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Xiaoning Chen
Shanghai Jiao Tong University, China, People's Republic of, chenxn0731@163.com

Ziqi Zhang
Shanghai Jiao Tong University, China, People's Republic of, sheen1986@163.com

Junye Shi
Shanghai Jiao Tong University, China, People's Republic of, jyshi@sjtu.edu.cn

Zhiyu Yang
Shanghai Jiao Tong University, China, People's Republic of, zhiyuyang@sjtu.edu.cn

Jiangping Chen
Shanghai Jiao Tong University, China, People's Republic of, jpchen_sjtu@163.com

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Research on the Operating Characteristics of Floor Heating System with Residential EVI Air Source Heat Pump in China

Xiaoning CHEN, Ziqi ZHANG, Junye SHI, Zhiyu YANG, Jiangping CHEN*

Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University,
Shanghai, China
Contact Information (Phone: 86 21 34206087, Fax: 86 21 34206775, E-mail: jpchen_sjtu@163.com)

* Corresponding Author

ABSTRACT

Air source heat pump is considered a commendatory way to help solve the environmental problems resulting from coal-fired heating, especially in the cold region of China. The heat pump uses air as low-grade heat source, so the atmospherical temperature plays a key role in the operating performance of units. And the technology of economized vapor injection (EVI) is used to improve the performance in the low temperature condition. Beijing is one of the most typical cities in China cold region. Therefore, this paper took a residence in Beijing as the test site. A long-term and high-frequency monitoring was performed to investigate the operating characteristics and heating effect of floor heating system with EVI air source heat pump, and the economy was also analyzed. Equivalent carbon dioxide emission was also calculated to evaluate the carbon dioxide emission of such a heating system from cradle to grave. The results showed that the heating seasonal performance factor (HSPF) of the heating system in Beijing was 3.28, and the running condition was stable on the premise of satisfying the heating need of uses. Attentions were also paid to the behavior of residents. The irregularity revealed the apparent need and the energy saving awareness, which directly affected the power consumption.

1. INTRODUCTION

In China, a large amount of coal resources consumption has made the atmosphere be suffering from the severe damage. Especially when the winter comes, the most northern area relies on coal-fired boiler to achieve heating a large scale. As a consequence, the coal-smoke air pollution is getting worse and worse. In order to ease this pressure, a lot of plans and regulations were formulated by the relevant departments. Among these, the State Council of China (2013) issued No.37 document “air pollution prevention and control action plan”. It is pointed out in this plan that, by 2017, inhalable particle concentration in prefecture-level and above cities should decrease more than 10% compared with 2012. And the govern target of Beijing, Tianjin and Hebei was to decrease 25%. The annual concentration of fine particulates in Beijing must be controlled below 6060mg/m3. Therefore, Air source heat pump hot water system emerged to be an effective way to replace the conventional heating systems for, and it had a remarkable energy-saving effect (Li, 2014; Zhang *et al*., 2015; Ai *et al*., 2015).

In 2009 the European Union enrolled air source into renewable energy. Some regions in China, such as Zhejiang (2012), Beijing (2014) and Shandong (2014), also brought air source into this category. These measures made contributions to the application of air source heat pump hot water heating system divorcing from the other energy resource, effectively pushing the further research and promotion of this new technique. The heat pump takes air as heat source, so as to have advantages of energy utilization ratio and flexible installation. Duo to the outstanding merit it is always one of the most concerned heat source types. Many challenges are still in the way. On the one hand, when the ambient temperature decreased, the pressure ratio would grow, inducing that the heating capacity and energy efficiency would drop with it (Hewitt *et al*, 2008). On the other hand, if the outdoor heat exchanger got frosting, the increasing resistance would lower the air velocity, so as to the falling of the heat transfer coefficient (Kondepudi *et al*., 1991). But compressor and refrigerant technology can help improve this issue (Neil, 2011). Many specialists found that economized vapor injection compressor could be successfully applied in the low temperature heat pump water heaters (Ma *et al*., 2003; Deng *et al*., 2014). And thanks to the frequency conversion technique, the power consumption was cut down to some extent, which optimized the unit performance and improved the economic benefit of residential heating (Beeton *et al*., 2003).

