SET 2015 NOTTINGHAM

211: Investigation on the Performance of Air Source Heat Pump System with new Environment Friendly Refrigerants for a Low Carbon Building

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Energy is an important development factor. It is consumed in different format from different sources in daily human activities. Solar energy, as the most fundamental renewable energy resource, serves in a clean, domestic and environmentally friendly way with minimum impact on surroundings. Due to the ability of transferring heat from low temperature to high temperature, heat pump systems can make great use of natural resources and waste heat resources for the purpose of space heating. Based upon this theoretical principle, this paper presents an investigation on the performance of air source heat pump (ASHP) system with new environment friendly refrigerants, such as R1233zd(E), R1234YF, R1234ze(Z) and R1234ze(E). At the same time, some conventional refrigerants (R134a, R245fa and R123) have been investigated as well for results comparison. A MATLAB program has been developed with the assistance of the database of CoolProp. The results show that the use of some selected environment friendly refrigerants in air source heat pump system for building application alongside other refrigeration applications in strongly recommended.

Keywords: heat pump, refrigerants, air source

1. INTRODUCTION

Due to the ability of transferring heat from low temperature to high temperature, heat pump systems can make great use of natural resources and waste heat resources for the purpose of space heating. With the assistance of external power, a heat pump accomplishes the work of transferring energy from the heat source to the heat sink. Ground Source Heat Pump (GSHP) systems, also known as geothermal heat pumps, generally have higher efficiencies since they draw heat from ground soil which is at a relatively constant temperature throughout the year. Air source heat pump (ASHP) is another branch of heat pumps, but draws heat from low temperature ambient air and boosts it to a higher temperature. Heat in the air is absorbed at low temperature into a fluid, which then passes through a compressor where its temperature is increased, and transfers its higher temperature heat to the heating and hot water circuits of the residence. Although the efficiency of ASHP may be lower, it also presents various merits over water or ground source heat pump, involving lower maintenance and easier installation. An ASHP system can provide a full central heating solution and domestic hot water up to 80^{o}C if it is correctly specified.

2. CONCEPT AND PRINCIPLE OF OPERATION

The theoretical model and simulation of new refrigerants are based on the reversed Carnot Cycle and heat transfer laws in different form, which relate the environmental variables with the thermal energy absorbed by the collectors and the mechanical compression refrigeration cycle. The refrigerant thermodynamic cycle of heat pump systems is indicated by Figure 1, which includes four processes: compression to condensing pressure in compressor (1 to 2s theoretically or 1 to 2 practically), isobar condensation to saturation liquid state in condenser (2 to 3), isenthalpic expansion through TEV or capillary tube (3 to 4) and constant isothermal evaporation. Therefore, the model and simulation allow one to obtain the operating temperatures and parameters starting from the following conditions: temperature, wind speed and PV/heat insulation solar glass power input (solar radiation).

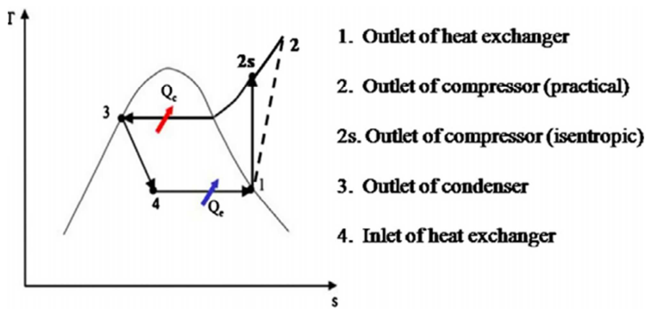


Figure 1: Indication of the heat pump thermodynamic cycle in T-s diagram

2.1. Condenser and evaporator model

When simulating the performance of innovative refrigerants, the energy rate absorbed at the evaporator and released at the condenser can be determined in terms of the refrigerant enthalpy changes in Eq. (1) and (2) respectively.

$$Q_{evap,ref} = m_r \cdot (h_1 - h_4) \tag{1}$$

$$Q_{cond,ref} = m_r \cdot (h_2 - h_3) \tag{2}$$

However, in the process of actual ASHP system test, the real heating and cooling capacity are obtained from Eq. (3) by measuring the air temperature difference between inlet and outlet of condenser and evaporator, and the air mass flow rate at the same time.

