Feasibility study on using evaporator condensate to subcool refrigerant in a vapor-compression refrigeration system

Kiattisak Roonprasang¹, and Eakasit Sritham^{1,*}

¹Food Engineering Department, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand

Abstract. A computer simulation based on MATLAB was developed to investigate the effectiveness of using evaporator condensate to subcool refrigerants in a vapor-compression refrigeration system. Three different types of refrigerant including R22, R410a, and R134a were studied. The simulation clearly showed the effectiveness of the technique to subcool refrigerant using evaporator condensate. Throughout the RH range of surrounding in this study, 40%-100%RH, the vapor-compression model system using R22 as a refrigerant provided the highest COP linearly ranging from 3.40 to 3.76. The greatest improvement in COP was found in the model system with R410a where the COP values increased by 3.33% to 15.36.

1 Introduction

Refrigeration plays an essentially important role in food industry. It involves in transportation and storage of both raw materials and final products, and in a number of processing lines. Hence, any improvement in the efficiency of a refrigeration system—known as the coefficient of performance (COP), would help reducing the production cost of food products and consequently increasing the market potential of the products.

Refrigeration systems widely adopted in food industry are of a vapor-compression type which mainly includes a compressor, a condenser, an expansion valve, and an evaporator. The COP is defined as a ratio between evaporator heat load and compressor work [1-2]. A common technique to improve COP is done by subcooling liquid refrigerant after exiting a condenser using the refrigerant from evaporator outlet, theoretically in the state of saturated vapor. A subcool unit is basically sort of a heat exchanger. Once absorbed heat from liquid refrigerant during passing through a subcool unit, the refrigerant would turn into superheat causing the increase of compressor work—thing to be sacrificed when doing subcool this way.

Under tropical climate like in Thailand, refrigeration systems release considerable amount of condensate from evaporator. The part of evaporator workload spent to condensate moisture in the air is quite a large portion. Accordingly, there seems to be a room to improve the efficiency of a vapor-compression refrigeration system if we could gain back the energy by using evaporator condensate to subcool liquid refrigerant after exiting a condenser. Once subcooled, the enthalpy of liquid refrigerant would decrease, and, theoretically, the vapor quality of the refrigerant after exiting an expansion valve would lower. These two effects would yield a result in

the same direction—increasing the ability of evaporator to absorb heat, and the higher COP could be expected.

This study was aimed at proposing a technique to improve the efficiency of a vapor-compression refrigeration system by using an evaporator condensate to subcool the refrigerant. A schematic diagram of the proposed systems is given in Fig. 1 along with the P-H diagram in Fig. 2.

2 Methodology

2.1 Computer simulation

Computer simulation was developed on MATLAB®. Three different refrigerants including DuPont™ Freon® 22 (Chlorodifluoromethane), DuPont™ Suva® 410A (R-410-A), and HFC-134A (1,1,1,2-tetrafluoroethane) were considered. Thermal properties data base of these refrigerants [3-5] were also created in MATLAB. A computer function module that was written is capable of fetching the refrigerant properties from data base and performing interpolation. The surrounding humidity shall directly affect the amount of condensate being released from an evaporator, and hence the effectiveness of the proposed technique—subcooling. Hence, the range of a surrounding humidity was set to cover that of the year-round climate condition in Thailand, approximately 40% – 100%RH [6].

2.2 Parameters for a refrigeration model system in the simulation

The parameters for a vapor-compression refrigeration model in this simulation were set similar to those found in common residential air conditioning systems as follows.

* Corresponding author: ekasit.sr@kmitl.ac.th

The evaporator heat load (Q_{ev}) was 26,000 BTU/hr (7.6198 kW), the inlet and outlet air temperatures at the evaporator were, respectively, 27°C and 4°C (T_{ev}). The surface area and the operating temperature of the condenser (T_{cond}) were 0.114 m² and 50°C, respectively. The velocity of air flowing through a condenser was assumed to be 2 m/s. The ambient temperature was fixed at 35°C.

Fig. 1. A schematic diagram of vapor-compression refrigeration system with a subcool unit. Adapted from [1-2].

Fig. 2. P-H diagram for a vapor-compression refrigeration system: with and without subcooling. Adapted from [1-2].

2.3 Calculation

2.3.1 Refrigerant flow rate

The total flow rate of refrigerant (m_R) was calculated as follows:

$$m_R = m_v + m_l \quad (1)$$

$$m_l = Q_{ev}/q_{ev} \quad (2)$$

$$m_v = (m_l \cdot x)/(1-x) \quad (3)$$

where m_v and m_l are flow rates of vapor and liquid refrigerant (kg/s), respectively, and x is a vapor quality.

2.3.2 Properties of refrigerant in a vapor compression cycle

State 1: Saturated vapor

$$P_1 = P \text{ at } T_{ev}=4^\circ\text{C} \quad (4)$$

$$h_1 = h_g \text{ at } P_1 \quad (5)$$

$$s_1 = s_g \text{ at } P_1 \quad (6)$$

State 2: Superheated vapor

$$P_2 = P \text{ at } T_{cond}=50^\circ\text{C} \quad (7)$$

$$h_2 = h \text{ at } P_2 \text{ and } s_1 \quad (8)$$

State 3: Saturated liquid

$$P_3 = P_2 \quad (9)$$

$$h_3 = h_f \text{ at } P_3 \quad (10)$$

State 4: Totally saturated liquid

$$h_4 = h_f \text{ at } P_3 \quad (11)$$

where h is the enthalpy of refrigerant (kJ/kg) and s is the entropy of refrigerant (kJ/kg.K) [2]. Subscripts g and f represent the states of saturated liquid and saturated vapor, respectively.

