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Wenyi Wang
University of Texas at Dallas, United States of America, wxw161230@utdallas.edu

Yaoyu Li
The University of Texas at Dallas, United States of America, yxl115230@utdallas.edu

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Extremum Seeking Control for an Air-source Heat Pump Water Heating System with Flash Tank Cycle based Vapor Injection

Wenyi Wang[1] and Yaoyu Li[2]*

[1]The University of Texas at Dallas, Department of Mechanical Engineering,
Richardson, Texas 75080, USA
E-mail: wxw161230@utdallas.edu

[2]The University of Texas at Dallas, Department of Mechanical Engineering,
Richardson, Texas 75080, USA
E-mail: yaoyu.li@utdallas.edu

*Corresponding Author

ABSTRACT

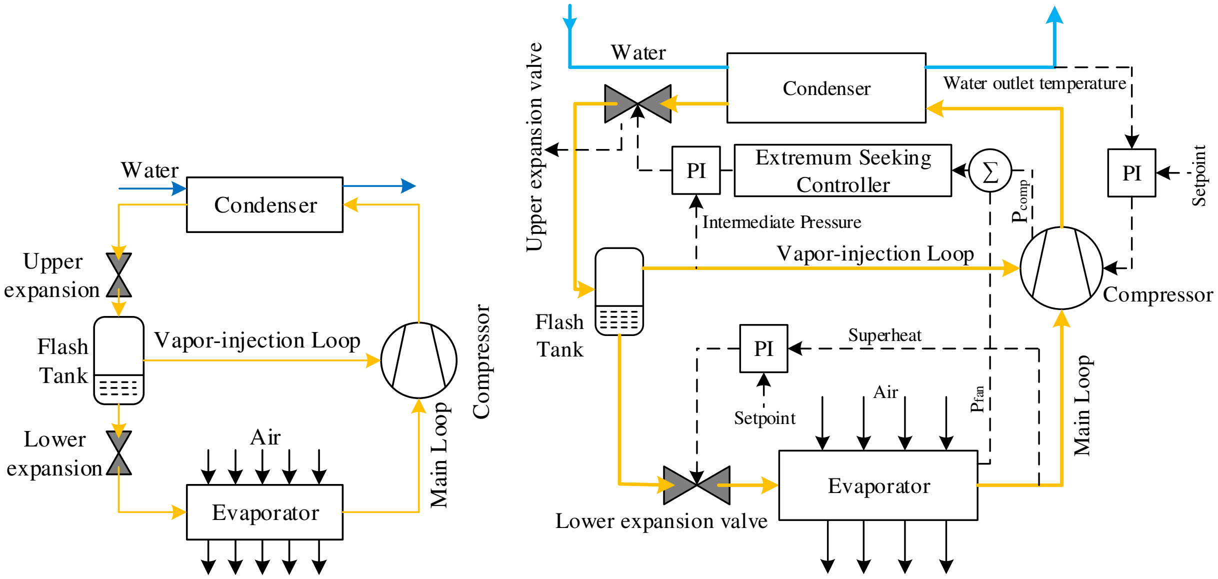
The flash tank cycle (FTC) vapor injection technique has been well received as a promising solution to heat pump systems under cold climate, however, development of effective control strategy has been a barrier for practical acceptance for such system. This paper presents a novel control strategy for heat pump operation with flash tank cycle (FTC) vapor injection configuration. The intermediate pressure setpoint for the vapor injection loop is regulated by the upper electronic expansion valve. Then, a real-time optimization or optimal control framework can be applied to minimize the total power consumption by adjusting the intermediate pressure setpoint, provided that the inner loop controller can satisfy the load demand via compressor capacity. In particular, the extremum seeking controller is applied as a model-free real-time optimization strategy for such purpose. To evaluate the proposed control strategy, a Modelica based dynamic simulation model is developed for an FTC vapor injection heat pump water heater. Simulations under fixed and variable ambient temperature validate the effectiveness of the proposed control strategy.

1. INTRODUCTION

Vapor injection (VI) techniques (Umezu and Suma 1984) have attracted intensive interest from the industry of refrigeration and air conditioning equipment because they can improve the heating capacity and the system coefficient of performance (COP), as well as decrease the discharge temperature with slight increase in power consumption, especially beneficial for the operation under low ambient temperature. Therefore, VI has been well received as an effective technology for improving the performance of air-source heat pump (ASHP) in cold climate.

