CFD Simulation and Experimental Study on Single Phase Dual Temperature Ejector

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ABSTRACT

An adjust ejector was designed based on classical gas dynamical function method in single phase dual temperature ejector refrigeration system. Further more ejector optimal dimension influenced by mass flow distribution ratio, high and low evaporating temperature was also analyzed in this paper. The velocity field and pressure field of the adjustable ejector was simulated by CFD software. Moreover, the simulated ejector ratio agreed with experimental ejector ratio well. The effect of primary flow pressure, suction flow pressure and out flow pressure on ejector ratio was investigated through using CFD software. Finally the experimental comparison result indicated that the single phase dual temperature ejector system expressed superior performance than on off valve dual temperature system. The maximal cooling capacity and EER elevation was close to 12.9% and 9.5% respectively as high and low temperature evaporating temperature difference reached 16℃, this means that the single phase dual temperature ejector system was suitable for larger temperature difference situation such as freezing and cooling storage area.

1. INTRODUCTION

Throttling loss is one of the thermodynamic losses in a conventional vapor compression refrigeration cycle. In order to reduce this loss, various devices such as expander and ejector have been attempted to use instead of the conventional throttling devices. Ejector is a device that uses a high-pressure fluid to pump a low-pressure fluid to a higher pressure at diffuser outlet. Its low cost, simplicity and reliability make it attractive for being the expansion device in the refrigeration system.

With the abundant demand for refrigeration function, a lot of refrigeration systems should supply two or more evaporating temperature. Such as the refrigerator have cooling compartment and freezing compartment. Also for temperature humidity independent control system should supply 18℃ medium temperature water and 7℃ low temperature water, so the system need two different evaporating temperature. The conventional dual temperature system is using two parallel evaporators, which the high temperature side evaporator connect with pressure adjust device such as the on off valve, and thus throttling to low evaporating pressure then the two flow mixing and sucked by compressor. However, for on off valve dual temperature system it has the disadvantage of low efficiency, so many researchers consider how to improve the on off valve dual temperature performance. Much attention has been paid to use ejector to substitute on off valve to recover the expansion loss. The role of ejector acts as pre-compression, the compressor suction pressure increases then the compressor work decreases.

Lee and Kim (2002) experimental investigated on the performance of dual-evaporator refrigeration system with an ejector and found that the system COP was superior to that of the single-evaporator vapor compression system by 3~6%. Su and Ge (1998) designed and experimental studied of compression/injection hybrid refrigeration system for domestic double door refrigerators, the system COP increased about 8~12% compared with on off valve system. Liu and Cao (2008) studied on a new-type compression/injection hybrid refrigeration cycle for household refrigerator and the system energy consumption could be reduced by 9%.

In this paper, we calculate the ejector dimension according to classical aerodynamics function method at given working condition. Furthermore we design an adjust ejector by means of electronic expansion valve with a needle to control the flow pass area. Then we setup the experimental apparatus of single phase dual temperature ejector and on off valve system and compare their performance. Moreover we simulate the single phase ejector performance using CFD software based on real gas R410A model and validate with experimental result.

2. EJECTOR DESIGN

2.1 Ejector design

The adjustable 3D ejector graph is shown in Fig1. The ejector is made of three parts including the needle, nozzle and main body. The principle of flow adjustable for ejector is similar with electronic expansion valve. The flow path area of nozzle is regulated by the needle position through manually rotating the needle loop to satisfy the different load demand.

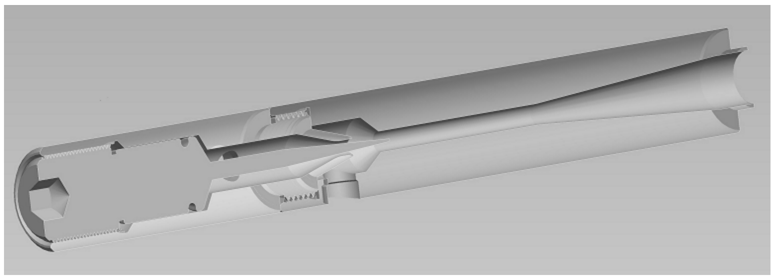


Fig 1: The adjustable ejector 3D graph

In order to calculate ejector dimension and system performance, we make an EES program according to supposed working condition. The key ejector subprogram is based on classical aerodynamics method in the published book of ejector written by Sokolov et al. The main program considering compressor theoretical displacement, isentropic efficiency, volumetric efficiency, condenser temperature, high and low temperature evaporator temperature, sub cooling degree, high and low temperature superheating degree, condenser saturation temperature drop, high and low temperature evaporator saturation temperature drop, suction and displacement saturation temperature drop, suction superheating degree, primary flow, suction flow and outflow velocity. The detailed design parameters are shown in table 1.

