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ABSTRACT

In order to investigate the feasibility of R161 applied in residential air conditioner, the thermodynamic performance and comprehensive theoretical thermodynamic cycle of R161, R22 and R290 under various air-conditioner operating condition were carried out. Further more, the cooling and heating performance of R161 and R22 under various operating condition was investigated experimentally in a 3.5kW residential heat pump air conditioner. Property and thermodynamic cycle comparison showed that R161 has better thermodynamic performance than R290, the rated cooling and heating capacity is lower than R22 but higher than R290, the rated cooling and heating COP is higher than both R22 and R290. The experimental rated cooling capacity reduced 7.6% and rated cooling EER increased 6.1%, rated heating capacity reduced 6.8% and rated heating COP increased 4.7%, refrigerant optimized charge reduced 43% compared to R22 system, theoretical and experimental test revealed that R161 has lower discharge temperature than R22 system.

1. INTRODUCTION

Calm (2008) summarized the progress of refrigerants since the emergence of refrigerants and classified four generations. The third and fourth generation refrigerants were focused on ozone protection and global warming, respectively. Concerning ozone depletion potential (ODP), CFCs and HCFCs refrigerants have been banned in developed countries and gradually phased out in developing countries as required by the Montreal Protocol (1987). In refrigeration and air-conditioning industries, the R22 is the most widely used refrigerant as far as now, but its ODP is 0.05 and global warming potential (GWP) is 1800, still have some influence on the environment. Complying with Montreal Protocol, R22 is being phased out in developed and developing countries. R410A refrigerant has been recommended and applied in actual equipment to replace R22 by most researchers and refrigerant manufactures in recent years. However, R410A has high global warming potential (GWP=2100). Therefore, in long term view, R410a can only be used as one of transitional candidates.

Recently, the natural refrigerant R290 has been recommended as one of the refrigerant alternatives in household air conditioner. However, R290 has high flammability, lower cooling capacity and high POCP value, restricts its widely using. R161 is environment friendly and it has many similar properties compared to R22 except flammability. It has zero ODP and GWP of about 12. The literature available about use of R161 in air conditioning is very little. Some researchers reported studies of system performance with mixtures of R161 and other refrigerants. However, performance with alone R161 has not been reported yet. Han et al (2007) used ternary non-azeotrope mixture of R32/R125/R161 as an alternative to R407C and found that refrigeration capacity as well as coefficient of performance was superior to R407C. Xuan et al (2004) used ternary mixture of R161/R125/R134a(10/45/45% by weight) as drop-in for R404A in refrigeration application and found COP was nearly equivalent to R404A. Guo (2009) introduced the character of R161, the theoretically and experimentally result showed that R161 exhibited superior properties than R290 in the field of R22 replacement. Padalkar and Mali (2011) compared the refrigerant properties of R161, R22 and R290, the simulated result showed that R161 has higher energy efficient, comparable cooling capacity, lower discharge temperature, lower power consumption and smaller refrigerant charge than R22 refrigeration system.

The main objective of the paper was to study the performance and energy efficiency of R161 used in common residential air conditioners. So the comparison of thermodynamic and thermo-physical properties and theoretical and actual performance of R161 and R22 when applied in residential air conditioners were discussed in detail. the theoretical and experimental result showed that R161 was an ideal alternative refrigerant for R22.

2. REFRIGERANT PROPERTIES

Refrigerant properties consist of thermodynamic properties, thermo-physical properties and chemical properties. The chemical properties contain flammability, toxicity, compatibility with other substance such as compressor lubricant and construction materials. The following discussion will focus on comparison of thermodynamic and thermo-physical properties of the three refrigerants which may have effect on system performance. In this paper, R22 and R290 refrigerant thermodynamic properties calculated by REFPROP 8.0 version and R161 refrigerant property calculated by REFPROP 9.0 version for R161 refrigerant is not included in version 8.0. Table 1 shows several basic thermodynamic parameters of R22, R161 and R290.

