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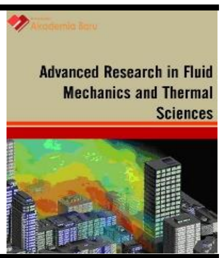

Evaluation of Subcooling with Liquid-Suction Heat Exchanger on the Performance of Air Conditioning System Using R22/R410A/R290/R32 as Refrigerants

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ABSTRACT

This paper presents a numerical study to investigate the effect of subcooling with liquid-suction heat exchanger (LSHX) on the performance of air conditioning system using R22, R410A, R290 and R32 as refrigerants. In the near future, R290 and R32 refrigerants are projected to replace R22 and R410A as working fluids in the residential air conditioning. In this study, four parameters, i.e., the refrigerating effect, compressor work, COP and discharge temperature were investigated. In the numerical modelling, the evaporating and condensing temperatures were assumed constant at 5°C and 40°C, respectively. The results showed that the COP improvements increased with the increase in the subcooling. R32 and R290 had the lowest and the highest COP improvement when subcooling was applied, i.e., 3.3% and 5.3% for subcooling of 5K and 6.2% and 10.2% for subcooling of 10K, respectively. Due to low global warming potential and almost identical refrigerant properties as compared to R22, system with LSHX and R290 has huge commercial potential as a replacement for conventional system in the future.

Keywords:
Air conditioning, cooling capacity, COP improvement, R290, R32

1. Introduction

In hot and humid conditions, air-conditioning system is required to provide good indoor air quality as well as thermal comfort to building users [1]. A part from that, an increased demand of having air-conditioning system and awareness to protect the environment from ozone depletion, global warming and etc. had led to two major issues; using energy efficient air-conditioning system and using friendly refrigerant as working fluid for the air-conditioning system itself.

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Nowadays, refrigerants of R22 and R410A are widely used as working fluid for residential air conditioner (A/C) in South East countries like Malaysia and Indonesia. However, their global warming potential (GWP) is considered high. Therefore, these refrigerants (R22 and R410A) have to be phased out and replaced by more environmental friendly refrigerant. Two of the potential candidates are R290 and R32. The properties of normal boiling point and critical temperature for R290 are almost identical with R22, while R32 is almost identical with R410A as shown in Table 1. It can also be seen from Table 1 that R22 and R410A have high global warming potential (GWP), whereas R290 and R32 have low GWP. In addition, Figure 1 shows that the curve line of pressure versus saturation temperature is nearly coincident between R22 and R290, and between R410A and R32. As a result, significant potential is identified for R290 and R32 to become alternative refrigerant for R22 and R410A, respectively in the future.

Table 1
Refrigerant properties [2,3]

Refrigerant	Composition	Normal Boiling Point (°C)	Critical Temperature (°C)	GWP (100-year)	ODP
R22	Pure fluid	-40.8	96.2	1700	0.055
R410A	R32(50%):R125(50%)	-51.5	72.5	1725	0
R20	Pure fluid	-42.1	96.7	3	0
R32	Pure fluid	-48.3	78.1	675	0