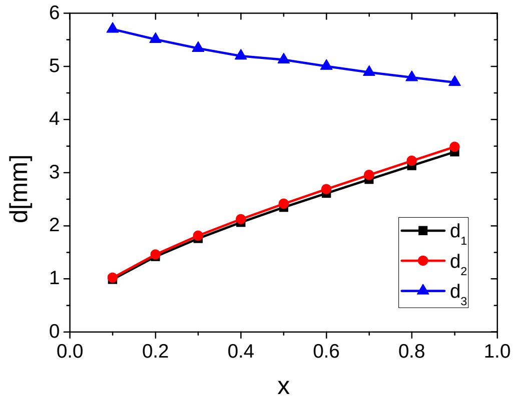
Table 1: The ejector design condition

Parameters	Q_e	$\dot{V}_{dis}$	T_c	T_{eh}	T_{el}	T_{sc}	$\triangle T_{shh}$	$\triangle T_{shl}$	$\triangle p_c$	$\triangle p_{eh}$
Units	kW	m^3/h	℃	℃	℃	℃	℃	℃	℃	℃
Value	8	5.52	44	15	2	3	3	3	1	2
parameters	$\triangle p_{el}$	$\triangle p_{suc}$	$\triangle p_{dis}$	$\triangle T_{suc}$	η_v	η_{is}	V_p	V_s	V_o	
Unit	℃	℃	℃	℃			m/s	m/s	m/s	
Value	2	1	0.5	8	0.9	0.73	10	15	10	

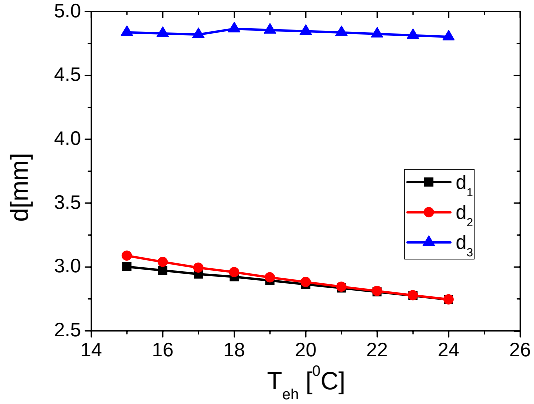
It's known to us that working condition have much influence on ejector structure dimension. The mainly impact factors such as flow distribution coefficient, high and low temperature evaporator temperature are analyzed in the article.

Fig 2a shows that flow distribution coefficient (the ratio between high temperature mass flux and total mass flux) impact much on ejector dimension remarkably. When flow distribution coefficient increases, the high temperature side refrigerant flow increases obviously which result in the throat diameter and nozzle outlet diameter linear increasing. However, the increasing of high temperature side refrigerant flow leads the high temperature side refrigerant kinetic energy which converted from pressure energy also increases, and thus that the refrigerant velocity in mixing chamber increases. This result in the mixing chamber diameter reduces since the total flow is constant.

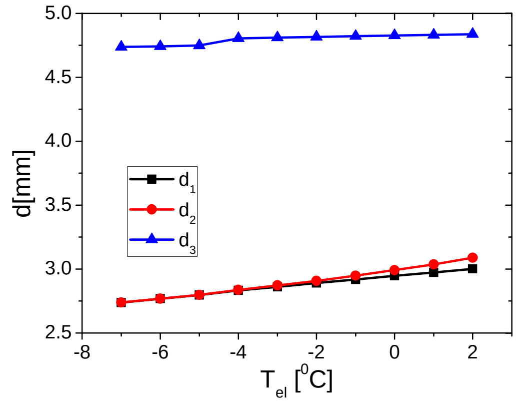
Fig 2b and Fig 2c show that high and low evaporator temperature impact much less on ejector dimension. The pressure difference between nozzle inlet and nozzle outlet increases when high temperature evaporator temperature increases or low temperature evaporator reduces. This leads the refrigerant kinetic energy which converted from pressure energy also increases, and thus that the refrigerant velocity in the nozzle increases result in the increase of nozzle diameter. For refrigerant total flow and velocity in mixing chamber are approximately constant, the mixing chamber changes little with the variation of evaporator temperature.



