Applied Thermal Engineering 92 (2016) 210–218

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Refrigerant flow through electronic expansion valve: Experiment and neural network modeling

Xiang Cao, Ze-Yu Li, Liang-Liang Shao, Chun-Lu Zhang *

Institute of Refrigeration and Cryogenics, School of Mechanical Engineering, Tongji University, Shanghai 201804, China

HIGHLIGHTS

- Experimental data from different sources were used in comparison of EEV models.
- Artificial neural network in EEV modeling is superior to literature correlations.
- Artificial neural network with 4-4-1 structure and S function is recommended.
- Artificial neural network is flexible for EEV mass flow rate and opening prediction.

ARTICLE INFO

Article history:
Received 30 July 2015
Accepted 19 September 2015
Available online 22 October 2015

Keywords:
Electronic expansion valve
Refrigerant
Experiment
Model
Artificial neural network

ABSTRACT

Electronic expansion valve (EEV) plays a crucial role in controlling refrigerant mass flow rate of refrigeration or heat pump systems for energy savings. However, complexities in two-phase throttling process and geometry make accurate modeling of EEV flow characteristics more difficult. This paper developed an artificial neural network (ANN) model using refrigerant inlet and outlet pressures, inlet subcooling, EEV opening as ANN inputs, refrigerant mass flow rate as ANN output. Both linear and nonlinear transfer functions in hidden layer were used and compared to each other. Experimental data from multiple sources including in-house experiments of one EEV with R410A were used for ANN training and test. In addition, literature correlations were compared with ANN as well. Results showed that the ANN model with nonlinear transfer function worked well in all cases and it is much accurate than the literature correlations. In all cases, nonlinear ANN predicted refrigerant mass flow rates within ±0.4% average relative deviation (A.D.) and 2.7% standard deviation (S.D.), meanwhile it predicted the EEV opening at 0.1% A.D. and 2.1% S.D.

1. Introduction

For energy saving in part-load operations, variable refrigerant flow becomes more and more popular in refrigeration and heat pump systems. Electronic expansion valve (EEV) shows excellent performance in prompt and precise flow control for a wide range of refrigerant flow rate, which is helpful to reach steady state rapidly and reduce the energy consumption during the repeated regulation. Aprea and Mastrullo [1] compared it with thermostatic expansion valves by experiments and found that EEV shows over 10% energy saving in transient tests.

Nowadays, modeling and simulation become important in efficient system design. An accurate EEV model plays a meaningful role in component sizing and control design, as summarized in Table 1. A suitable EEV should satisfy the following conditions. Its capacity should match not only the rated capacity but also the maximum and minimum operation loads. In addition, the EEV opening should work at a reasonable position. Hence the demands of flow rate prediction in sizing are only for specific operating conditions. By comparison, the requirements of off-line and on-line control design on EEV model are quite stricter. The model-based off-line control design requires a dynamic model to simulate the system transients so that various control algorithms could be tested on the platform. Robust EEV model is required to get the job done smoothly. For on-line control design, such as the model predictive control [2], in which the EEV model should get involved in not only the system dynamic simulation to determine the direction of optimization, but also the real-time correction of the model itself. Higher robustness of the model is therefore required to keep safe operations. Beyond that, real-time opening prediction is essential in on-line control design [3,4].

However, the existing EEV models could not meet all requirements in application. There are two major challenges.

First, what exactly happens in EEV is intensely complex. The refrigerant passway in EEV is somewhat similar to the convergent–divergent nozzle and its throat area can be adjusted by a needle,

* Corresponding author. Tel.: +86 136 71825 133; fax: +86 21 69589750.
E-mail address: chunlu.zhang@gmail.com (C.-L. Zhang).

http://dx.doi.org/10.1016/j.applthermaleng.2015.09.062

Table 1
Requirements for EEV model.

	Sizing	Off-line control design	On-line control design
Mass flow rate prediction	Prediction under specific operating conditions	Prediction in a dynamic process	Real-time prediction with sampling data
EEV opening prediction	Optional	Optional	Yes
Calculation speed	Low	Medium	High, time bound to sample interval
Robustness	Low	Medium	High

which is driven by a pulse controlling stepping motor. When subcooled liquid flows into EEV, due to pressure drop, the refrigerant turns into superheated liquid and flashes at the throat [5]. Regarding the existence of choked two-phase flow, there is a debate. Zhang et al. [6] found in experiments that the mass flow rate is insensitive to the outlet pressure when the outlet pressure reaches a low value. However, the experimental results from Park et al. [7] showed that the decreasing evaporating pressure could raise the mass flow rate continuously under some conditions. Therefore whether the choked flow happens in EEV might depend on the flow channel design.