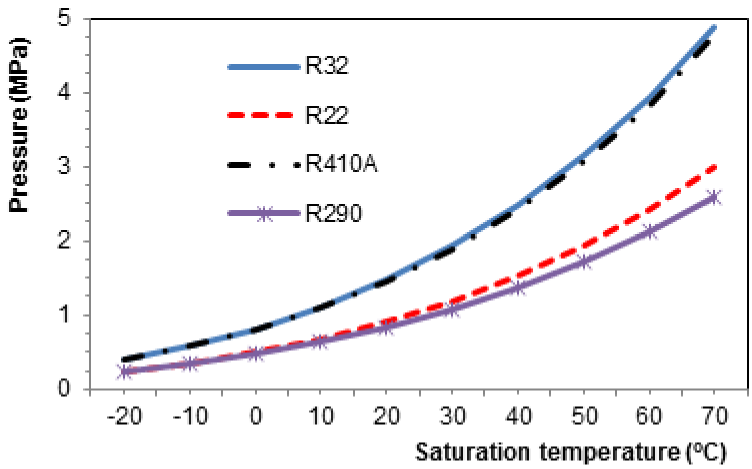
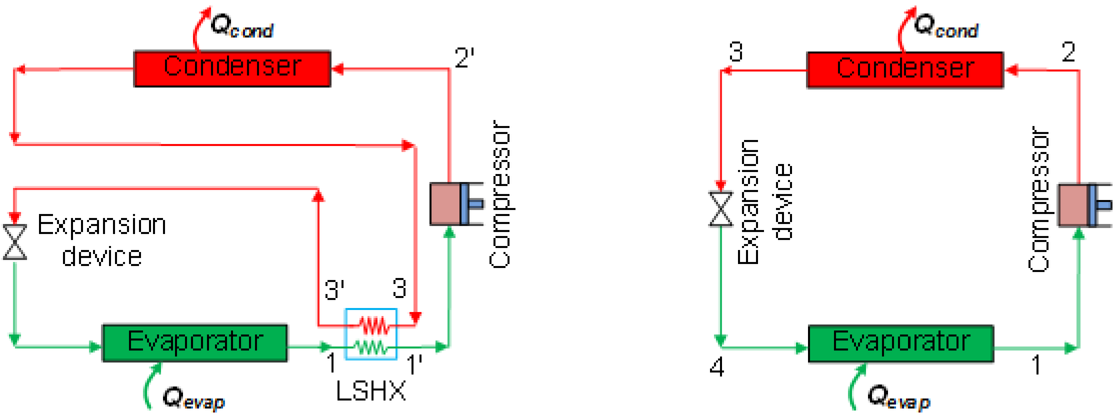


Fig. 1. Pressure versus saturation temperatures of R32, R22, R410A and R290

In general, there are several methods to improve the performance of a system, such as using an ejector as an expansion device [4-7], by inserting nanoparticles in refrigerant or in compressor lubricant to enhance the heat transfer process [8-10] and subcooling to increase the cooling capacity [11-21]. Furthermore, subcooling method can be categorized into four techniques/types, namely dedicated subcooling [11-13], integrated subcooling [14-16], condensate assisted subcooling [18] and using liquid-suction heat exchanger (LSHX) [19-21].

Figure 2 and 3 show schematic and *P-h* diagrams of basic cycle and cycle with LSHX of an air conditioning system. For basic cycle, point 1 and 3 are usually assumed to be saturated vapor and liquid, respectively. By using LSHX, heat from liquid line (the condenser outlet) will be transferred to the suction of the compressor. Then, point 3 moves to point 3′ (saturated liquid to sub-cooled liquid) and point 1 moves to point 1′ (saturated vapor to superheated vapor). The difference of temperature between point 3 and 3′, and between point 1 and 1′ are known as degree of subcooling and superheating. A part from that, an increase in cooling capacity from $(h_1 - h_4)$ to $(h_1 - h_{4'})$ as shown in Figure 3 is generated.

Consequently, it prevents vapor refrigerant from entering the expansion device and prevents the liquid refrigerant from entering the compressor. The disadvantage of using LSHX is an increase in the discharge temperature that is caused by the increase in the superheating in the compressor suction. As a result, the superheating will raise the compressor work. In other words, the increase in cooling capacity due to the use of LSHX is always followed by an increase in superheating. Due to this reason, the performance improvement of an air conditioning system depends on the amount of increment in cooling capacity and compressor work. If the increase in cooling capacity is higher than the increase in compressor work, the COP improvement will be positive, otherwise it will be negative.



(a) (b)

Fig. 2. Schematic diagrams of a vapor compression refrigeration cycle. (a) Basic cycle (b) Cycle with LSHX

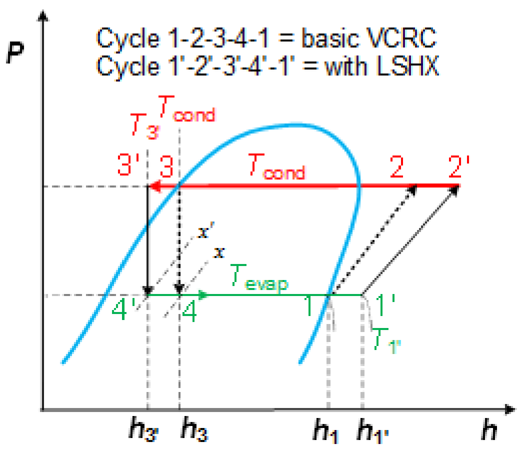


Fig. 3. *P-h* diagrams of vapor compression refrigeration cycle for basic system and system with LSHX

