficiency is thus increased, there is a restriction that the MSS point must not be too close to the compressor.

From the aspect of control, the goal is to keep MSS at the temperature sensor within the allowed limits. MSS is usually determined in such a way that the increase in the flow causes the first fluctuations at the temperature sensor. The calculated value of superheat (1) approximately represents MSS for the given load. The superheat set point ($T_{sh,ref}$) is determined by adding another reserve on MSS which prevents unpredictable disturbances.

This paper presents determination of the dependence between the control signala (U_c) and the evaporator superheat temperature (T_{sh}) in a stationary regime.

III. EXPERIMENTAL RESULTS

The water-to-water domestic heat pump heating capacity of 20 kW is used for experimental collection of data. The working fluid is freon R410a.

The process part of the evaporator superheat control loop (Fig. 2a) consists of the plate heat exchanger and the Emerson uni-flow EEV with the inlet/outlet connection of 3/8" ODF and 5/8" ODF, respectively. The capacity range is 10%-100%. The universal driver module with the input signal of 0-10V is used as the stepper motor driver.

The control signal of the valve is:

$$U_c = 6.5 + 2.5\sin(\frac{2\pi}{T}t) \ [V] \qquad (2)$$

with the period $T = 1500[s]$. The high value of the period was adopted in order to avoid the influence of transitional phenomena. The change of the ES temperature is shown in Fig. 3.

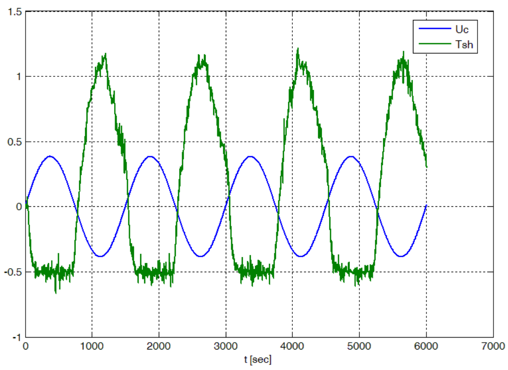


Fig. 3. Superheat temperature and control variable time propagation

The static characteristic of ES shown in Fig. 4 is obtained based on the collected data.

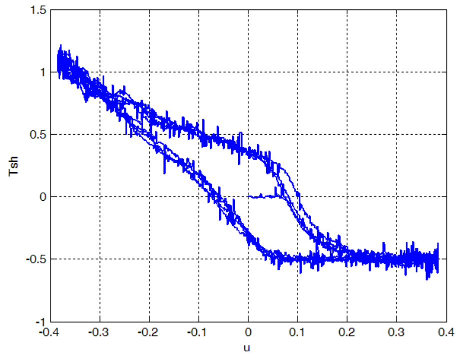


Fig. 4. Superheat temperature - Control variable static characteristic

The static characteristic is the nonlinearity of hysteresis type with a variable width. For the same value of control signal there are two values of superheat, depending on the direction of change. With the increase in the control signal, T_{sh} decreases, and vice versa. ES decreases only up to a certain value, after which the system enters saturation. Further increase in the control signal does not have any influence on the change of the output value. The reason is that the ES temperature cannot be lower than the temperature of the working fluid at the evaporator inlet (T_{ei}). T_{ei} is out of phase relative to the ES temperature. When T_{sh} is lowest, T_{ei} has the highest value. It seems that there is an inner feedback loop in the system which restricts the lowest value of superheat.

The noise present in determination of T_{sh} is the consequence of the noise during measurement of the evaporator output pressure. The sample time of data acquisition was 0.1 [s].

The most frequent cause of hysteresis in a VCC system is internal friction of EEV [7-9]. Hysteresis is present, to a larger or smaller extent, in all valves. In the course of time, the hysteresis at the valve increases because of wear and change of parameters that influence the inner friction of the valves. When hysteresis is present to a smaller extent, it can be used because it reduces the system sensitivity to disturbances. However, a greater width of hysteresis unfavourably influences static and dynamic characteristics of the valve, i.e. the whole system. During transitional processes, hysteresis can lead to self-sustainable oscillations in the system.