$$Q_{cond,air} = m_a \cdot c_p \cdot (T_{air,out} - T_{air,in}) \tag{3}$$

2.2. Compressor model

The compressor work, W_{comp} for a given pressure ratio P_2/P_1 can be determined by from the following equation:

$$W_{comp} = \frac{P_1 v_1}{\eta_{comp}} \left(\frac{k}{k-1}\right) \left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right] \quad (4)$$

Where k is the ratio of specific heat. The assumption of ideal gas behavior during the compression process is found to be fairly reasonable, because the compressor work expressed in this method is somewhat overestimated compared with the value obtained directly from the refrigerant property table. Since the coefficient of performance of the heat pump is inversely related to the compressor work, this will lead to conservative or underestimated values of COP. The compressor indicated power can be calculated in terms of the enthalpy change of the refrigerant from the inlet and outlet of the compressor as in Eq. (5).

$$W_{comp} = m_r(h_2 - h_1) \quad (5)$$

To simplify the calculation process, when doing simulation of refrigerant thermal performance on the basis of property chart, the enthalpy value of refrigerant at compressor outlet is replaced by the enthalpy value at the temperature of 5℃ or 10℃ higher than the condensing temperature.

2.3. Coefficient of performance

The relationship between the heat rejected by condenser and the work consumed by compressor is defined as coefficient of performance (COP) of the heat pump, which can be calculated from Eq. (6)

$$\mathrm{COP} = \frac{Q_{cond}}{W_{comp}} = \frac{m_r \cdot (h_2 - h_3)}{m_r \cdot (h_2 - h_1)} = \frac{h_2 - h_3}{h_2 - h_1} \quad (6)$$

However, the COP expressed above is a theoretical situation that only takes into account the enthalpy change of refrigerant. In reality, some auxiliary equipment, such as refrigerant pump, water pump (in water tank system) or fan, consumes electrical energy to run the system. Therefore, the effective coefficient of performance can be established by the following equation which replaces the compressor consumption by electrical input,

$$COP_{effective} = \frac{Q_{cond}}{W_{elec}} \quad (7)$$

3. WORKING FLUIDS: ENVIRONMENT FRIENDLY REFRIGERANTS

3.1. Hydrofluoro Olefin (HFOs)

The Investigation of halogenated olefins with fluorinated propane isomers is currently endured as potential low GWP replacements for R134a in automotive applications. This effort is mainly related to the European F-gas regulations that do not allow the use of refrigerants with GWP greater than 150 in new models starting from January 2011 and new manufactured vehicles on January 2017. Amongst HFOs, R1234yf is identified as the promising alternative of R134a in automotive applications [1]. R1234ze(Z) and R1234ze(E) are other HFO refrigerants that have been developed to substitute R134a in refrigeration applications where sink temperature is as high as 70°C [1, 2]. Yet, R1234ze's has been commercially available as foam blowing agent [3]. The performances of HFOs are reported to be similar to R134a and with similar system size and operation pressures. Moreover they are compatible with available R134a components. Unlike 134a, both R1234yf and both R1234ze types have mild flammability where they are classified as class two refrigerants. However, to ignite a class two refrigerant, significantly large energy is required [4].

3.2. Hydrochloroflouroolefins (HCFOs)

Particularly R1233zd(E), was developed by Honeywell as a foam blowing agent and cleaning solvent to replace CFCs and HFCs and HCFCs [5]. However, the refrigerant has been promoted by the developers as the promising alternative for R123 and R245fa in ORC applications, high capacity chillers, and high temperature applications [6]. Although R1233zd(E) has chlorine, the refrigerant is non-flammable, non-toxic, has negligible ODP, very low GWP, and very short atmospheric life time of 26 days [7]

The very recent undergoing investigations of new working fluids such as HFO's and HCFO R1233zd(E) gained attention. However few of HFOs has been evaluated theoretically for ORC applications such as R1234yf and

R1234ze(E) in [8]. The rest of these emerging refrigerants were not seen in either theoretical or real ORC applications. Most importantly, the promising HCFO R1233zd(E) which still unavailable commercially and with thermodynamic properties that are still not publicly available.