Table 1: Basic thermodynamic properties of R22, R161 and R290

Properties	**Unit**	**R22**	**R161**	**R290**
Molecular	g/mol	86.47	48.06	44.1
Normal boiling point	℃	-40.8	-37.6	-42.1
Critical temperature	℃	96.1	102.2	96.7
Critical pressure	MPa	4.99	5.09	4.25
Liquid state density(@25℃)	kg/m^3	1190	644	493
Ozone depletion potential	-	0.05	0	0
GWP_{100}	-	1800	12	20
Atmospheric life time	a	12	0.21	0.041
Lower flaming limit by mass	kg/m^3	-	0.075	0.038
Lower flaming limit by volume	%	-	3.8	2.1
Burning velocity	cm/s	-	38.3	46
Combustion heat	MJ/kg	-	26.6	50.3
Occupational exposure limit	ppm	1000	1800	1000
Safety Class		A1	A3	A3

As seen in table 1, the molecular weight of R161 is nearly 55% of R22 which indicates the same proportional charge required under drop-in conditions. The three refrigerants normal boiling point and critical parameters are close to each other which implicate similar working condition. The liquid state refrigerant density also reflects the refrigerant charge. The ODP of R161 is zero and GWP is relatively small compared with R22. The atmospheric life time of R161 is 76 days and R290 is much shorter for only 15 days. Figure 1 shows that the vapor pressure of R161 is closer to R290 and is slightly lower than R22. This means that lower tube resistance pressure required for R161.

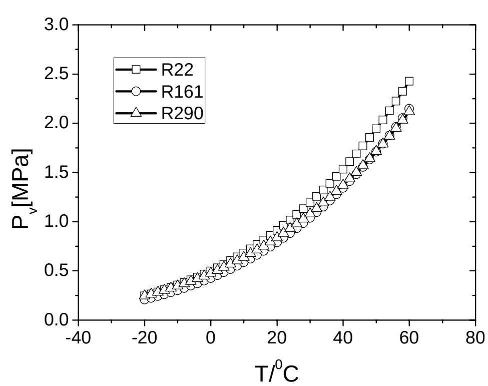


Figure 1: Saturation temperature vs pressure of R22, R161 and R290

The property parameter flammability and long term toxicity is significant. The ASHARE 34-2010 classified both R161 and R290 as A3. Table 1 show that the lower flammability by volume of R161 and R290 are 3.8% and 2.1% respectively, the burning velocity and combustion heat of R161 is 38.3cm/s, which is also lower than R290. In order to avoid the risk due to flammability, charge size in the system is required to be limited so that it is well below the LFL. Liang et al (2011) fully understood the EN60335-2-40 and calculated the maximum refrigerant charge per room floor area for flammability refrigerants, the result showed that R161 is 0.153kg/kw and R290 is 0.103kg/kw. The maximum refrigerant charge of R161 and R290 are 0.6kg and 0.3kg for unfixed installation unitary refrigeration system at the condition of 0.15 kw/m^2 cooling demand. The toxicity test shows that OEL of R161 is 1822 ppm when mouse suck the refrigerant for 28 days. Meanwhile, the OEL of R22 and R290 are both 1000 that make clear that R161 has higher toxicity safe index. The available experiments imply that R161 can be easily compatible with most of PAG or POE oil, so R161 can direct use R22 compressor lubricant oil.

3. THEORETICAL THERMODYNAMIC CYCLE SIMULATION

3.1 Simulation Conditions

In order to comprehensively compare the system performance of R161 to that of R22 and R290, a theoretic thermodynamic cycle simulation based on common experimental conditions was carried out. Pressure drops in suction line, discharge line, condenser and evaporator were all considered for keeping possibly consistent with actual cycle and were expressed in form of saturated temperature drops. Condensation temperature was the saturated temperature corresponding to inlet pressure of condenser and evaporation temperature was the saturated temperature corresponding to outlet pressure of evaporator. The parameters of simulation work condition were listed in table 2.