For analysis and design of nonlinear systems, there are numerous well-established techniques, especially from a control point of view. One of them is the use of quasi-linear operators which approximately describe the transfer characteristics of nonlinearity in the frequency domain. This operator is called the Describing Function (DF) [10]. The DF theory represents an approximative mathematical framework for analysing nonlinear systems in order to allow a frequency domain approach. It is primarily used to analyze the stability in the frequency domain and limit cycle analysis of nonlinear control systems. Although the DF can be determined for different forms of input signals, this paper uses the Sinusoidal Input Describing Function (SIDF). SIDF can be observed as the frequency response of the real (nonlinear) system. It should be borne in mind that the input-output characteristic does not depend only on the frequency of the input signal, but also on its amplitude.

The describing function of the ES system was determined in the following way: firstly, the real static characteristic (Fig. 4) was approximated by a set of linear segments (Fig. 5). The breaking points in Fig. 5 were taken from Fig. 4, and then rectilinear segments were drawn between them. The accuracy of approximation depends on the number of points. There should usually be a compromise between the accuracy and complexity of calculation. In that way, the real hysteresis is represented by a closed polygon which can be described analytically.

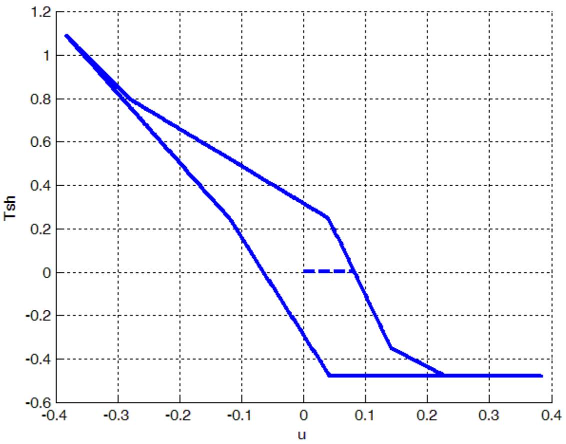


Fig. 5 Approximation of the static characteristic of ES by linear segments

DF shown in Fig. 6 was obtained based on the analytical expression, using simulation and FFT analysis, with sinusoidal signals (1) of different amplitude. The figure presents the real and imaginary parts of the complex gain of the ES static characteristic. The real part is negative because the superheat temperature decreases with the increase in the control signal and vice versa. The imaginary part indicates that there is a phase lag larger than 180^o between the input and output signals.

III. CONCLUSION

The static characteristic of the EEV-controlled evaporator is memory nonlinearity of hysteresis type with saturation on one side. The superheat temperature decreases by opening the valve, but only up to a certain value. Further decrease is not possible due to the increase in the input temperature of the evaporator. A probable cause is the existence of internal friction at the valve. In order to establish this, it is necessary to determine the static characteristic of the valve itself, i.e. to determine the dependence of the control signal-mass flow rate.

The describing function of the ES subsystem indicates the existence of the real and imaginary gains. The phase delay of the output signal is higher than π [rad] for all values of the amplitude of the input signal. It means that if there is a time delay in the EEV-evaporator subsystem, there is a possibility of occurrence of sustainable oscillations, the phenomenon is known as hunting.

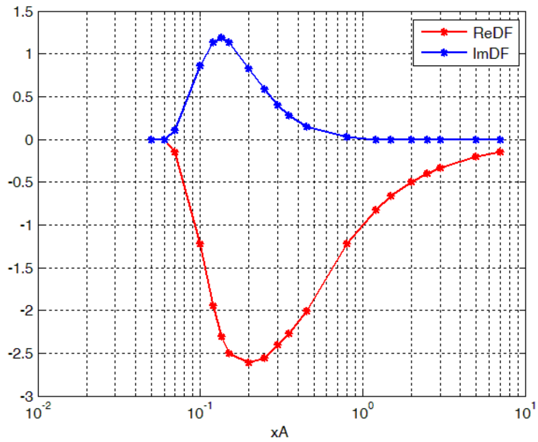


Fig. 6 Real and imaginary parts of the describing function

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