In this section the thermodynamic performance of selected HFO's and HCFO R1233zd(E) whose properties were supplied privately are evaluated in a heat pump system to supply space heating from PV/heat insulation solar glass. The performances of the new refrigerants were also compared to conventional refrigerants. Table 1 presents the evaluated refrigerants alongside their critical and environmental properties.

Table 1: Environment friendly and conventional refrigerants thermodynamic information

Refrigerant	Molecular weight [kg/kmol]	Critical Temperature [K]	Critical pressure [bar]	GWP	ODP	ASHRAE standard 34 and EN378 [9]
Environment friendly refrigerants						
R1233zd(E)	130.496	438.75	35.709	>5 [7]	0 [10]	A1
R1234YF	114.042	367.85	33.822	4[8]	0	A2L
R1234ze(Z)	114.042	423.27	35.33	6 [1]	0	A2L
R1234ze(E)	114.042	382.52	36.3625	6[8]	0	A2L
Conventional refrigerants						
R134a	102.03	374.21	40.59	1430	0	A1
R245fa	134.05	427.15	36.51	1030	0	B1
R123	152.93	456.82	36.70	77	0.02	B1

Keys: A1: Non-flammable and has very low toxicity.
A2L: Moderate flammability and low toxicity.
B1: Non-flammable, and has higher toxicity.

4. HEAT PUMP SYSTEM

The schematic diagram of the simulated heat pump is shown in Figure 2 and Figure 3, which include four main components: compressor, condenser, capillary tubes (operates as expansion valve) and evaporator with some proposed refrigerants (see Table 1) flowing inside as working fluid. Both condenser and evaporator are finned heat exchanger and two fans are installed besides the condenser and the evaporator for the purpose of exchanging heat with these two components through the circulation of air.

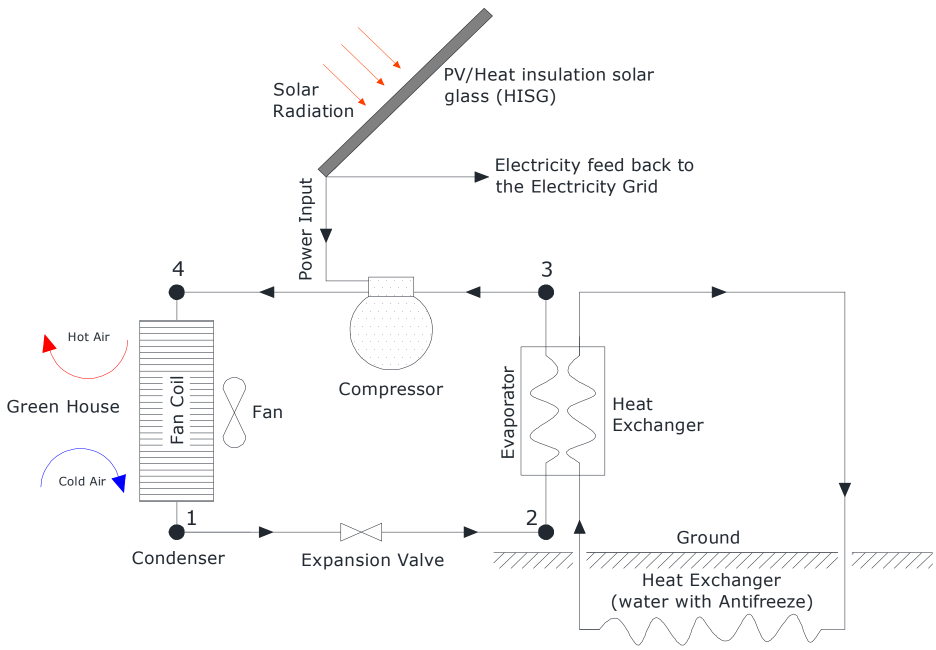


Figure 2: Heat pump system for green house (winter)