Numerical investigation on 38 different refrigerants in the refrigeration system using LSHX was carried out by Domanski *et al.,* [20]. They reported that refrigerants with low vapor molar heat capacity did not improve the COP as compared to the basic cycle. Furthermore, Mastrullo *et al.,* [22] numerically investigated the advantage of LSHX in the VCRC. They investigated 19 ozone friendly refrigerants in their study and varied the evaporating and condensing temperatures. They introduced a simple chart that allowed the estimation of the effectiveness of using LSHX in the VCRC for various working fluids and specific operating conditions. They also found that the advantage of LSHX was depending on the combination and operating conditions. The property of vapor heat capacity was the most influential on the performance improvement of VCRC.

Pottker and Hrnjak [17] extended their numerical investigation on the air conditioning system using LSHX with newly developed refrigerants known as R1234yf, R410A, R134a and R717 in 2015. They reported that the maximum COP improvements due to the optimum subcooling for R1234yf, R410A, R134a and R717 were 8.4%, 7.0%, 5.9% and 2.7%, respectively. Later, an experimental investigation on the air-conditioning system using LSHX was also carried out by Pottker and Hrnjak [19]. In their experiments, they tested the A/C system performances using R134a and R1234fy as refrigerants. Based on the experimental data, they reported that the COP increased up to 9% for R134a and up to 18% for R1234yf.

An experimental study was also performed earlier by Navarro-Esbri *et al.,* [21] to investigate the effect of subcooling using LSHX in VCRC using R22, R134a and R407C as working fluids. The experimental results showed the mass flow rate reduction occurred in R22 and R134a when LSHX was applied. However, although the mass flow rate decreased, the COP did not decrease because the increase in the cooling capacity using LSHX was slightly higher than the mass flow rate. Different results were also exhibited by R407C. As the mass flow rate and the cooling capacity increased, the COP improvement of R407C was the highest for the compression ratio below 5.

Recently, investigations on other friendly refrigerant such as natural refrigerant of CO_2 were also reported. It is because VCRC systems using CO_2 as refrigerant will have an operating temperature of the condenser above critical point. As a result, the application of subcooling on this system will generate better COP improvement as compared to using conventional refrigerant. Llopis *et al.,* [23] and Pitarch *et al.,* [24] reported that the use of subcooling on the CO_2 refrigerator enhanced the system performance up to 12%. Generally, the performance improvement of CO_2 is better than the conventional refrigerants such as R134a, R22, R32 and R290. However, the operation of above critical point leads to higher operating pressure of the system, especially for condenser. Consequently, more rigid and complex VCRC needs to be built, which leads to higher cost.

So far however, study focusing on suitability of R290 and R32 as alternative refrigerants for R22 and R410A for air conditioning system equipped with LSHX is yet to be conducted, at least to the point of authors' knowledge. Therefore, it is the aim of this article to numerically investigate the performance of the air conditioning system equipped with LSHX using R290 and R32 as alternative refrigerant for R22 and R410A.

2. Methodology

2.1 Thermodynamic Analysis of Liquid-Suction Heat Exchanger

Thermodynamics analysis by using LSHX in Figure 2 and 3 resulting in Eq. (1) – (8). The degree of subcooling ($T_{cond} - T_{3'}$) and the degree of superheating ($T_{1'} - T_{evap}$) are not the same due to the difference in specific heats of the vapor and liquid phases. An energy balance analysis of LSHX by using the effectiveness-NTU method can be utilized to predict the outlet temperatures of the hot refrigerant leaving LSHX ($T_{3'}$) and cold refrigerant leaving LSHX ($T_{1'}$). By assuming the LSHX in Figure 2(a) is well insulated, the actual heat transfer rate in the LSHX ($\dot{Q}_{act}$) is given in Eq. (1), where

$$\dot{Q}_{act} = C_c(T_{1'} - T_1) = C_h(T_3 - T_{3'}) \tag{1}$$

where C_c and C_h are heat capacity rates of refrigerant at suction compressor and liquid line (condenser outlet), respectively.