Second, the flow rate is a nonlinear function of geometric parameters. Many researchers developed semi-empirical models of EEV flow rate based on a single-phase orifice model with variable flow area and flow coefficient correlation [3]. However, the flow coefficient of EEV is much more complex than that of orifice because even small change of parameters would significantly influence the flow rate. Kasayi and Takahashi [8] put up meticulous experimental results and found that valve needle's half taper α could heavily influence the flow coefficient. Fig. 1 shows the flow rate characteristics of three EEVs in the same series from one manufacturer. Three EEVs have almost the same channel design but different orifice inner diameters. They were measured with the same refrigerant and operating

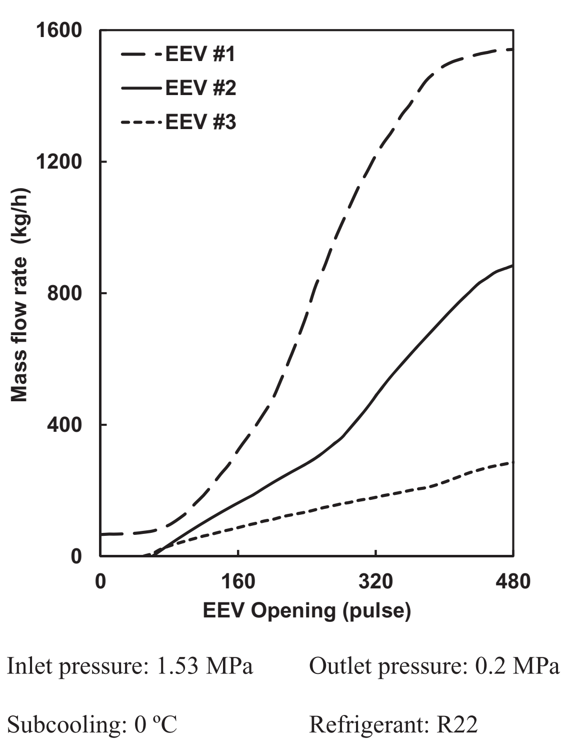

Fig. 1. Characteristic curves of EEVs in one series.

conditions. As seen, their performance curves are quite different from each other. EEV #1 has the largest diameter and its flow rate characteristics show strong nonlinearity. The throat area of EEV #3 is the smallest and its flow rate curve is nearly linear. Moreover, the flow coefficient of EEV is much more complex than fixed-area orifice because the opening of EEV is dynamically tuned by a stepping motor and the flow coefficient might differ a lot for different opening values [9]. Therefore, EEV modeling faces greater challenges in comparison with the fixed-area expansion devices.

Due to complex throttling mechanism and geometrical complexities, EEV model must be multivariate and nonlinear. It is difficult to develop a generalized physics-based EEV model in a simple form. In fact, empirical and semi-empirical models are widely used in engineering practice nowadays.

In earlier researches of EEV modeling, mass flow rate was typically expressed by the hydraulic formula derived from the Bernoulli equation, which is

$$\dot{m} = C_d A_{th} \sqrt{2\rho_{in}(P_{in} - P_{out})} \quad (1)$$

where q_m is the mass flow rate, C_d is the flow coefficient, A_{th} is the throat area, ρ_L is the inlet refrigerant density, and P_{in} and P_{out} are the inlet and outlet pressure, respectively. According to Eq. (1), prediction accuracy of EEV mass flow rate essentially depends on how to calculate the flow coefficient. Power-law dimensionless correlation is one of the most popular empirical models of EEV flow coefficient and its general form is

$$\pi_1 = e_1 \cdot \pi_2^{e_2} \cdot \pi_3^{e_3} \cdot \pi_4^{e_4} \cdot \pi_5^{e_5} \cdot \pi_6^{e_6} \cdot \pi_7^{e_7} \cdot \pi_8^{e_8} \cdot \pi_9^{e_9} \quad (2)$$

where the dimensionless Pi-groups should satisfy the Buckingham π-theorem.

The power-law correlation was applied to the modeling of capillary tubes and short tube orifices and was recommended by ASHRAE [10]. Thus this approach has received great attention in the researches of EEV modeling as well. According to Park et al. [7], when chocked flow is not significant, the mass flow rate through EEV could be calculated by the single-phase orifice model, namely Eq. (1). They regressed the mass flow rate C_d with power-law correlation and the relative deviation was within ±15%. Some models with power-law correlation in open literatures are listed in Table 2.

The power-law correlations could meet the requirements on EEV sizing, but neither off-line nor on-line control designs. First, as stated above, the robustness of model plays an important role in control design. When one Pi-group approaches zero, the mass flow rate estimated by the power-law correlation would be 0 or infinity, which is not real and the control system can be broken. For example, the system with liquid receiver could have zero subcooling before the valve, while the mass flow rate could not be zero all times. In addition, the control signal of stepping motor might be zero pulse during the start-up process in actual operation, but the refrigerant flow could still exist (as curve of EEV #1 in Fig. 1). In these cases, the defect of power-law correlation would reduce the robustness and accuracy severely. Second, all power-law models in Table 2 need either more difficult measurement or to invoke refrigerant property routines for the Pi-groups, which is not applicable in real control designs [3,14,15].

Besides the power-law correlations, a few researchers proposed polynomial models. Li [9] gave a quadratic polynomial correlation with dimensionless parameters for C_d as a simplified EEV model.

$$C_d = a_0 + a_1 z + a_2 z^2 + a_3 z\left(\frac{T_{sub}}{T_c}\right) + a_4\left(\frac{T_{sub}}{T_c}\right) + a_5\left(\frac{T_{sub}}{T_c}\right)^2 \quad (3)$$

where z is the control signal pulse of stepping motor and T_c is the critical temperature of refrigerant. Li's model was tested using the