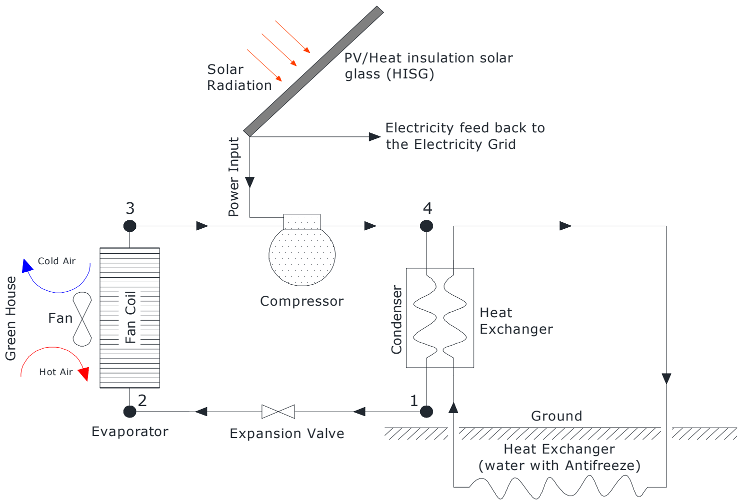


Figure 3: Heat pump system for green house (summer)

5. SIMULATION RESULTS AND ANALYSIS

The simulation is conducted within the range of condenser temperature varies from 25°C to 95°C and evaporator temperature sets at 5°C (winter) and 15°C (summer) to compare the environment friendly new refrigerants to conventional refrigerants. An average scroll compressor isentropic efficiency reported in literatures of 80% was used for the heat pump system. External PV/heat