Meanwhile, by knowing that refrigerant at suction compressor and liquid line are from the same cycle, and due to continuity equation, then the refrigerant mass flow rate at suction compressor is equal to the refrigerant mass flow rate at the liquid line. As a result, Eq. (1) can be written as

$$q_{sub-cooling} = q_{superheated} = h_{1'} - h_1 = h_3 - h_{3'} \quad (2)$$

The cooling capacity per unit mass of refrigerant, q and compressor work per unit mass of refrigerant, w for basic cycle and cycle with LSHX can be expressed as in Eq. (3) – (6).

$$q_{basic} = h_1 - h_4 \quad (3)$$

$$q_{LSHX} = h_1 - h_{4'} \quad (4)$$

$$w_{basic} = h_2 - h_1 \quad (5)$$

$$w_{LSHX} = h_{2'} - h_{1'} \quad (6)$$

Then, the COP of basic cycle (COP_{basic}) and cycle with the effect of using LSHX (COP_{LSHX}) are expressed as in Eq. (7) - (8), where

$$COP_{basic} = \frac{h_1 - h_4}{h_2 - h_1} \quad (7)$$

$$COP_{LSHX} = \frac{(h_1 - h_4) + (h_4 - h_{4'})}{h_{2'} - h_{1'}} \quad (8)$$

2.2 Modelling Procedure

In this study, the effect of using LSHX on three parameters, i.e., the cooling capacity, the input power and the COP were investigated. The CoolPack and Refprop software [25] were utilized to determine the refrigerant properties. There are some assumptions where

- The LSHX is well insulated and therefore the actual heat exchange rate of LSHX can be given as in Eq. (2).
- The subcoolings are 5 and 10K. Subcooling of 0K represents basic VCRC.
- The evaporating and the condensing temperatures are 5°C and 40°C, respectively.
- The compressor isentropic efficiency is 0.7.
- The expansion process is isenthalpic and the superheating is not calculated as the refrigerant effect.
- The pressure drops in all of the components are ignored.

The objectives of the use of LSHX subcooling are to enhance the refrigerating effect and the COP. However, the increase in the refrigerating effect is always followed by the increase in superheating. As a result, it increases the compressor work. By assuming the continuity in refrigerant mass flow rate throughout the VCRC, the percentage of improvement in refrigerating effect, Q_{imp}, increment in compressor work, W_{inc} and the improvement in COP, COP_{imp} due to the use of LSHX subcooling are calculated using Eq. (9) – (11), respectively.

$$Q_{imp} = \frac{q_{LSHX} - q_{basic}}{q_{basic}} \tag{9}$$

$$W_{inc} = \frac{w_{LSHX} - w_{basic}}{w_{basic}} \tag{10}$$

$$COP_{imp} = \frac{COP_{LSHX} - COP_{basic}}{COP_{basic}} \tag{11}$$

3. Results and Discussion

3.1 Refrigerating Effect

Figure 4 illustrates the refrigerating effect versus subcooling for all four refrigerants. The figure shows that the refrigerating effect increases with the increase in the subcooling. It can be seen that the increments of the refrigerating effect due to subcooling are different for each refrigerant. The increment of the cooling capacity is represented by the slope line. R290 has the greatest slope line (4.61), follows by R32 (3.29), R22 (2.06) and R410A (2.01). It indicates that R290 has the largest potential to increase the refrigerating effect as compared to other refrigerants when LSHX is applied. The figure also shows that both R410A and R22 have almost identical slope line. It means that the increase in refrigerating effect of R410A and R22 is almost the same with the use of LSHX. However, the refrigerating effect per unit mass of refrigerant of R140A is slightly higher than R22 for the same subcooling. In addition, R290 not only has the largest slope line as compared to other refrigerants, but it also has the greatest refrigerating effect. For example, at subcooling of 5K, the refrigerating effects per unit mass of refrigerant for R290, R32, R410A and R22 are 296.9, 257.4, 175.1 and 167.6 kJ/kg, respectively.

