

Experimental Investigation of Droplet Dynamics and Spray Atomization inside Thermostatic Expansion Valves

2011-01-0129

Published
04/12/2011

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doi:[10.4271/2011-01-0129](https://doi.org/10.4271/2011-01-0129)

ABSTRACT

In this paper, experimental investigation on spray atomization and droplet dynamics inside a thermostatic expansion valve (TXV), a component commonly used in vehicle refrigeration system, was conducted. A needle and an orifice were copied from a commercial TXV and machined to be mounted inside a chamber with optical access so that the flow inside the TXV is simulated and visualized at the same time. The break-up and atomization of the refrigerant were documented near the downstream of the orifice under different feed conditions for two TXV with different geometry. A Phase Doppler Anemometry (PDA) system was used later to measure the size and velocity of atomized refrigerant droplets. The results showed that the droplet size variation along the radial direction is slightly decreased at near downstream and increased at farther downstream due to the coalescence. The increase of the pressure drop through throttling induces more droplets splashed from the needle plate and more violent secondary breakup at the downstream for TXV 1, which is featured by wide expansion space between the needle and orifice. Such trend is less apparent on TXV 2, of which the expansion space is much narrower. Further study of the impingement effect indicate that a more active coalescence of incoming droplets and ejected droplets is taking place in TXV2, which potentially offset the effect of the secondary breakup induced by the impingement. This makes TXV2 operating more stable and less likely to be subjected to the hunting.

INTRODUCTION

The thermostatic expansion valve (TXV) has been widely applied in refrigeration systems for a long period as throttling and flow regulation device. The opening of the TXV is adjusted based on the balances of forces and thus is able to regulate the refrigerant flow based on the superheat of the evaporator. The disadvantage of TXV is the moving parts and response lag compared with orifice tubes and not be able to cope with wide range of operating conditions [1]. To achieve more accurate control, electronic expansion valve (EEV) has been applied due to their quick response along with the increasing use of variable speed compressor, even though, a number of reported studies suggest that the hunting was still observed in EEV-controlled refrigeration systems [1, 2, 3]. For air conditioning systems used in automobiles, the disturbance suffered by the system is mainly the sudden change of the system response according to the variation of the automobile speed and ambient conditions. A number of experimental investigations on the system hunting had been conducted. Gruhle and Isermann [4] demonstrated unstable control behavior with a TXV for a step disturbance of air temperature at evaporator inlet and compressor rotary speed. Tian and Dou [5] investigated experimentally the hunting phenomena caused by the large external disturbance in the automobile air conditioning system with a variable displacement compressor and a TXV and showed the system stability was dependent on the direction of the external disturbance. It is found that the system is apt to cause hunting when the condensing pressure decreases excessively since it may cause two-phase state at the throttling device inlet and make a large disturbance to the system. Li et al. [6] applied a

fuzzy self-tuning control algorithm to the EEV on the automobile air conditioning system and showed that the new method could feed adequate refrigerant flow into the evaporator under abrupt changing of the compressor's speed. The new method was an improvement over the conventional PID since the conventional PID control cannot make quick response to the abrupt changes in the refrigerant flow rate when the automobile speed changes.

Although the general macro features of the valve hunting had been wildly discussed, few studies actually “went into” the valve and studied the throttling process through visualization and droplet size measurement. Therefore, the objective of this study is to build an “optical valve” so that the refrigerant spray can be visualized and measured using laser diagnostics. The details of the experiment setup will be given in the later section. It should be pointed out that the spray and atomization process inside the TXV/EEV is complicated and involves many physical processes such as droplet breakup, flash boiling, spray wall impact, and different phase changes such as vapor, liquid, and metastable state. From the backlit photography results, spray wall impact is found to be crucial to the refrigerant atomization under the current nozzle configuration, since most of the liquid refrigerant is unable to be fully atomized before impinging on the needle plate. Homogeneous two phase flow featured by fully atomized small droplets is desirable in the system operation while large droplets and liquid films inside the valve resulted from poor atomization can cause problems such as valve hunting and poor refrigerant distribution in the evaporator as aforementioned. Therefore, the behavior of the droplets induced by the spray wall impact is of great importance to the TXV/EEV performance.

Spray plate nozzle has been studied by a number of investigators in the past decades [7, 8, 9]. Most of these studies used water or fuel as the working fluid, while refrigerant has been rarely studied. In general, there are two outcomes of droplet impinging on the solid surface, the droplet will either deposit on the surface and form a liquid film or splash and break into secondary droplets. A number of researchers had attempted to establish correlations for the deposition-splashing limit using Weber number ($We = \rho LU^2 / \sigma$, U is jet velocity). These experiments, however, were restricted to normal impact of a single droplet onto dry or wetted surface where the impingement conditions can be carefully controlled [10, 11, 12, 13]. Tropea et al [14,15] performed experiments on drop impingement in a spray and they found the resulted drop behavior differed significantly from that of an isolated single droplet. They proposed new models where correlations are based on the mean statistics of the spray rather than on a single droplet. Other models can be found in terms of the droplets size and velocity correlation [7, 8, 9]. The experiment results of McCreery et al [7] showed a mean drop diameter dependency on pressure to

approximately -0.3 power for a spray plate nozzle, which was a reasonable agreement with Fraser's correlation [8].