(a) Flow distribution coefficient



(b) High temperature evaporator temperature



(c) Low temperature evaporator temperature

Fig 2: The variation of ejector radial dimension with flow distribution coefficient, high and low temperature evaporator temperature

3. CFD SIMULATION

3.1 CFD model and boundary conditions

A lot of published papers have validated that CFD software can well predict single phase ejector performance. In this paper we use STAR-CD software to simulate ejector interior flow field and analyze the needle position influence on ejector performance.

We choose 2-Dimensional axisymmetric model, based pressure implicit solver, side suction flow inlet simplified to axis annular inlet, viscous choose “realizable k-ε” model for realizable k-ε model can model the dissipation rate of the round or axisymmetric ejector as in our model accurately with the introduction of a new eddy-viscosity formula and a new model dissipation rate equation and the parameters are default set, near wall treatment adopt standard wall function method, refrigerant property choose R410A superheating vapor, ideal gas model, Cp is 1.2 kJ/(kg.k), thermal conductivity is 0.012w/(m.k), viscosity is 1.2e-5kg/(m.s), molecular weight is 72.585kg/(kg.mol), boundary conditions for primary flow, suction flow and out flow are pressure inlet, pressure inlet and pressure outlet respectively.

3.2 CFD model validation

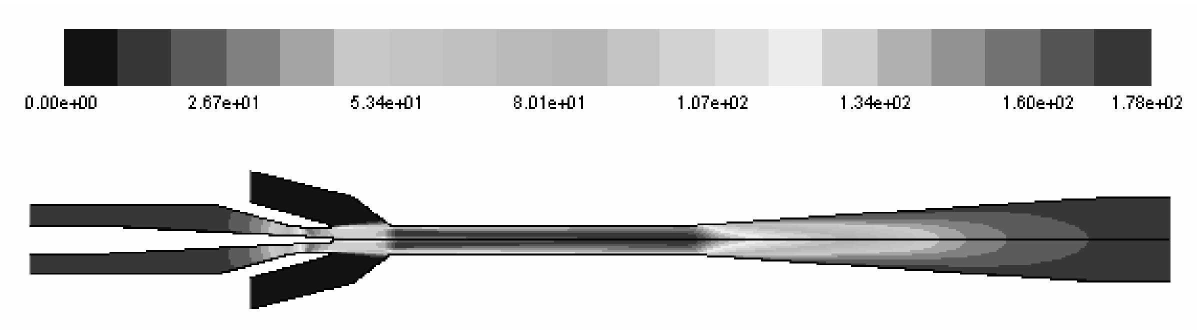
In order to validate simulation accuracy, we setup the single phase dual temperature ejector experimental apparatus and test four different throat area conditions, Table 2 shows that CFD simulated ejector ratio match well with experimental ejector ratio.

Table 2: Comparison of CFD simulation with experiment result

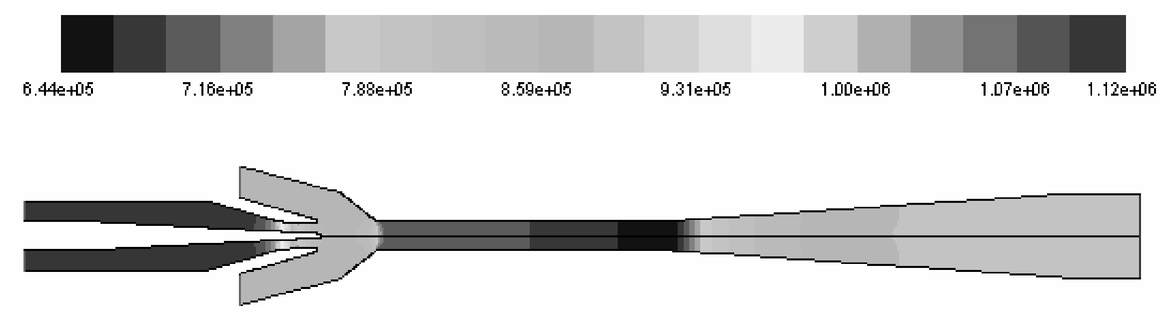
Parameters	**A_1**	**P_p**	**T_p**	**P_s**	**T_s**	**P_o**	**T_o**	**u_{cal}**	**u_{exp}**	**Err%**
Units	mm^2	kPa	℃	kPa	℃	kPa	℃			
1	9.424	1125	20.3	860	6.1	893	16.1	0.314	0.33	-4.8
2	9.067	1106	22.8	837	10.7	878	19.1	0.375	0.327	14.6
3	8.635	1125	21	814	14.3	863	18.2	0.337	0.323	4.5
4	8.135	1185	15.4	729	25.1	807	10	0.32	0.317	0.94

3.3 Ejector interior flow field

Fig 3a and Fig 3b show the velocity field and pressure field of the adjust ejector respectively, Fig 3a clearly shows that primary flow continuously accelerate and drop pressure through the nozzle. Then primary flow and suction flow exchange momentum at the inlet of mixing chamber and accelerate farther in mixing chamber. After that the mixing refrigerant velocity reduces and kinetic energy converts to pressure energy. The Fig 3b also shows that at the inlet of mixing chamber inlet and diffuser chamber inlet exist sharp pressure break.