The flash tank cycle (FTC) and the internal heat exchanger cycle (IHXC) are the two major VI configurations. FTC has the merit of low cost and potential for achieving higher efficiency. Heo et al. (2011) evaluated the performance of various VI cycles for an ASHP heater at an ambient temperature of −15°C and concluded that FTC achieved the highest heating capacity. In principle, FTC can achieve higher performance than IHXC because that the saturated vapor from the flash tank has a lower temperature which helps reduce the compressor discharge temperature and thus power consumption. Due to such advantages of FTC, a great deal of research has been conducted on FTC at the system and component levels, from the perspective of injection location, injection pressure, injection ratio, among others (Winandy and Lebrun, 2002; Park et al., 2002; Ma and Zhao, 2008; Bertsch and Groll, 2008; Cho et al., 2009; Wang et al., 2009a; Park et al., 2015).

However, in spite of the aforementioned merits of FTC, the lack of proper control/operational strategy for the vapor injection loop has severely hindered the adoption of FTC and to practical ASHP systems, as compared to the ramification of IHXC application. As shown in Fig. 1(a), the refrigerant is present as liquid and saturated vapor phases in the flash tank. The liquid refrigerant enters the lower-stage expansion valve and then circulates through the evaporator before entering the suction side of compressor, while the saturated-vapor refrigerant is injected into the intermediate pressure port of compressor. So the conventional superheat adjustment via the thermostatic expansion valve (TEV) is no longer viable. The use of electronic expansion valve (EEV) has been deemed more suitable for FTC. A liquid level sensor has been used to measure the liquid refrigerant level in the flash tank, which works as feedback for the EEV control; however, this would increase the overall system cost significantly (Xu et al. 2011a).



(a) FTC vapor injection for heat pump (b) ESC for FTC vapor injection for heat pump

Figure 1: FTC Vapor Injection based Heat Pump Water Heater Operation with ESC.

There have been some recent efforts made to control the FTC systems. For a FTC heat pump system, Xu et al. (2011b) propose to use an electric heater in the vapor injection line in order to reinforce certain degree of superheat as a control signal for the upper-stage EEV. Both transient and steady-state system behaviors were studied. The proposed cycle control strategy was found to be able to provide reliable control to the system. Qiao et al. (2015) study the dynamic behavior of an FTC vapor-injection heat pump system from a numerical simulation perspective. A first-principles transient model is developed for the heat transfer and flow processes involved. The lumped-parameter models are developed for the flash tank and expansion devices. Then, the model is evaluated in detail with experimental data. They show that the EEV opening has a significant impact on the system performance and the liquid level in the flash tank, but exhibits little effect on the suction pressure. Ko et al. (2013) study an air-to-water heat pump (AWHP) system with an inverter-driven two-stage rotary compressor and an FTC VI cycle. By optimizing the volume ratio of the two-stage rotary compressor, the AWHP system showed a 48% increase in heating capacity and a 36% increase in COP at water temperature of 60°C and ambient temperature of −15°C, compared to the conventional AWHP.

In spite of these progress, the lack of effective control logic remains a critical problem for the FTC without availability of superheat. Adjustment of the degree of superheat in the VI loop is not a desirable control strategy, as the FTC is designed to inject saturated gas (with zero superheat) into the compressor. Heating the outlet gas from the flash tank to achieve some degree of superheat induces more energy consumption, increases the system complexity and cost, and effectively undermines the system efficiency that is achievable for the original FTC design.

In this paper, we propose a novel control strategy for FTC vapor injection systems that features two respects: 1) the EEV in the VI loop is regulated to achieve a given setpoint of intermediate pressure, and 2) an online optimization or optimal control framework is used to maintain the optimum intermediate pressure for the VI loop in real time, which minimizes the power consumption (or maximizes the energy efficiency). Such control strategy does not need the use any additional device like a heating element, i.e. it would not affect the achievable optimum efficiency of the FTC system, but simply find the actual optimum. Also, such strategy can maintain the liquid level in the flash tank within the range of operational safety by reinforcing the liquid level requirement as a state constraint for the underlying real-time optimization algorithm being implemented.