In summary, the spray wall impact will greatly affect the refrigerant atomization inside a TXV/EEV. Although studied in many other applications, the spray wall impact of refrigerant is rarely investigated. Also, pressure is found to be an important parameter regarding the drop size distribution. In this article, the refrigerant atomization in an orifice needle plate is visualized and measured. Results include the short duration (3 μ s) photographs of refrigerant spray wall impingement, and droplets size distribution measured by PDA system. The impact of the pressure drop through the TXV on system stability is discussed

EXPERIMENTAL SETUP

To simulate the real working conditions of TXV and EEV, a refrigerant loop is introduced as shown in Fig. 1. HFC-134a, a commonly used refrigerant in air conditioning systems which has a formula CH_2FCF_3 , was chosen as the working fluid in this study. The gear pump was used to provide the pressure head to R134a; a recycle bypass was then introduced to control the pressure of the fluid. A resistance heater coupled with a variac was used to heat the refrigerant. The temperature and pressure of the upstream refrigerant (before entering the test section) could then be precisely controlled and measured. The measuring devices are listed in Table1. After the test section, two-phase R134a was condensed in a plate heat exchanger by cooling water. A specific R134a receiver was mounted before the pump to avoid cavitations inside the gear pump before the cycle started again.

Table 1. Measuring devices

	Model	Accuracy
Thermocouple	Omega K Type	± 0.15 °C
Pressure Transducer	Setra 280 E	$\pm 0.11\%$ FS
	Setra 205-2	$\pm 0.11\%$ FS
Flow meter	Micro Motion DH012S100SU	$\pm 2\%$ of reading

The test section, so called as the “optical valve”, is a chamber with optical access which is centered by the laser based measuring devices. The dimension of the inlet path, orifice and needle plate of a commercial TXV were copied out and machined into an adapter which can be further mounted inside the optical chamber. A push rod, coupled with a meter head at one end penetrated through the bottom plate and can be moved vertically as illustrated in Fig. 2. The needle plate was mounted on the top of the push rod which can be aligned with the orifice using the slide jack. The configuration of the needle/orifice nozzle is shown in Fig. 3 and the dimensions of two different nozzles are listed in Table2. The equivalence diameter D_e is defined as $D_e = d_o - d_i$. With d_o fixed and d_i changeable, the open/close of the valve can easily controlled by lifting up and down the push rod.

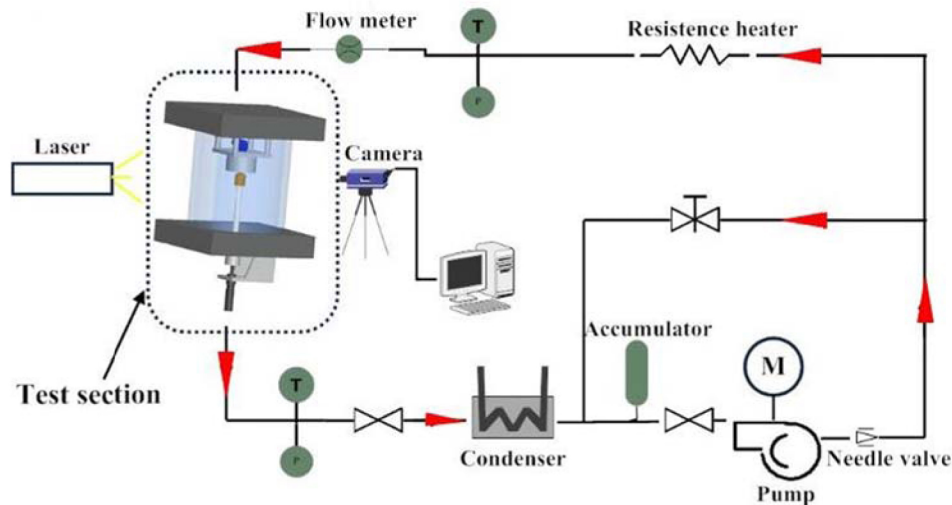


Figure 1. Refrigeration Loop

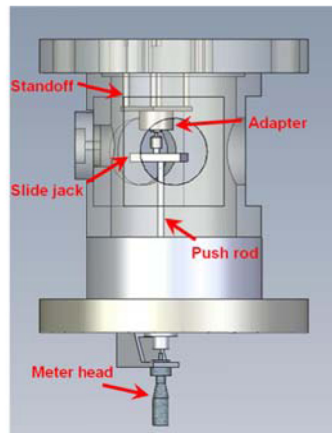


Figure 2. Optical chamber Setup

Backlight illumination technique was employed to investigate the spray formation and breakup processes, allowing qualitative study on the spray shapes and structure. The laser shined onto a diffuser to provide a homogenous background while the camera is placed at the other side of the chamber as shown in Fig. 4. A Phantom Research v7.1 high-speed camera was used with a frame rate of 10,000 fps and an exposure time of 3 μ s; an Oxford copper vapor laser was used as the light source with a pulse rate of 10,000 Hz to achieve the laser/camera synchronization.

The optical chamber has four side windows whose positions were specifically arranged to meet the requirement of the PDA system. A Dantec Dynamics PDA system was used in this study to provide a quantitative analysis of the spray inside the TXV. Dantec P60 Flow & Particle processor was used for signal processing, while an Argon Ion Laser (Stabilite 2017) by Spectra-Physics was used as the light source. Spatial adjustments were done with a Dantec manual

transverse system. In this setup, the spatial profiles of droplet size were measured by a one-dimensional PDA. The beam separation was 50 mm and the laser power was 900 mW at a wavelength of 514 nm per beam. The scattering light collection lens on the Dantec receiver optical system has a focal length of 310 mm. The receiver was positioned at a scattering angle of 70° to ensure only the first order refractions were collected.

Table 2. Nozzle dimensions

	Nozzle 1	Nozzle 2
Orifice diameter d_o (mm)	4.57	4.57
Nozzle angle α	85	90
Nozzle length L (mm)	5.13	3.50
Poppet diameter D_p (mm)	14.32	18.12