This paper focused on hot water heating system composed of the air source heat pump with economized vapor injection technique and floor radiation terminal. A high–frequency and long-term measurement was carried out in a residence in Beijing. Systematical analysis of seasonal, daily, hourly characteristic and heating effect was performed to explore the energy conservation and comfort under the condition of residents' autonomous control.

2. TEST SYSYEM AND METHOD

2.1 Test System and Unit Structure

The experiment was carried out in a bungalow house located in Beijing with an area of 130m^2. The heating system consisted of variable-frequency air source heat pump with economized vapor injection technique and floor radiation terminal. And the parameters were in Table 1.

Table 1 Rated heating performance of air source heat pump unit

Contents	Value	Unit
Rated Voltage	220	v
Refrigerant R410A	4.3	kg
Rated Heating Capacity	16.0	kW
Rated Heating Input Power	3.37	kW
Rated COP	4.7	-
Rated Heating Operation Condition	Outdoor 7db 6wb	-

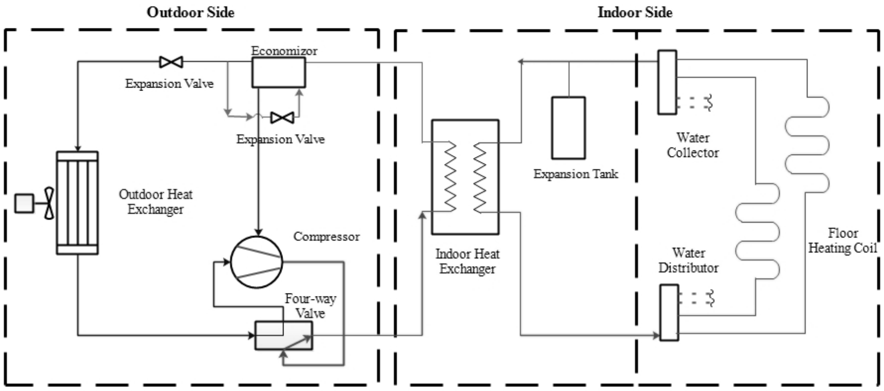

Figure 1: Schematic diagram of residential floor heating system with air source heat pump

Figure 1 was the schematic diagram of this test heating system. The outdoor side included compressor, throttle mechanism and evaporator module. The compressor carried the economized vapor injection technique, which meant that the refrigerant flow rate could increase though an intermediate inspiratory loop, so as to improve the heating capacity and energy efficiency. The indoor side included the condenser water module and terminal. And the floor heating coil adopted wet method.

2.2 Field Test Content and Method

The test was carried out from Dec 11th 2014 to Mar 15th 2015, during which time two residents were being active. In case of people being limited, test parameters included supply and return water temperature, water flow rate, power consumption, instantaneous power, air temperature and relative humidity and floor temperature, and time interval of date logger is 1min. Table 2 shows the details of parameters and instrument.

Table 2 Parameters of test content and instrument

Project	Parameter	Test Instrument	Range	unit	Precision	unit
Heating Capacity	Supply and Return Water Temperature	NTC	-80~150	℃	±0.1	℃
	Water Flow Rate	Electromagnetic Flowmeter	0.3~43	m^3/h	0.5	%
Power Consumption	Power、Quantity	Dynamometer	$0\sim10^5$	kWh	0.5	%
Heating Effect	Outdoor Temperature	NTC	-80~150	℃	±0.1	℃
	Relative Humidity	Humidity Sensor	0~100	%	3	%
	Surface Temperature	NTC	-80~150	℃	±0.1	℃

3. RESULTS AND ANALYSIS

3.1 Seasonal Performance

According to the statistical results of field test data, the heating seasonal performance factor was 3.28 in Beijing. Figure 2 - 4 showed daily power consumption, daily heating capacity and daily energy efficiency of the floor heating system with air source heat pump in Beijing. It could be seen that the minimum outdoor temperature reached -12^{o}C, and the calculated mean temperature was -0.4^{o}C. The power consumption and heating capacity decreased and energy efficiency increased when the outdoor temperature increased. Still this regulation could be seen in a certain range under the condition of uncertain factor of artificial control existing. Accordingly, the variation range of system energy efficiency is 2.35-6.28, which increased remarkably when the outdoor temperature rose up in March.