Table 2: Simulation conditions

Conditions	High Temp. Cooling	Rated Cooling	Rated Heating	Low Temp. Heating
Condensation Temp. (℃)	56	44	40	32
Evaporation Temp. (℃)	12	10	2	-15
Subcooling (℃)	2	5	6	8
Superheat(℃)	5	5	5	5
Condensation Temp. Drop(℃)	1	1	1	1
Evaporation Temp. Drop(℃)	3	3	3	3
Discharge line Temp. Drop(℃)	0.5	0.5	0.5	0.5
Suction line Temp. Drop(℃)	2	2	2	2
Suction line Superheat (℃)	3	3	3	3

The isentropic efficiency, volumetric efficiency, conversion efficiency (shaft work to power consumption by compressor unit), and power consumption ratio (power consumption by compressor unit to the total power consumed by air conditioner) were all regarded as constant, which were given in table 3. A compressor with 3.5m^3/h volumetric displacement was chosen to calculate cooling or heating capacity and compressor power consumption.

Table 3: Compressor parameters

Isentropic Efficiency	Volumetric Efficiency	Conversion Efficiency	Power Consumption Ratio
0.7	0.85	0.85	0.9

3.2 Simulation results

The theoretic thermodynamic cycle simulation results of mass cooling capacity and heating capacity, volumetric cooling capacity and heating capacity, cooling capacity and heating capacity of R22, R161 and R290 are plotted in fig 2,3,4 respectively. The work condition of A, B, C, D are stands for rated cooling, high temperature cooling, rated heating, low temperature heating operation.

The mass cooling capacity at rated cooling condition of R161 and R290 were 85.8% and 77.1% higher than that of R22, and mass heating capacity at rated heating condition of R161 and R290 were 84.8% and 75.7% higher than that of R22. Higher mass cooling or heating capacity indicated smaller refrigerant mass flow rate of R161 for the same capacity system. From the fig 6, it can be seen that R161 cycle was about 51.1% lower mass flow rate than that of R22 at all conditions.

The volumetric cooling or heating capacity determined the compressor displacement. In this paper, the same compressor displacement was chosen in simulation, so compared to R22, R161 and R290 cycle cooling or heating capacity improvement in fig 4 was similar to volumetric cooling or heating capacity in fig 3. Compared to R22, volumetric cooling capacity of R161 and R290 reduced 9.2% and 15.1% at rated cooling work condition, volumetric heating capacity of R161 and R290 reduced 9.8% and 13.7% at rated heating work condition. Lower volumetric capacity of R161 and R290 showed that R161and R290 should use larger displacement compressor with similar or heating capacity.