In particular, we adopt the extremum seeking control (ESC) as a model-free real-time optimization solution to realize the proposed control strategy. ESC is a dynamic gradient search method with an online gradient estimation realized by a dither-demodulation scheme (Tan et al. 2010), which has been applied to a number of heating, ventilation and air conditioning (HVAC) systems in the past decade (Li et al., 2010; Burns et al., 2012; Li et al., 2013; Hu et al., 2015). For ESC applied to an FTC based heat pump water heater, the intermediate pressure setpoint of the injection-loop vapor is used as the manipulated input of ESC, while the total power consumption of the system is the only feedback. The opening of upper EEV is used to regulate the intermediate pressure, and the water outlet temperature is regulated by the compressor capacity.

The remainder of this paper is organized as follows. The dynamic simulation model of the FTC based heat pump system is described in next section. Section 3 reviews ESC principle and design guidelines. Simulation results are presented in Section 4. Section 5 concludes the paper with future work discussed.

2. DYNAMIC SIMULATION MODELING OF FTC BASED VI ASHP SYSTEM

For evaluating the proposed control strategy, a Modelica based dynamic simulation model of an FTC-VI ASHP is developed using Dymola (Dassault Systèmes, 2017) and TIL Library (TLK-Thermo, 2017), with the schematic shown in Figure 1. The water outlet temperature opening of the upper EEV by an inner-loop proportional-integral (PI) controller, and the hot-water outlet temperature setpoint is regulated by the compressor by another PI controller. The intermediate pressure setpoint as the input of the ESC, and the total power consumption is the only feedback needed. Two dynamic scroll compressors are combined as a quasi-secondary compression to model the vapor-injection compressor. A tube-and-tube condensing heat exchanger is employed to reject the heat to the water. A fin-and-tube evaporator is used as the outdoor unit heat exchanger. The lower expansion valve is used in the main loop with another PI controller to make sure a proper degree of superheat is maintained for the primary loop.

The flash tank is an equipment that it can separate the liquid-vapor refrigerant mixture that enters the flash tank and then exits as single-phase with the different port. In this study, a Modelica based transient model of the flash tank is developed by enhancing the *Separator* model in TIL with the modeling framework by Qiao et al. (2015). The flash tank is modeled as an adiabatic volume with ideal mixing process, and the pressure drop is neglected. Transient energy and mass balances are formulated as

$$\frac{dh}{dt}=\frac{1}{\rho V}\left(\dot{m}_{in}(h_{in}-h)+\dot{m}_{liq}(h_{liq}-h)+\dot{m}_{gas}(h_{gas}-h)+V\frac{dp}{dt}\right) \tag{1a}$$

$$V*\frac{d\rho}{dt}=\dot{m}_{in}+\dot{m}_{liq}+\dot{m}_{gas} \tag{1b}$$

The normalized liquid level of the flash tank δ_{liq} can be found as

$$\delta_{liq}=\frac{H_{liq}}{H}=\frac{\rho}{\rho_{liq}}(1-q)=\frac{(h_{gas}-h)\rho}{\rho_{liq}(h_{gas}-h_{liq})} \tag{2}$$

where h_{in}, h_{liq} and h_{gas} denote the enthalpies in the inlet, liquid outlet and gas outlet of the flash tank, respectively. h denotes the mass-based refrigerant mean enthalpy in flash tank. m_{in}, m_{liq} and m_{gas} denote the mass flow rates at the inlet, liquid outlet and gas outlet of the flash tank, respectively. ρ is the average density in the flash tank, ρ_{liq} is the density at the liquid outlet, H_{liq} is the height of liquid in the tank, H is the height of the tank, V is the volume of the flash tank, and q is the steam mass fraction. Table 1 shows the specifications for the FTC ASHP being simulated.

Table 1: Design Specifications of Major Components of IHXC

Components	**Design Specifications**
1st Compressor	Scroll compressor; displacement: 72×10^{-6}m^3; variable speed
2nd Compressor	Scroll compressor; displacement: 30×10^{-6}m^3; variable speed
Condenser	Tube-in-tube; counter flow; copper; refrigerant tube: ϕ = 7.92mm; parallel tubes 7; water tube: cross sectional area = 577.7 mm^2; perimeter = 325mm; parallel tubes 1; length = 4.5m.
Evaporator	Fin-and-tube; aluminum; length of finned tubes 0.8m; number of serial tubes 3; distance between serial tubes 22mm; number of parallel tubes 16; distance between parallel tubes 25.4mm; thickness of fins 0.2mm; distance between fins 2.2mm; inner diameter of tubes 7mm; thickness of tube walls 1.5mm; number of parallel tube side flows = 6.
Flash tank	Height 0.32m; Diameter 0.07m; Volume 0.0015m^3.