This measurement was based on the real life environment, which depended on the residents' thermal sensation and adjustment. Therefore, this result revealed the subjective initiative of people. For instance, during Feb.12th to 18th it showed lower power consumption and heat capacity. And taken the general trend into consideration, a spurt of power consumption and heat capacity would occur after running in a low stage for a period of time. The partial irregularity reflected residents' autonomous control and energy-saving awareness. It also could be seen in the other data as well.

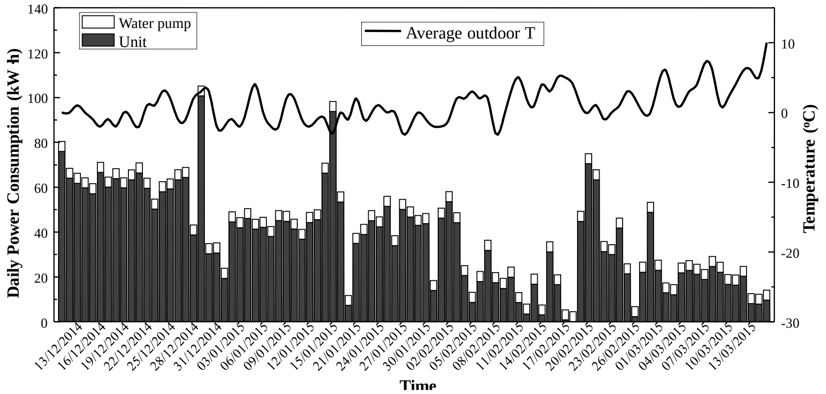

Figure 2: Daily power consumption and average environmental temperature

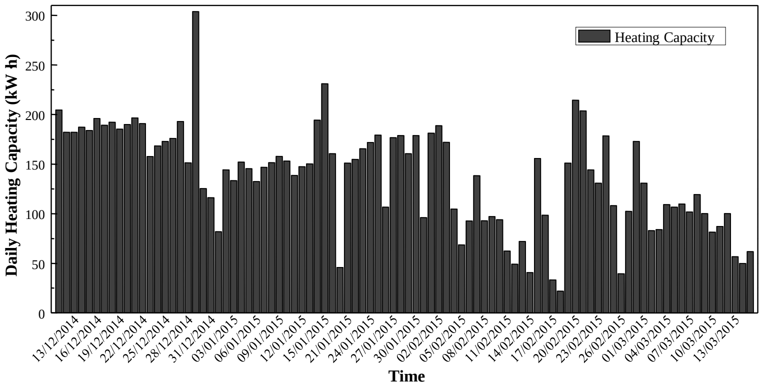

Figure 3: Daily heating capacity

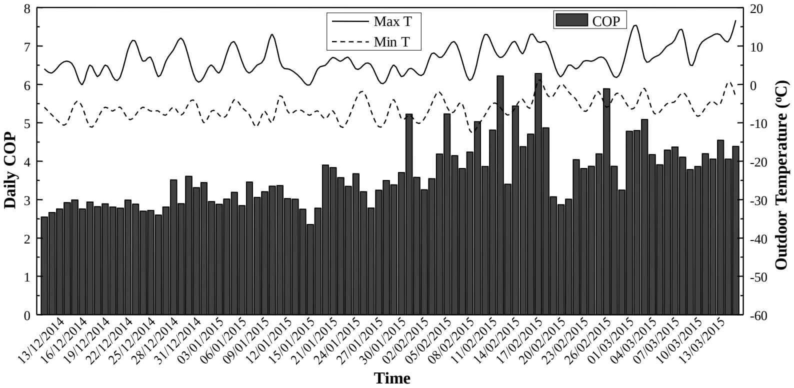

Figure 4: Daily COP and maximum and minimum environmental temperature

3.2 Heating Effect

Figure 5 showed the daily average temperature of supply and return water, from which it could be seen the power consumption was in connect with the mode of residents' autonomous control. The average temperature of supply and return water in the entire heating season was 27.4 and 23.9°C, respectively. Especially in late February and early March, the supply water at about 25°C could help maintain the room above 18°C. In view of the safety and convenience, it was air and floor temperature of dining room and bedroom that were the main test object. And from Figure 6 it could be seen that the average and minimum temperature of dining room were 20.4, 18.2°C, respectively, satisfying the basic heating demand.