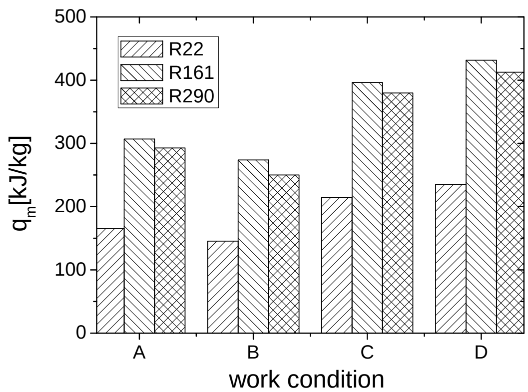


Fig 2: Mass cooling or heating capacity

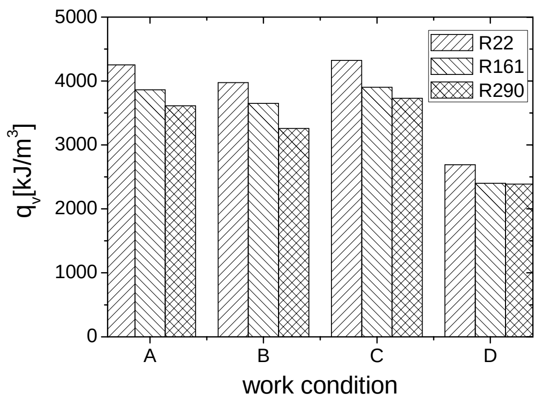


Fig 3: Volumetric cooling or heating capacity

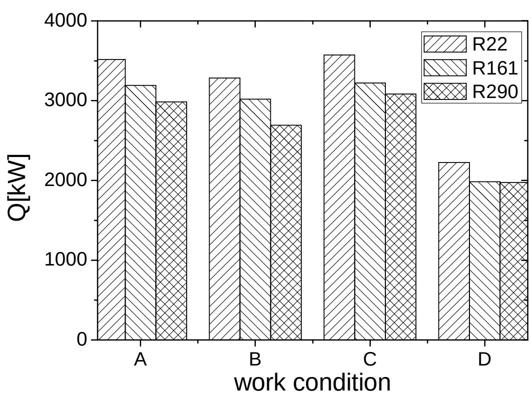


Fig 4: Cooling or heating capacity

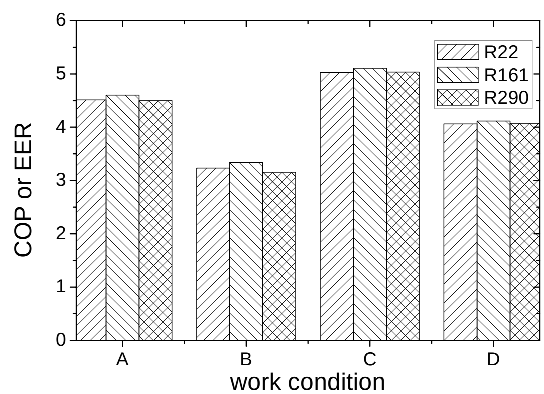


Fig 5: EER or COP

Figure 5 showed that cooling EER of R161 increased 2% and R290 reduced 0.3% at rated cooling mode compared with R22, heating COP of R161 increased 1.63% and R290 reduced 0.18% at rated heating mode. As shown in figure 7, the compressor discharge temperatures of R161 and R290 reduced 5℃ and 17℃ at rated cooling mode, respectively. The lower discharge temperature was beneficial for compressor.