3. ESC DESIGN FOR FTC BASED VAPOR INJECTION ASHP

3.1 Overview of Extremum Seeking Control

ESC deals with the online optimization problem of finding an optimizing input $u_{opt}(t)$ for the generally unknown and/or time-varying cost function $l(t, u)$ (Krstic 2000; Rotea 2000). As illustrated in Figure 2, a pair of dither-demodulation signals are used along with high-pass and low-pass filters to extract the gradient information. Closing the loop with integral controller can drive the input to optimality if the closed loop system is stable. A typical design guideline for ESC follows (Krstic 2000): 1) perform open-loop step test to estimate the input dynamic; 2) The dither frequency should be chosen well within the bandwidth of the input dynamics. 3) the dither amplitude should be chosen such that the dithered output has sufficient signal-to-noise ratio at the dither frequency; 4) the dither frequency is generally located in the pass band of the high-pass filter and in the stopband of the low pass filter; 5) The dither-demodulation phase difference integral gain should be chosen to guarantee the asymptotic stability based on some estimate of the input/output dynamics and the Hessian of the static map near the equilibrium.

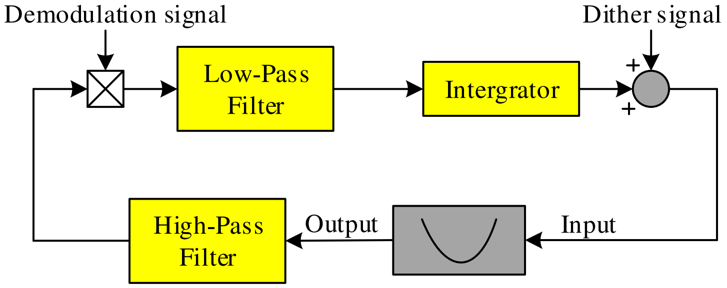
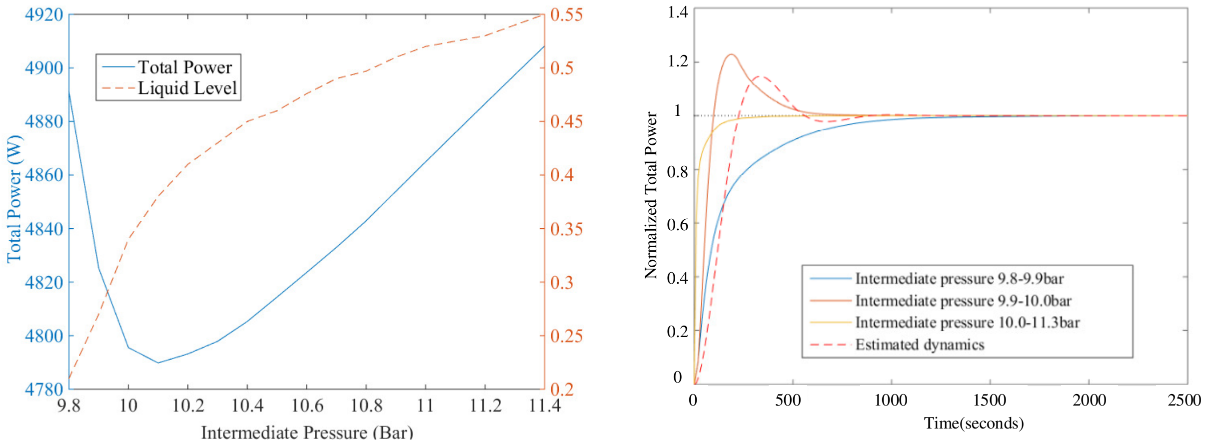


Figure 2: Block diagram of Extremum Seeking Control

3.2 ESC Design for FTC based Vapor Injection Heat Pump

The steady-state characteristic of the FTC heat pump system is first evaluated under a fixed condition. The hot water inlet temperature is fixed at 50°C and the hot-water mass flow rate is set to be 0.5 kg/s. The outlet water temperature is regulated to 55°C by compressor speed control via a PI controller, i.e. the total heat transfer rate across the condensing heat exchanger is approximately constant. The ambient air temperature and relative humidity are set to be -20°C and 50% respectively, and the mass flow rate of evaporator fan is set to be 1.4 kg/s. The primary-loop superheat is set to be 5°C.