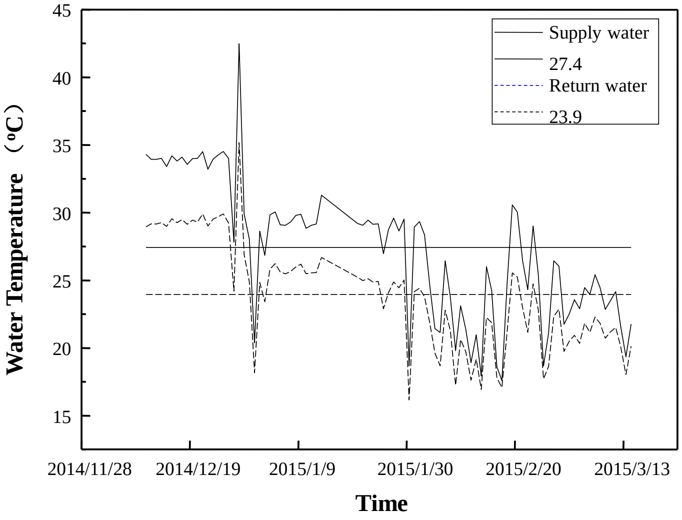

Figure 5: Daily average temperature of supply and return water

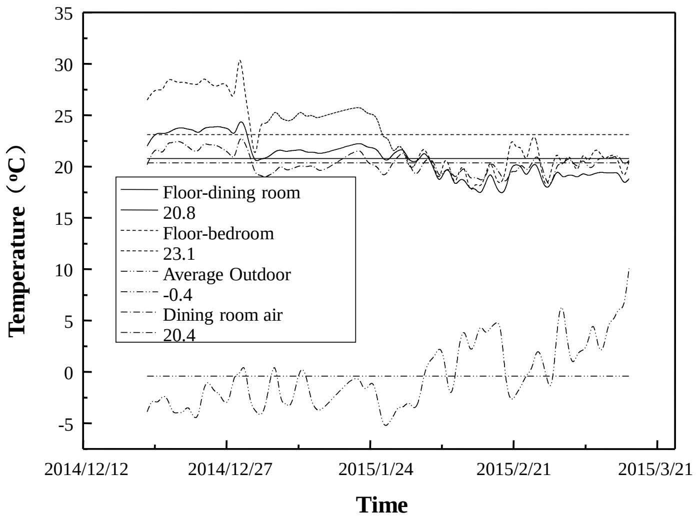

Figure 6: Monitoring Results of heating effect

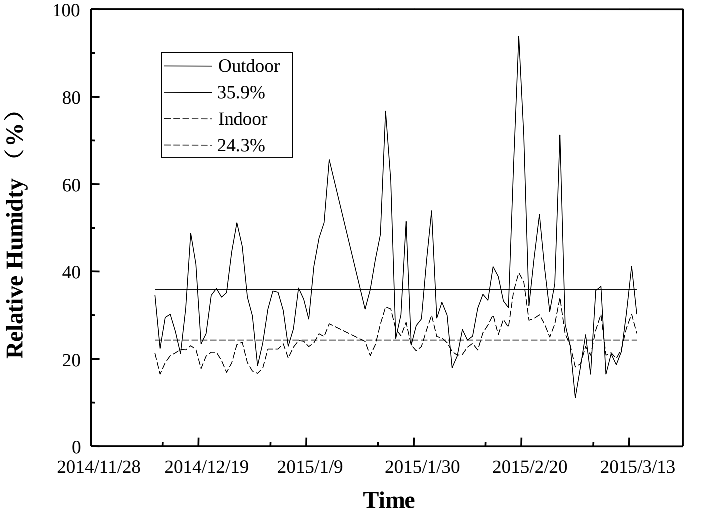

Figure 7: Monitoring results of average daily outdoor and indoor relative humidity

3.3 Hourly Performance

In order to analyze the system running characteristics in the low temperature ambient, Jan 27th was picked as the object to obtain a typical hourly performance. On the very day, the minimum outdoor temperature was -11ºC, while the average was -3ºC. As shown in Figure 8-10, the average hourly heating capacity was 7.65kWh, the hourly power consumption 2.33kWh, and the energy efficiency was 3.29.

It is noted, however, that during 12:00-15:00 and 18:00-19:00 the power consumption was very low. As for instantaneous power and supply-return water temperature in