2.3.3 Subcooling process

Given q as the amount of heat being exchanged at a subcool unit and ε is the effectiveness of heat exchanger/subcool unit [7]:

$$q = \varepsilon q_{\max} \quad (12)$$

$$q_{\max} = C_R(T_4 - T_{W1}), \text{ when } C_R < C_W \quad (13)$$

$$\text{or } q_{\max} = C_W(T_4 - T_{W1}), \text{ when } C_W < C_R \quad (14)$$

C_R is the specific heat of refrigerant; $C_R = m_R c_{p,R}$, where $c_{p,R} = h_4/T_{cond}$. C_W is the specific heat of condensate $C_W = m_W c_{p,w}$ where $c_{p,w} = 4.2166$ kJ/kg°C. The ε was assumed to be 0.8 in this study.

Then, from Fig. 1., the enthalpy of refrigerant after subcooling (state 5) could be calculated using Eq.15.

$$q = m_R(h_4 - h_5) \quad (15)$$

2.3.4 COP of the system with subcooling

In order to calculate the COP of a system with subcooling, a new state of refrigerant before entering an evaporator needs to be determined. Details of the calculation were given below;

$$x_{\text{subc}} = (h_6 - h_{f@P6}) / h_{fg@P6} \quad (16)$$

$$m_{v,subc} = x_{subc}(m_R) \quad (17)$$

$$m_{l,subc} = m_R - m_{v,subc} \quad (18)$$

$$q_{ev} = h_1 - h_6 \quad (19)$$

$$w_{comp} = h_2 - h_1 \quad (20)$$

$$Q = m_l(q_{ev}) \quad (21)$$

$$W = m_R(w_{comp}) \quad (22)$$

$$COP = Q/W \quad (23)$$

3 Results and Discussion

The results obtained with computer simulation are as follows.

3.1 The dependence of condensate flow rate on relative humidity of surrounding air (RH)

The condensate flow rate at evaporator strongly related to the humidity of surrounding air. The rate linearly increased with RH. The calculated flow rate was in a range of 0.001 – 0.0046 kg/s when the RH was set to 40% – 100% (Fig. 3). It was found that condensate flow rate increased for 6×10^{-5} kg/s at every percentage increase of RH.

Fig. 3. The relationship between mass flow rate of a condensate and relative humidity of the surrounding

3.2 Effects of RH on vapor quality of refrigerants

The simulation showed that vapor quality of refrigerant before entering an evaporator was linearly dependent on RH for every type of refrigerants. This was as expected since the greater flow rate of condensate would be obtained when the system is operated under higher RH atmosphere (see also Sec.3.1 above). The higher amount of condensate would exhibit the greater subcooling effect.

The vapor quality before entering an evaporator gradually decreased with the increasing RH, for every

refrigerant. The lowest vapor quality was found in the model system with R410a, while the system with R134a showed the highest vapor quality. The vapor quality fell in the ranges of 0.1617-0.2075, 0.2430-0.2794, and 0.2993-0.3308, for the systems with R410a, R22, and R134a, respectively (Fig. 4).

Fig. 4. The vapor quality of refrigerants before entering the evaporator and relative humidity of the surrounding

3.3 Performance of vapor-compression refrigeration system with subcool unit

As for comparison, the simulated COP values for typical (without subcooling) vapor-compression refrigeration systems were 3.31, 3.22, and 3.01, respectively, when using R22, R410a and R134a as refrigerants.

It was found that the COP obtained for the model systems with subcooling linearly increased with the increasing RH. The model system with R22 and R410a refrigerants provided comparable COP throughout the range of RH considered in this study. The COP ranged from 3.40 to 3.76, and from 3.33 to 3.72, for the system with R22 and R410a, respectively. The model system with R134a showed lower COP, in a range of 3.09–3.39. In general, the rates of increase in COP values with RH appeared to be similar for all three different types of refrigerant (Fig. 5).

Though the model system with R22 could provide the highest COP value, the greatest improvement in COP, as compared to that of the system without subcooling, was obtained from the model system using R410a as a refrigerant. The COP of R401a model system increased by 3.33% to 15.36%. It could be also seen that, the higher the RH, the greater rate of improvement in COP the system exhibited. The rate of change of percentage increase of COP was 0.201% per %RH (Fig. 6).

The improvement of COP for the model systems with R22 and R134a were rather similar, with the values fell in a ranges of 2.96%–13.64%, and 2.75%–12.65%, respectively. The rates of change of percentage increase of COP were 0.178% and 0.165% per %RH, respectively, for the system with R22 and R134a (Fig. 6).

Fig. 5. The dependence of COP for a vapor-compression refrigeration model system (with subcool unit) on RH

Fig. 6. The percentage increase in COP as a function of RH for a vapor-compression refrigeration system with three different refrigerants

4 Conclusions

A computer simulation developed in this study clearly showed the effectiveness of a technique to subcool refrigerant using the condensate from an evaporator. Throughout the RH range of surrounding considered in this study, 40%–100%RH, the vapor-compression model system using R22 as a refrigerant provided the highest COP values which linearly ranged from 3.40 to 3.76. The greatest improvement in COP was found in the model system with R410a as a refrigerant, where the COP values increased by 3.33% to 15.36.

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