(a) Static map of total power vs. intermediate pressure (b) Input dynamic estimate via normalized step response

Figure 3. Static and dynamic characteristics of FTC vapor injection heat pump water heater

Fig. 3(a) shows the relationship between intermediate pressure, liquid level and total power, we can see an optimal intermediate pressure and liquid level exist for the FTC ASHP for minimum power consumption, and the liquid level increases with the intermediate pressure. As we mentioned above, the liquid level is very sensitive to the intermediate pressure that will be obtained by regulating the opening of upper expansion valve through the PI controller. With several open-loop step tests as shown in Fig. 3(b), the input dynamics is estimated as

$$\hat{F}_I(s) = 0.011^2/(s^2 + 2\times0.52\times0.011s + 0.011^2) \tag{3}$$

The dither frequency is chosen as 0.75*10^{-4} Hz, the high-pass and low-pass filters are chosen as $F_{HP}(s) = s^2/(s^2 + 2\times0.8\times0.001s + 0.001^2)$ and $F_{Lp}(s) = 0.0025^2/(s^2 + 2\times1.9\times0.0025s + 0.0025^2)$, respectively. The dither amplitude is selected as 4000Pa.

4. SIMULATION RESULTS

The proposed control strategy is evaluated under both fixed and variable ambient conditions.

4.1 ESC under Fixed Condition

ESC is first evaluated under the condition that has been used for ESC design as described in the previous section, i.e. the ambient temperature is fixed at −20°C. Figure 4 shows that ESC starts at t = 1 hr with the initial intermediate pressure of 9.8 bar, which corresponds to the initial liquid level of 21% and the initial effective flow area of 5.34 × 10^{-7} m^2 for the upper EEV. After approximate 4000 seconds, the optimal intermediate pressure at 10.2 bar is reach, which corresponds to the optimal liquid level of 41.6%, and the effective flow area of the upper EEV increase to 6.69 ×10^{-7} m^2.