Figure 11, the compressor nearly did not work except for the water pump in these two period of time. The water cycle continued with the action of water pump, keeping the heat transfer temperature difference for about 2ºC. Therefore, heating capacity could be guaranteed. And the heating effect was shown in Figure 12. At the off-operation stage of compressor, room temperature was not remarkably influenced because of the high specific heat capacity of construction. In addition, the sudden drop of temperature was caused by conventional ventilation.

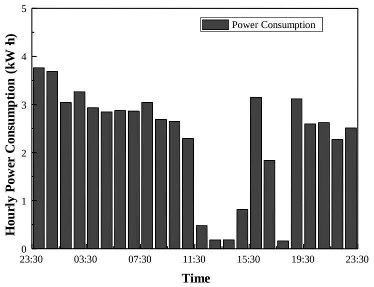

Figure 8: Hourly power consumption

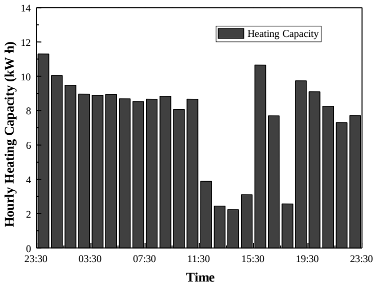

Figure 9: Hourly heating capacity

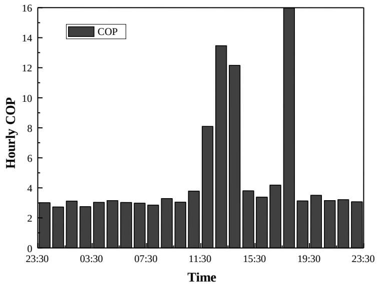

Figure 10: Hourly COP

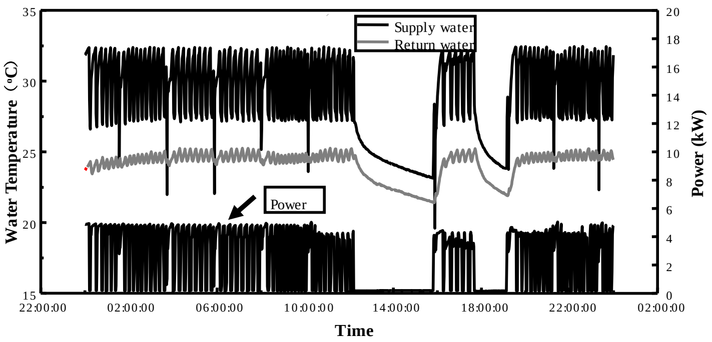

Figure 11: Relationship between supply-return water temperature and power in Jan. 27th, 2015