insulation solar glass power input is set up to 1kW. After simulation with the assistance of MATLAB and refrigerant thermodynamic properties chart from CoolProp, the comparison of thermal performance and coefficient of performance on these proposed refrigerants (R134a, R245fa, R123, R1233zd(E), R1234yf, R1234ze(Z) and R1234ze(E)) have been carried out, as shown in Figure 4 to Figure 7.

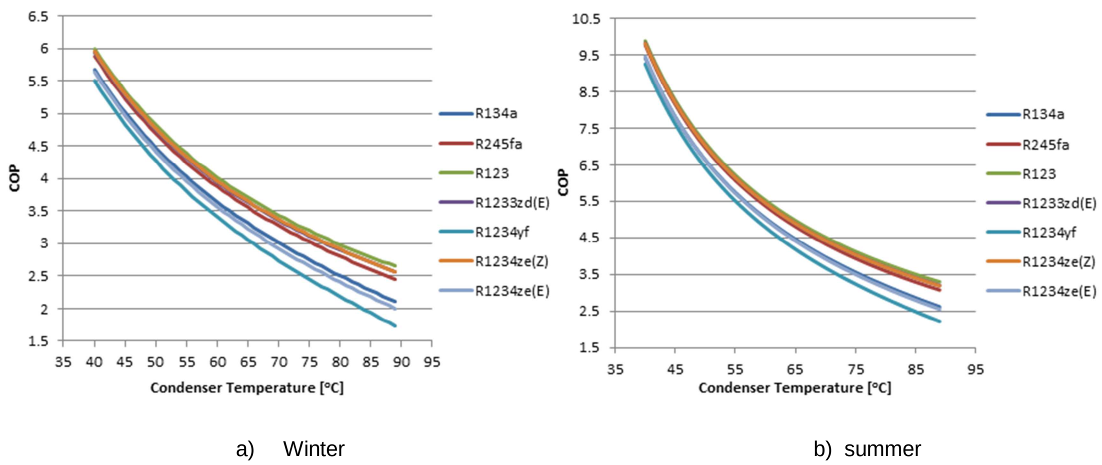
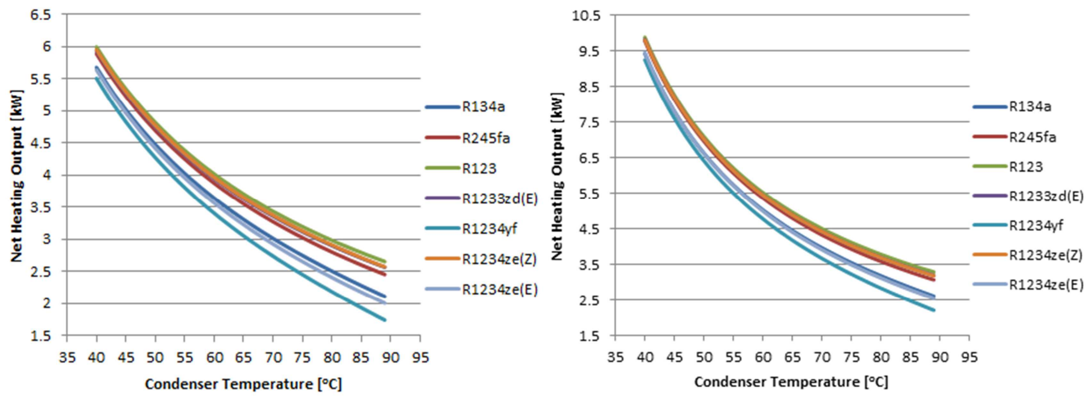
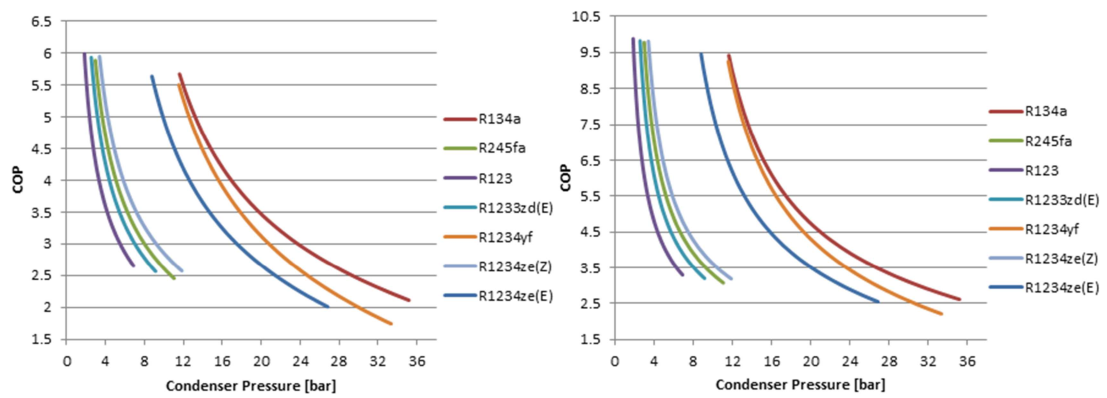