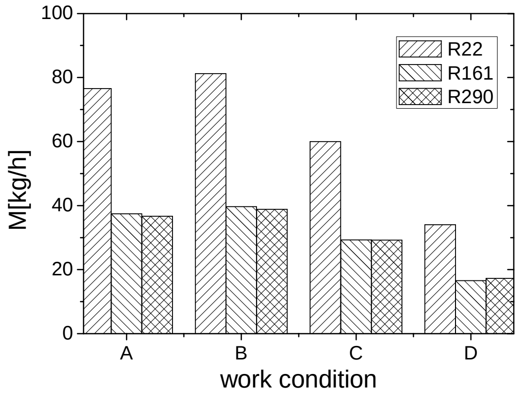


Fig 6: Refrigerant mass flow rate

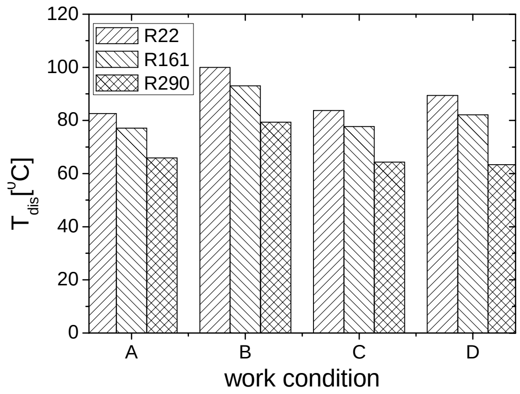


Fig 7: Compressor discharge temperature

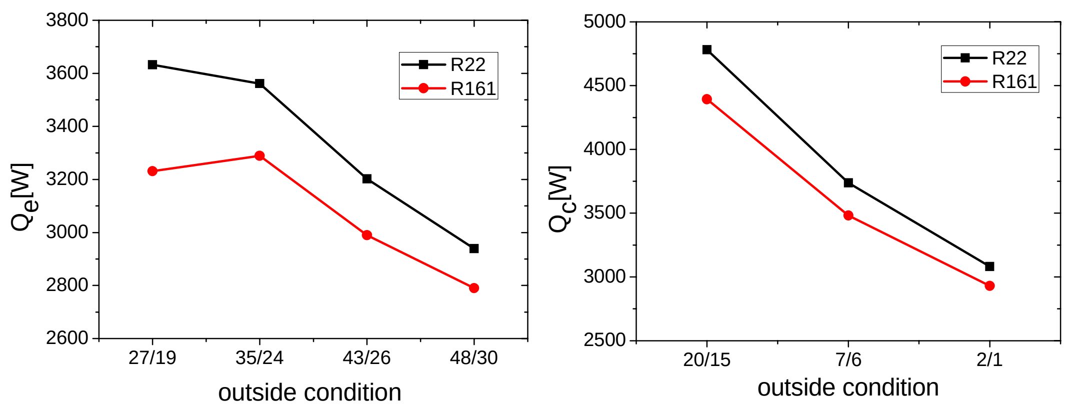
4. EXPERIMENT

Based on mentioned properties comparison and theoretic thermodynamic analysis, it was found that R161 had superior system performance. A detail and comprehensive comparison experiment was carried out to evaluate the performance of R161 as R22 alternative in a 3.5kW residential air condition system. The experimental conditions were listed in table 4. The prototype R22 system refrigerant charge was 1350g and the optimized refrigerant charge for R161 system was 770g. The refrigerant charge of R161 system was about 57% of R22 system and this matched well with theoretical value of 55%.

Table 4: Experimental conditions

Conditions	Cooling mode (dry bulb / wet bulb)				Heating mode (dry bulb/ wet bulb)		
Outdoor	27/24	35/24	43/26	48/30	20/15	7/6	2/1
Indoor	27/19				20/15		

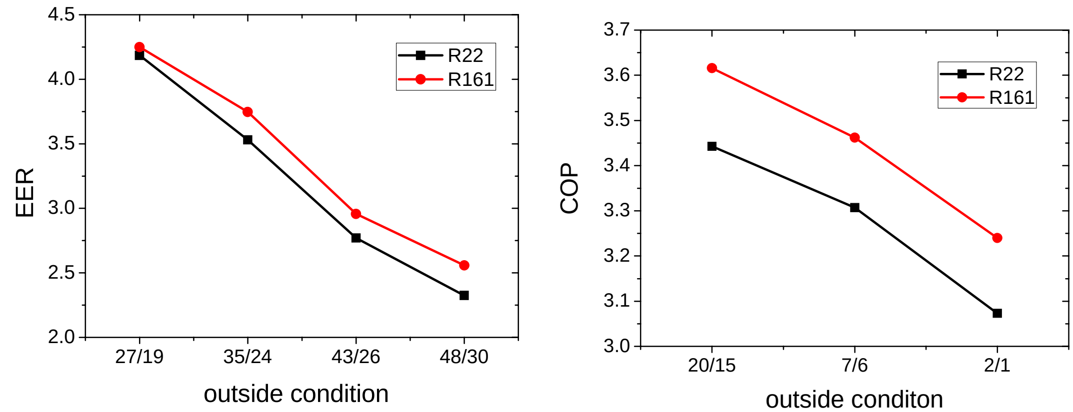
Figure 8, figure 9 and figure 10 showed the comparison of cooling and heating capacity, cooling EER, heating COP and compressor discharge temperature of R161 and R22 system in various outdoor environmental conditions. It can be found that R161 system had better lower capacity, higher EER or COP and lower discharge temperature performance.