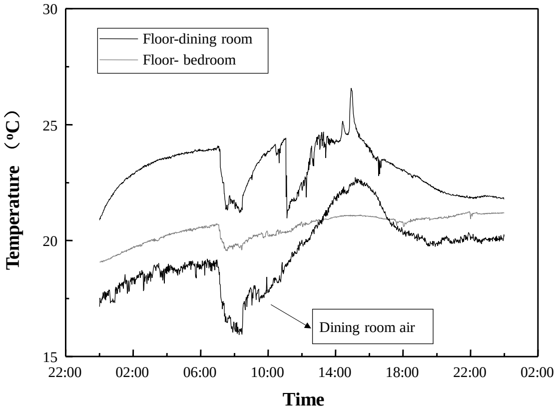

Figure 12: Monitoring results of floor and air temperature in Jan. 27th, 2015

3.4 Energy Efficiency under Variational Outdoor Temperature

Figure 13 showed the relationship between average daily energy efficiency and outdoor temperature in Beijing. Due to the limit of the complex ambient and human behaviors, the energy efficiency was different under the same outdoor temperature. Still a clear trend of positive correlation existed, based on a large number of statistical data and fitting results. And the unit could reach rated level under high outdoor temperature.

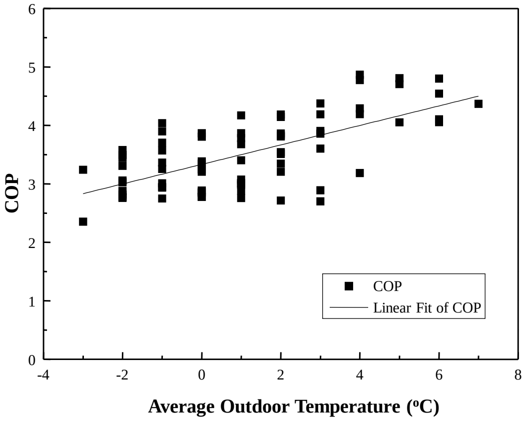

Figure 13: Relationship between average daily COP and outdoor temperature in Beijing

3.5 Economic and Environmental Analysis

Beijing residents can adopt peak-valley pricing method to pay the electric charge: at peak time (6:00-22:00), the standard price is 0.4883 CNY/kWh, while at the rest valley time it is 0.30 CNY/kWh. The gas price is 2.28 yuan /m3, and its calorific value takes 3557kJ/m^3. The heating system running cost was calculated in this way, and the comparison result of air source heat pump, central heating, gas water heater and electric heater was shown in Figure 14, referring to this field test condition. It could be seen that the running cost of air source heat pump was 50% and 70%, respectively, lower than that of gas water heater and electric heater, even being cheaper than central heating by 8.8 CNY/(m^2 season), which displayed a better economy.

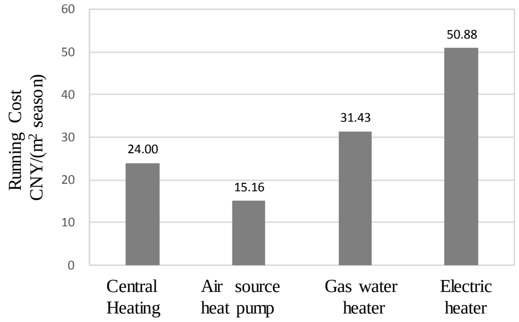

Figure 14: Economic analysis of different heating systems in Beijing

The equivalent carbon dioxide calculation model includes the direct impacts of refrigerant emissions, the indirect impacts of energy consumption used to operate the heat pump system, and the energy to manufacture and safely dispose the system and refrigerant.