(a) velocity field



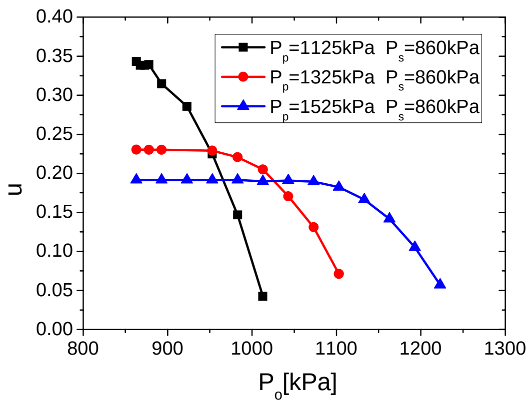
(b) pressure field

Fig 3: The single phase ejector flow field

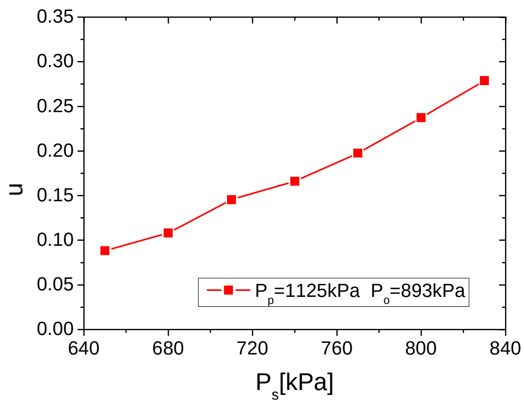
3.4 CFD simulated ejector performance analysis

Fig 4a shows the ejector ratio impacted by ejector out flow pressure, ejector ratio keep constant with the increasing of back pressure early. However, as the ejector outlet pressure reaches a critical valve Pc*, ejector ratio reduce rapidly and this indicates that ejector only run normally at an appropriate back pressure scope. Furthermore Fig 5 also shows that critical back pressure elevates with the increasing of primary pressure.

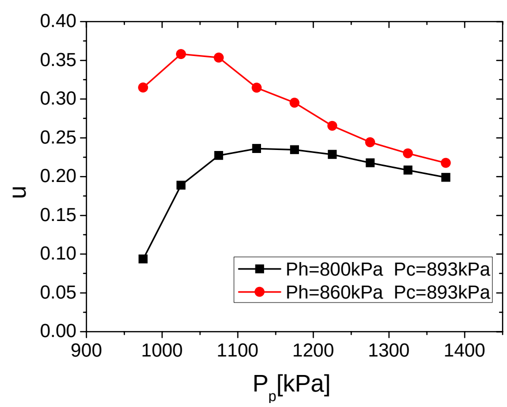
Fig 4b shows the ejector ratio impacted by ejector suction flow pressure, ejector ratio gradually increases as suction flow pressure elevates. The reason for such phenomenon is that the pressure difference between suction flow pressure and nozzle outlet pressure increases as suction flow pressure elevates which causes the primary flow dragging the suction flow strongly. Besides the elevation of suction flow pressure enhances the flow overcome the back pressure ability.
Fig 4c shows the ejector ratio impacted by ejector primary flow pressure. As the primary flow pressure elevates, the ejector ratio increases firstly and then gradually reduces. There exists an optimal primary flow pressure make the ejector ratio reach maximal value. Thus it is can be seen that adding primary flow pressure can't always improve the ejector performance, when increasing to a critical value, the performance drop on the contrary.



(a) Ejector out flow pressure



(b) Ejector suction flow pressure



(c) Ejector primary flow pressure

Fig 4: The variation of ejector ratio with ejector pressure

4. EXPERIMENT

4.1 Test facility

The schematic diagram of the single phase dual temperature ejector system experimental apparatus is shown in Fig 5. The refrigerant loop consists of compressor, condenser, total refrigerant flow meter, primary refrigerant flow meter, water flow meter, high and low temperature electronic expansion valve, high and low temperature evaporator, sight glass, ejector. The style of the compressor is R410A two-cylinder inverter single stage rotary which is produced by Mitsubishi Electric, the compressor rated displacement is 22cm3/rev, rated work and the cooling capacity are 2.2kW and 7.13kW respectively, refrigerant flow is regulated by the inverter, the heat exchangers contain one tube finned condenser and two tube in tube evaporators, the two electronic expansion valves control the high temperature side and low temperature side refrigerant flow respectively. The refrigerant and water flow meter use the same style and flow range is 0.3-18kg/min produced by Krohne, the accuracy of the flow meter is within 0.2%, the temperatures are measured by T-type thermocouples having accuracy of 0.1℃, the sight glass is to check whether the ejector refrigerant inlet is in superheating or two phase state.