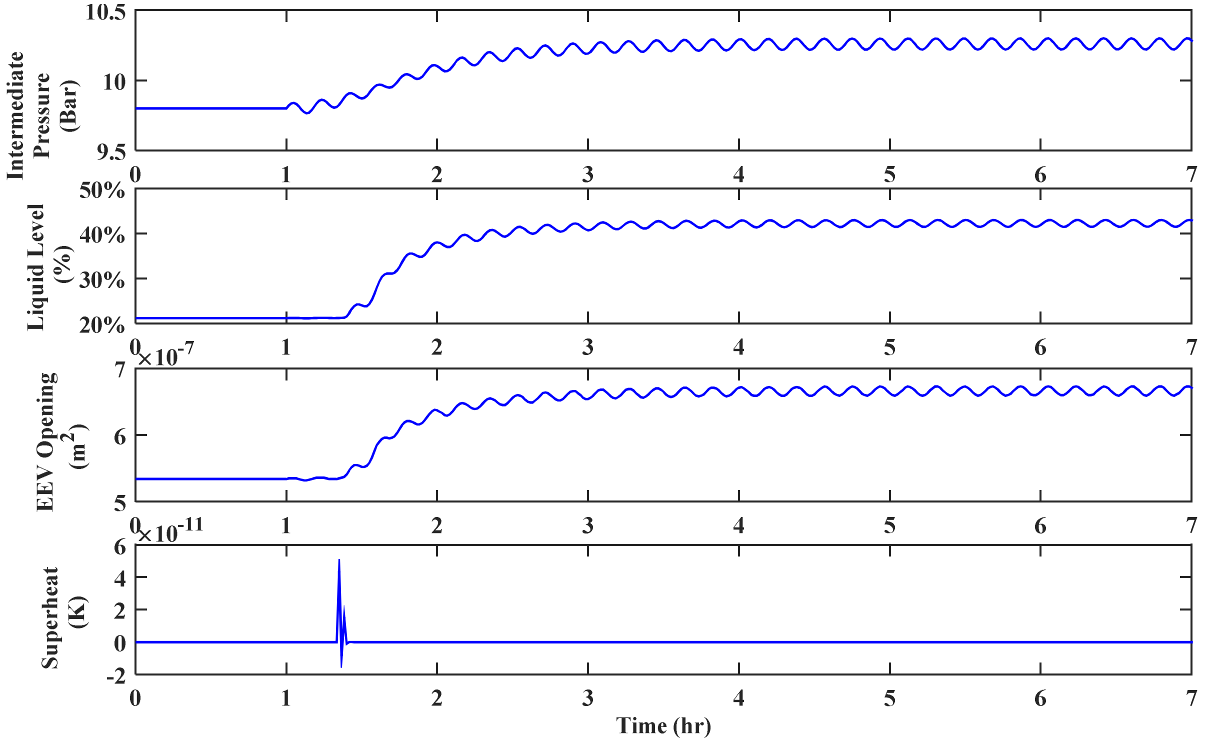


Figure 4. Trajectories of intermediate pressure, liquid level, upper expansion valve opening and superheat for ESC simulation under fixed ambient temperature

Figure 5 shows that the total power drops from 4996.1 W to 4890.9 W, and the COP increases from 2.14 to 2.18. Meanwhile the heat capacity remain the same because of the frequency conversion by PI controller. Compared to the estimated optimum in the calibrated static map, the steady-state error is about 2% for both the intermediate pressure and liquid level. These results reveal that ESC can effectively optimize intermediate pressure setpoint via EEV adjustment for minimizing the power consumption without violating the load demand. The extremum seeking process also leads to the optimal liquid level in the flash tank. Also, the liquid level is seen to increase from 21% to 41.6%, which is a reasonable level for operational safety. It is noteworthy that the superheat has been kept around zero throughout the simulation period, indicating that the control method that we have proposed can optimize the efficiency of FTC heat pump system without the need to adjust the superheat.

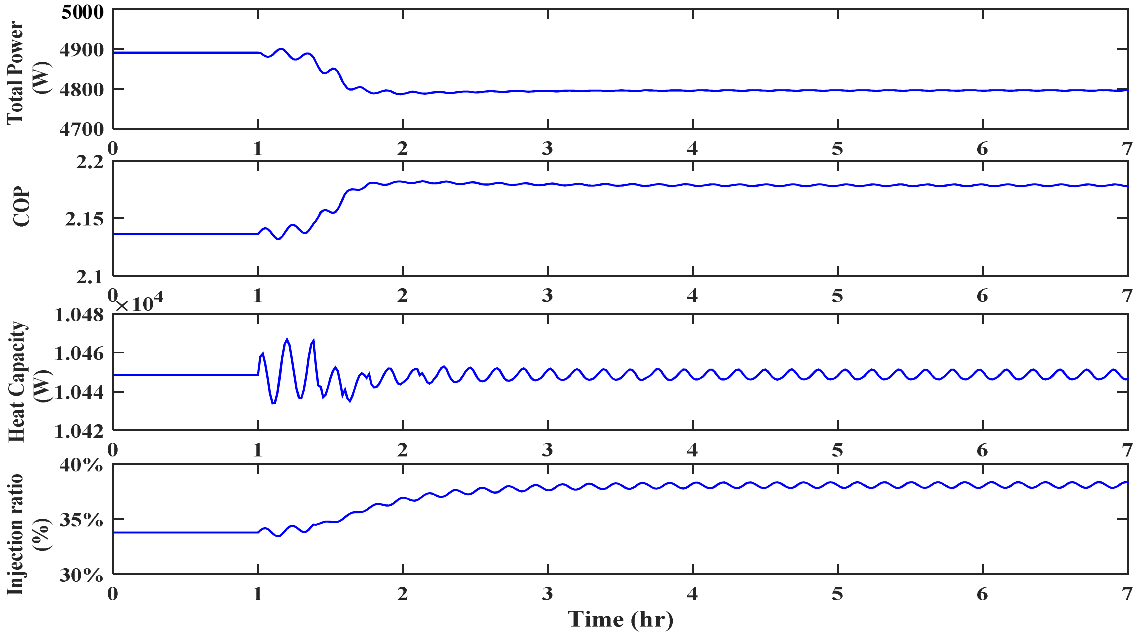


Figure 5 Trajectories of total power, COP, heat capacity and injection ratio for ESC under fixed ambient temp