Direct emission of refrigerant is the direct diffusion to the atmosphere, and its calculation is as follows:

$$DE_{ref} = GWP.ref \times C \times \left[(1-\alpha) + \beta \times N\right] \tag{1}$$

Indirect emission of refrigerant consists of embedded energy and fugitive emission. Embedded energy is the CO_2 emissions due to the energy needs in production per unit mass of refrigerant. Fugitive emission is not easy to collect, which is CO_2 emissions due to the by-product of unit mass of refrigerant in production. Their value both depend on refrigerant. Indirect emission of refrigerant is as follows:

$$IE_{ref} = (E+F) \times C \times \left[(1-\alpha) + \beta \times N\right] \tag{2}$$

Energy consumption always played a key role and accounted for a majority. This part is important for energy saving. As a part of indirect emission, its calculation is as follows:

$$IE_{eng} = N \times E_{ann} \times e \tag{3}$$

Thus,

$$DE_{tot} = DE_{ref} \tag{4}$$

$$IE_{tot} = IE_{ref} + IE_{eng} \tag{5}$$

$$Eq.CO_2 = DE_{tot} + IE_{tot} \tag{6}$$

Figure 15 showed the calculation results of equivalent CO_2 and its composition ratio. As could be seen, the equivalent CO_2 emission of the air source heat pump hot water heating system in Beijing was 62360kg with the recovery rate of 85%, the lifetime of 15years and the annual leakage rate of 2%. The direct emission was 3723kg, accounting for 5.97%. And the indirect emission was 58637, occupying 94.03%. The total value could also be divided into refrigerant, unit operation and water pump running part that accounted for 6.01%, 84.01% and 9.98, respectively. Thus the running emission was remarkably higher. And the role of water pump could not be ignored, even its contribution was more significant than the direct emission.

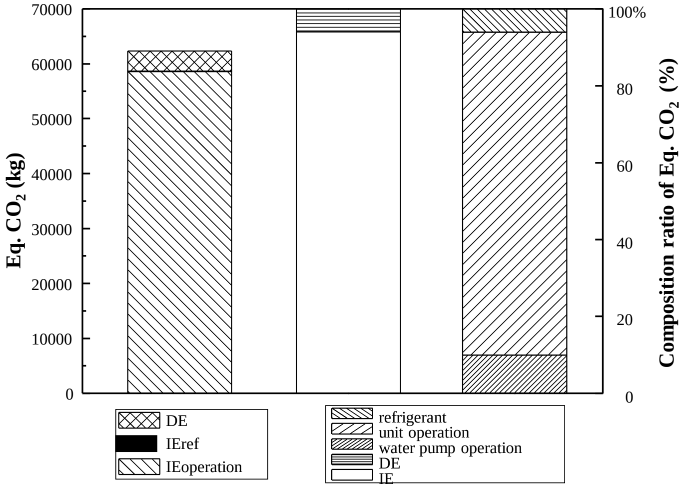

Figure 15: Equivalent CO_2 emission and composition ratio

4. CONCLUSIONS

A long-term monitoring of household floor radiation heating system with air source heat pump in Beijing area was carried out. And the heat pump unit with economized vapor injection technique could satisfy the basic demand in the entire heating seasonal test stage. Still the data revealed the contents in the following:

The heating seasonal performance factor of this air source heat pump system tested in Beijing was 3.28. The higher the outdoor temperature was, the higher the energy efficiency would be. The average supply water temperature of test period was 27.4°C, which could meet the heating demand. Although Human control brought the system irregularity, residents' energy-saving awareness helped decrease the power consumption according to their thermal sensation. The running cost of air source heat pump system was remarkably lower than that of gas water heater, electric heater and even central heating when providing continuous heating in winter.

NOMENCLATURE

DE	direct emission	(kg CO_2)
GWP	global warming potential	(kgCO_2/kg)

α	recovery rate of end-of-life	(%)
C	charge volume	(kg)
β	annual leakage rate	(%)
N	years of lifetime	(year)
IE	indirect emission	(kg CO_2)
E	Embedded energy	(kg CO_2/kg)
F	Fugitive emissions	(kg CO_2/kg)
e	Electricity emission factor	(kg CO_2/kWh)
E_{ann}	annual power consumption	(kWh/year)

Subscript

ref	refrigerant
eng	operation energy consumption
tot	total

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