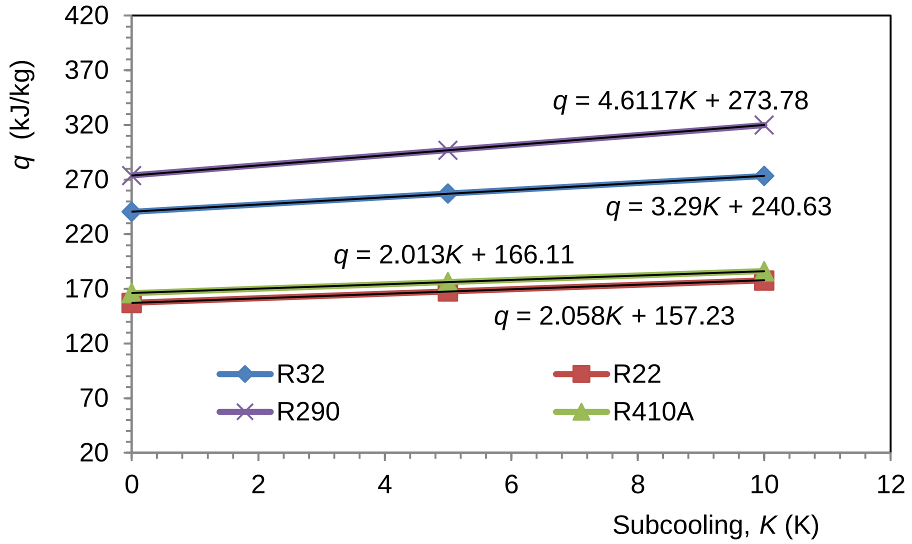


Fig. 4. The refrigerating effect versus subcooling

Figure 5 shows an increase of the refrigerating effect improvement with the increase in the subcooling for all four refrigerants. The smallest and the highest refrigerating effect improvements are R410A and R290, respectively. At subcooling of 5K and 10K, the refrigerating effect improvements for R410A are 6.3% and 12.5%, respectively, whereas the refrigerating effect improvements for R290 at subcooling of 5K and 10K are 8.5% and 16.8%, respectively. Based on these results, the use of LSHX subcooling is recommended for the air conditioner using R290 as refrigerant.

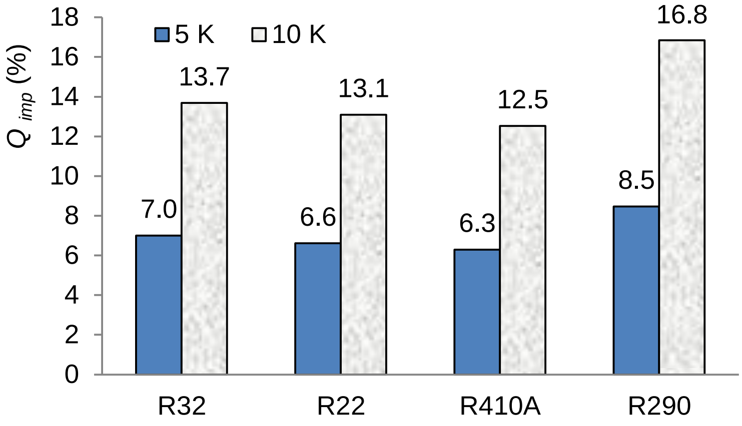


Fig. 5. The refrigerating effect improvement for four refrigerants

3.2 Compressor Work

It has been explained in the previous section that the use of LSHX subcooling will increase the compressor work due to the superheating occurrence in the suction of the compressor. Figure 6 illustrates the compressor work per unit mass of refrigerant for four refrigerants. The figure shows that the compressor work per unit mass of refrigerant increments due to subcooling are almost similar for four refrigerants. In addition, it can be seen that R22 and R290 have the highest and the smallest compressor work. Meanwhile, the compressor work of R22 and R410A are almost similar. As a result, the lines are almost coincided.