4.2 ESC under Variable Ambient Condition

The ESC controller is then tested under a staircase profile of ambient temperature, as shown in Figure 6: starting from -20℃, going up to -18℃, -16℃ and then returning to -20℃, each change being a 500-sec ramp. ESC starts at t = 1 hr. The intermediate pressure found by the ESC is converging to the respect optimal values of 10.25, 10.81, 11.39 and 10.25 bar, respectively, under the different ambient temperature.

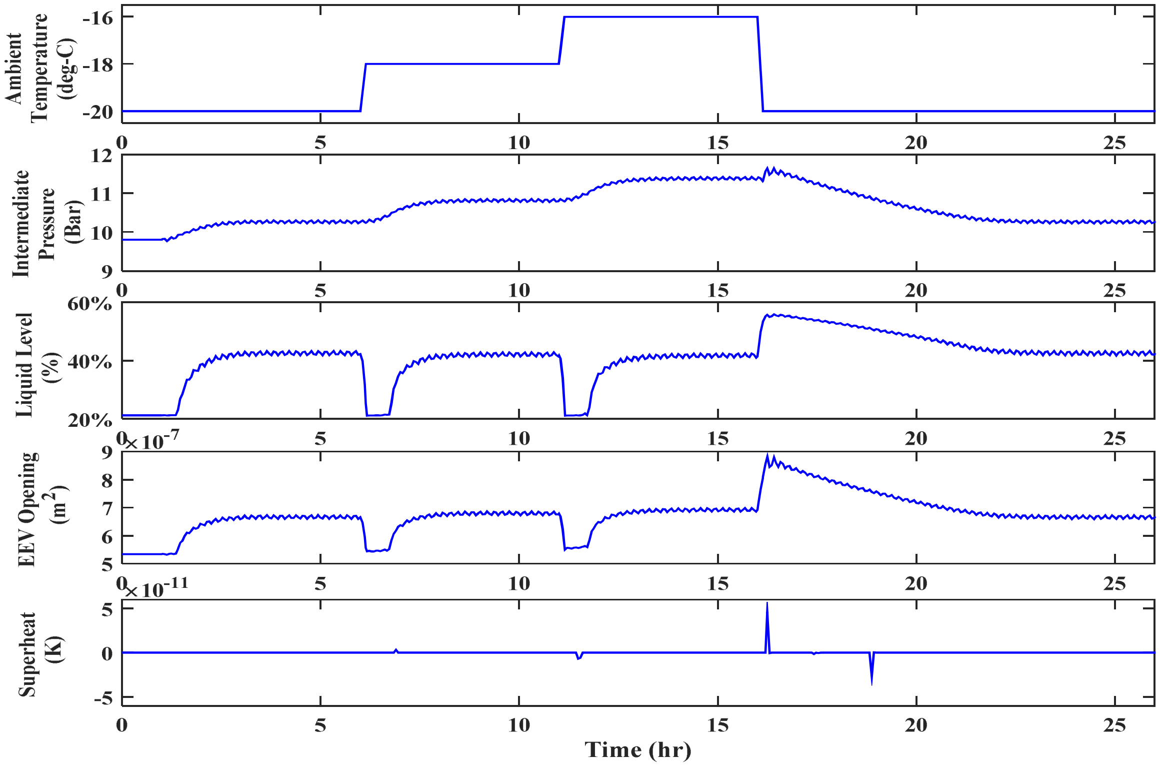


Figure 6 Trajectories of intermediate pressure, liquid level, upper expansion valve opening and superheat for ESC simulation under variable ambient temperature

Notice that the actual optimum values were found by a simulation based optimization procedure using genetic algorithm which is built in Dymola. Corresponding to these changes in the intermediate pressure, the liquid level was stabilized at 42.4%, 42%, 41.5% and 42.4%, respectively, i.e. demonstrating little variations. The liquid level is known as a critical parameter for FTC operation. If the liquid level is too low, the COP of system will be deteriorated, resulting in a high discharge temperature and pressure that will be harmful for the heat pump, especially in some extreme cold area. If the liquid level is too high, liquid refrigerant will flush to the injection port of the compressor and induce damage. The liquid level is shown to be kept at the safe and stable range throughout by making use of the ESC method.