(a) Cooling mode (b) Heating mode

Fig 8: Comparison of cooling capacity and heating capacity of R161 and R22

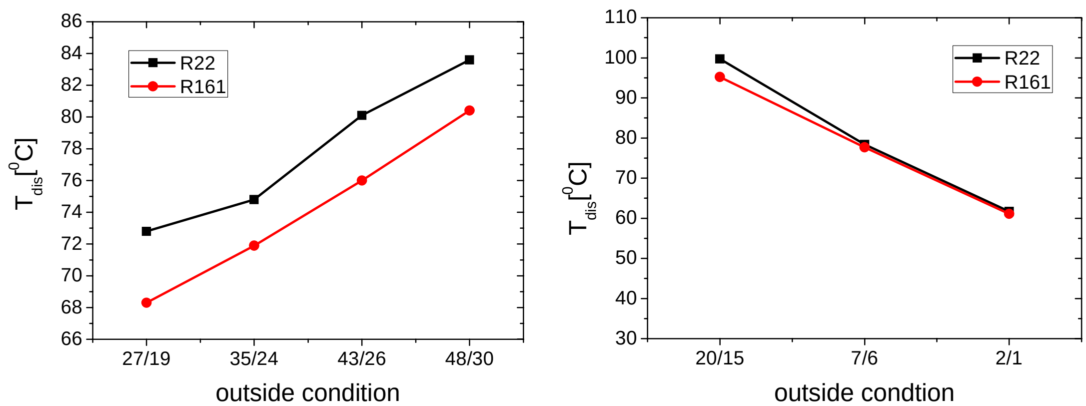
At the rated cooling condition, R161 system reduced 7.6% cooling capacity and increased 6.1% cooling EER than that of R22 system. With the increasing of outside temperature, the cooling capacity elevation ranged -11% to -5.1% and EER elevation ranged with the scope of 1.5%~10%. Similarly, the heating capacity elevation ranged -8.1% to -4.9% and COP elevation ranged with the scope of 5.0%~5.4%.



(a) Cooling mode (b) Heating mode

Fig 9: Comparison of cooling EER and heating COP of R161 and R22

As seen in figure 10, the compressor discharge temperature of R161 system in both cooling and heating mode was lower than that of R22 system. The R161 system discharge temperature was lower about 6℃ at varying outside temperature when in the mode of cooling. However, when in the mode of heating the R161 system discharge temperature was slightly lower than R22 system.



(a) Cooling mode (b) Heating mode

Fig 10: Comparison of cooling and heating discharge temperature of R161 and R22

5. CONCLUSIONS

Based on the results of properties comparison, theoretic thermodynamic cycle calculation and experimental study on R161 and R22 in an identical residential air conditioner, it can be found that R161 has an attractive advantage on thermodynamic and thermo-physical properties, the simulated result showed that EER of R161 increased 2% and cooling capacity reduced 9.2% compared to R22, at the same time discharge temperature declined and refrigerant charge reduced 45%, Furthermore, the experimental result validated the simulation result well. But the flammability was still the biggest challenge when using in residential air conditioning applications. A lot of measures should be taken such as using small diameter tube or microchannel heat exchanger to reduce the refrigerant charge. Further more, the ventilation should be done well. Besides, any electrical spark, hot surfaces, static electricity or a flame from brazing torch should be carefully used or protected.

NOMENCLATURE

ODP	Ozone depletion potential	**Subscripts**	
GWP	Global warming potential	v	volume
LFL	Lower flammability limit	m	mass
OEL	Occupational exposure limit	dis	displacement
P	pressure	e	evaporator
q	per cooling or heating capacity	c	condenser
Q	cooling or heating capacity		
EER	energy efficiency ratio		
COP	coefficient of performance		
M	mass flow rate		
T	temperature		

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