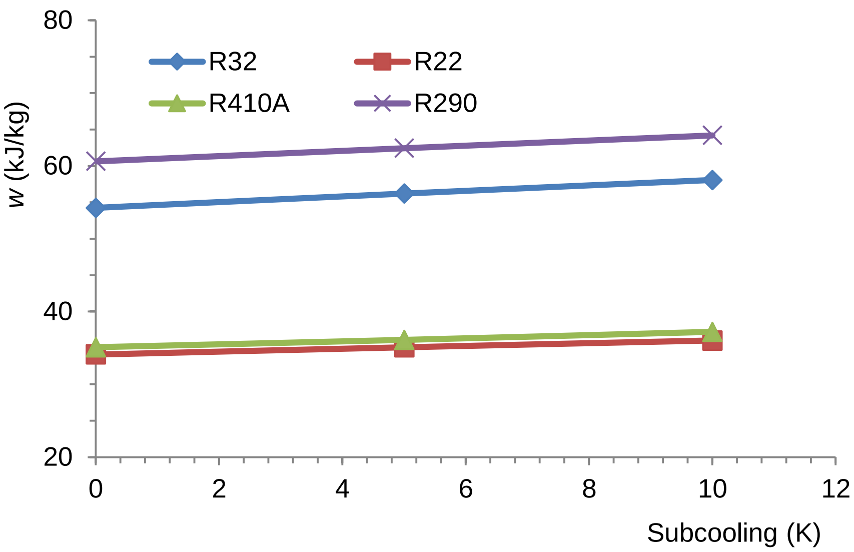


Fig. 6. The compressor work versus subcooling

Figure 7 shows the compressor work per unit mass of refrigerant increment increases as the subcooling increases. The values of compressor work per unit mass of refrigerant increment for subcooling of 10K are almost double the values of subcooling 5K. For instance, for R32, R22, R410A and R290, the compressor work increments for subcooling of 5K to 10K are 3.6% to 7.1%, 2.9% to 5.6%, 2.3% to 4.7% and 3.0% to 5.9%, respectively.

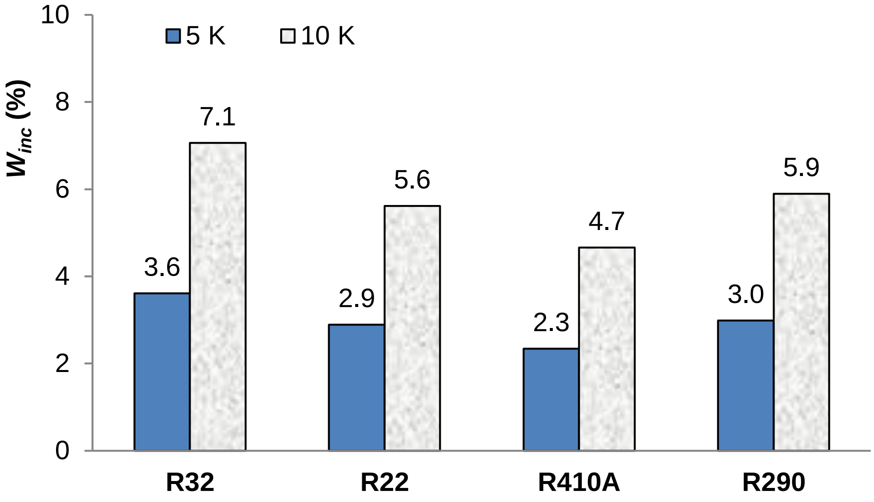


Fig. 7. The compressor input improvement for four refrigerants

3.3 Coefficient of Performance (COP)

The COP is widely used to represent the air conditioner performance. The better the air conditioner, the higher the COP. In general, to improve the COP, the refrigerating effect must be increased and the compressor work has to be decreased. COP improvement of the system will be positive if the refrigerating effect improvement is higher than the compressor work increment.

Figure 8 illustrates the A/C using R410A and R32 have the highest and the lowest COP, whether without or with the subcooling of 5K to 10K. The slope lines of Figure 8 represent the advantages of using LSHX subcooling. The figure shows that R290 and R32 have the highest and lowest the slope lines values of 0.046 and 0.027, respectively. It indicates that the use of LSHX yields minimum and maximum values of COP improvement for R32 and R290, respectively.