As shown in Figure 7, the minimum total power and the maximum COP of the heat pump can be obtained under different ambient temperatures. The total power converged to the respective optimum values at 4795.9, 4685.7, 4581.8 and 4796.6 W, respectively. The COP converged to the respective optimum of 2.18, 2.23, 2.28 and 2.18. In addition, we can see that the heat capacity was kept the same throughout the whole simulation period. The vapor injection ratio was 38%, 37%, 36% and then back to 38%.

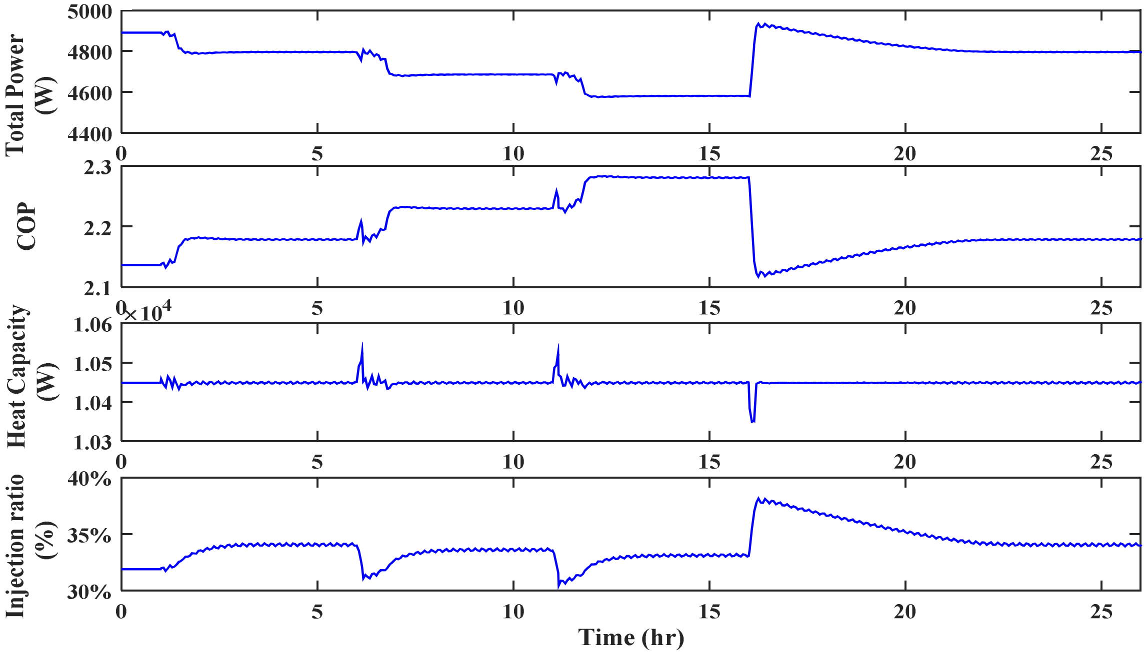


Figure 7 Trajectories of total power, COP, heat capacity and Injection ratio for ESC under variable ambient temp

5. CONCLUSION

In this paper, we propose a novel control strategy for the FTC vapor injection ASHP system. The system efficiency can be maximized by searching for the optimum intermediate pressure setpoint which is regulated by the upper EEV actuation. The ESC control strategy is used as a model-free real-time optimization framework to realize such objective. Simulations under both fixed and variable ambient temperatures have validated the effectiveness of the proposed method. It reveals that such control strategy can optimize the system efficiency with the vapor injection line superheat maintained at zero, which indicates that no comprise is needed regarding the achievable performance with the FTC vapor injection. Also, the liquid level of FTC is shown to be kept in a range for safe operation. These results have indicated that the proposed control strategy can greatly facilitate the operation of FTC vapor injection based heat pump systems, which would greatly facilitate the ramification of such technology. More simulations are carried out under way to demonstrate that constrained ESC can prevent a too low or too high liquid level from occurring. Also, work is under way to improve the ESC algorithm for achieving more consistent performance under different initial conditions.

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