Figure 4: COP variations of refrigerants under different condenser temperature



a) Winter b) summer

Figure 5: Heating outputs of refrigerants under different condenser temperature



a) Winter b) summer

Figure 6: COP variations of refrigerants under different condenser pressure

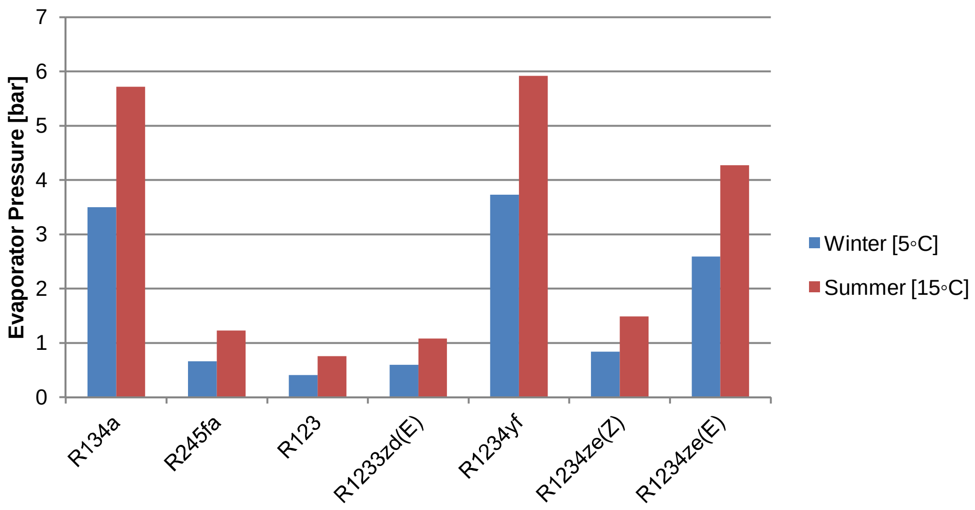


Figure 7: Evaporator pressures of refrigerants for winter and summer

In the Figure 4, the results indicate that the highest coefficient of performance (COP) is achieved by the conventional R123 refrigerant followed closely by the environment friendly R1234ze(Z). The environment friendly R1233zd(E) achieved the third highest COP with almost identical performance to the R1234ze(Z). The conventional R245fa refrigerant has the fourth highest COP. All the proposed refrigerants showed to cluster together and follow similar trend. The environment friendly R1234ze(E) and the conventional very popular R134a showed almost identical performance. R1234yf has lowest COP during simulated cases (winter and summer). As shown in Figure 5, the net heating output showed the similar linear trend of COP and the R1234ze(Z) and R1233zd(E) achieved higher heating output in their environment friendly refrigerants group. Figure 6 illustrates the heat pump COP, for different refrigerants, as a function of condenser pressure and Figure 7 shows evaporator pressures of refrigerants under different seasons of winter and summer. At lower condenser pressures (under 12 bar), R245fa, R123, R1233zd(E) and R1234ze(Z) achieved similar linear trend of COP during condenser temperature range (25^{o}C to 95^{o}C). On the other hand, R134a, R1234yf and R1234ze(E) have higher condenser pressures range (12 bar to 36 bar) in terms of condenser temperature range (25^{o}C to 95^{o}C), which is the same as evaporator pressures requirements.

6. CONCLUSION

This paper presented an overview of the heat pump system covering key aspects such as the selection of working fluids which mainly characterise the performance of the system. The report presented the results of conducted simulation on various conventional and new emerging environment friendly refrigerants. The simulation results revealed the capability of the new refrigerants to replace conventional refrigerants. R1233zd(E) and R1234ze(Z) showed outstanding performance that is similar to R123 while R1234ze(E) showed similar performance to R134a. However, R1234yf showed the lowest performance with higher condenser and evaporator pressures than others. Therefore, the use of some selected environment friendly refrigerants (R1233zd(E) and R1234ze(Z)) in heat pump system for green house alongside other refrigeration applications is strongly recommended.

7. ACKNOWLEDGMENT

The authors would like to express their gratitude for financial support from the Innovate UK for this project (code: 131784).

8. REFERENCES

BROWN, J.S., C. Zilio, and A. Cavallini, *The fluorinated olefin R-1234ze(Z) as a high-temperature heat pumping refrigerant.* International Journal of Refrigeration, 2009. **32**(6): p. 1412-1422.

BIGONHA, Tibiriçá, C., G. Ribatski, and J. Richard Thome, *Flow Boiling Characteristics for R1234ze(E) in 1.0 and 2.2 mm Circular Channels.* Journal of Heat Transfer, 2011. **134**(2): p. 020906-020906.

BEATTIE, R.J. and J.A. Karnaz, Investigation Of Low GWP Refrigerant Interaction With Various Lubricant Candidates, in The International Refrigeration and Air Conditioning Conference. 2012: Purdue University, West Lafayette, Indiana, USA.

BROWN, Steven, J., HFOs: New low globar warming potential refrigerants ASHRAE journal, 2009.

Honeywell. *Honeywell Solstice® 1233zd(E) Technical Information*. [cited 2014 12 April 2014]; Technical Information]. Available from: http://www.honeywell-blowingagents.com/?document=solstice-lba-technical-brochure&download=1.

Honeywell. *Solstice Range of Refrigerants*. [Brochure] 2012 [cited 2014 15 April 2014]; Solstice Refrigerants Brochure]. Available from: http://www.honeywell-refrigerants.com/europe/?document=the-future-begins-with-solstice&download=1.

HULSE, R.J., et al., *Physical Properties of HCFO-1233zd(E).* Journal of Chemical & Engineering Data, 2012. **57**(12): p. 3581-3586.

BALA VARMA, D. and B. Joost. Organic Rankine Cycle System Analysis for LowGWP Working Fluids. in The International Refrigeration and Air Conditioning Conference. 2012. Purdue University, West Lafayette, Indiana, USA.

WALTER, B., Refrigerants: Now And In The Future (Presentation), in Carrier's Sustainability Symposiums. 2012: SYRACUSE, N.Y, USA.

SCHMIDT, T., et al., *Biotransformation of trans-1-chloro-3,3,3-trifluoropropene (trans-HCFO-1233zd).* Toxicology and Applied Pharmacology, 2013. **268**(3): p. 343-351.