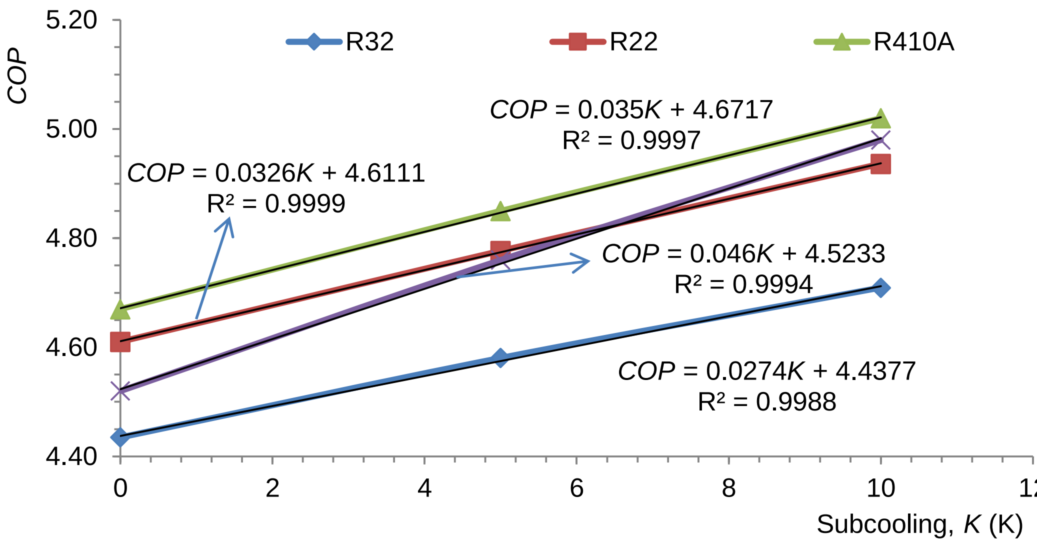


Fig. 8. The COP versus subcooling

Figure 9 illustrates the COP improvement increases when the LSHX subcooling is used on the A/C. In general, the COP improvement increases with the increase in the subcooling. These results confirm the results in Figure 8, where the steeper the slope line yields a higher COP improvement. For instance, the COP improvements with subcooling of 10K for R32, R22, R410A and R290 are 6.2%, 7.1%, 7.5% and 10.2%, respectively.

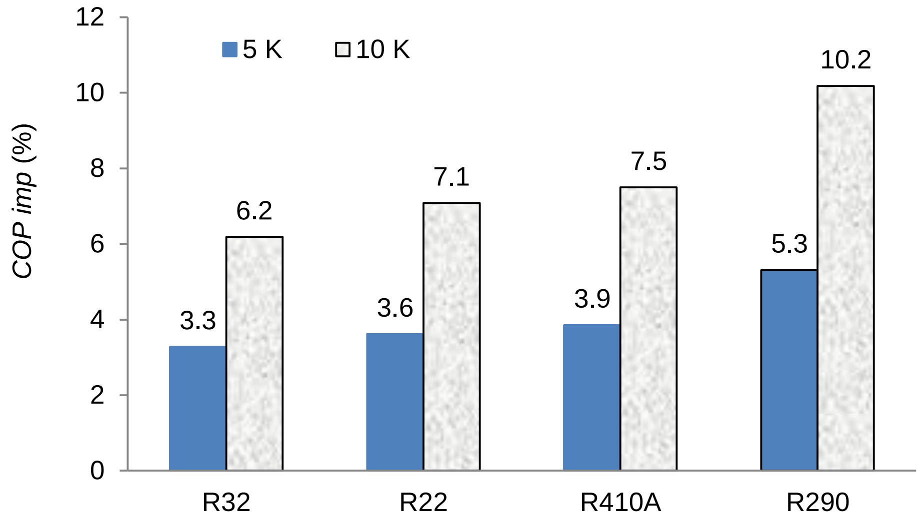


Fig. 9. The COP improvement for four refrigerants

4. Conclusions

Numerical evaluations on the system performances of air conditioner using LSHX subcooling had been investigated. There were four evaluated refrigerants in this study, which were R32, R22, R410A and R290. The results showed that the use of LSHX subcooling increased the refrigerating effect, where the lowest and the highest refrigerating effect improvements were achieved by R410A and R290, respectively with the values of 6.3% and 8.5% for subcooling of 5K and 12.5% and 16.8% for subcooling of 10K.

In addition, due to superheating effect, the use of LSHX increased the compressor work. The lowest and the highest compressor work increments were achieved by R410A and R32, respectively, namely 2.3% and 3.6% for subcooling of 5K and 4.7% and 7.1% for subcooling of 10K. Furthermore, the lowest and the highest COP improvement occurred at R32 and R290, namely 3.3% and 5.3% for subcooling of 5K and 6.2% and 10.2% for subcooling of 10K, respectively.

As a result, it is recommended to apply the LSHX subcooling in the air conditioning system using R290 as an alternative refrigerant of R22 in the future. However, more intensive studies involving experimental works are still required to verify the advantage of this alternative refrigerant as compared to the current refrigerant used in the A/C. In addition, further study especially on system design with the aim to reduce the flammability risk of R290 has to be carried out in the future.

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