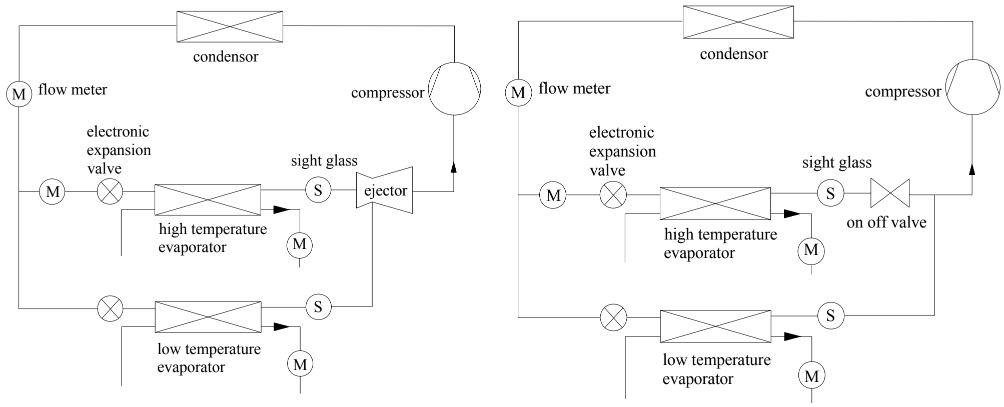


Fig 5: Single phase ejector and on off valve dual temperature system

The ejector is manufactured by a precision mechanism manufacture corporation. Compared with single phase dual temperature ejector system, the on off valve is using on off valve to substitute the sing phase ejector and the rest parts for the two systems are alike with each other.

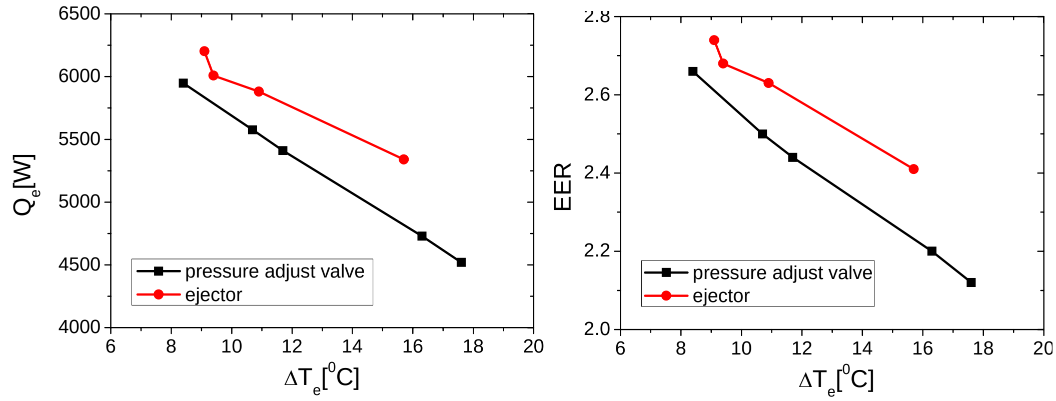
The experimental conditions are similar for the two systems and test conditions are listed in table 3, the total water flow (the sum of high and temperature side) is 500 L/h, the high side water flow rate is 7.6 L/min, the high temperature and low temperature side inlet water temperature is 25℃, the refrigerant charge for both two systems is 4380g. The expression of high and low temperature evaporator temperature difference is through controlling the position of needle or on off valve.

Table 3: The experimental test conditions

High and low temperature evaporator temperature difference	High temperature electronic expansion valve opening	Low temperature electronic expansion valve opening	Compressor frequency
℃	steps	steps	HZ
8	310	120	70
12	310	120	70
16	310	120	70
8	290	120	70
8	300	120	70
8	320	120	70
8	330	120	70
8	350	120	70
8	310	90	70
8	310	100	70
8	310	110	70
8	310	130	70
8	310	140	70
8	310	120	60
8	310	120	50

4.2 Experimental result

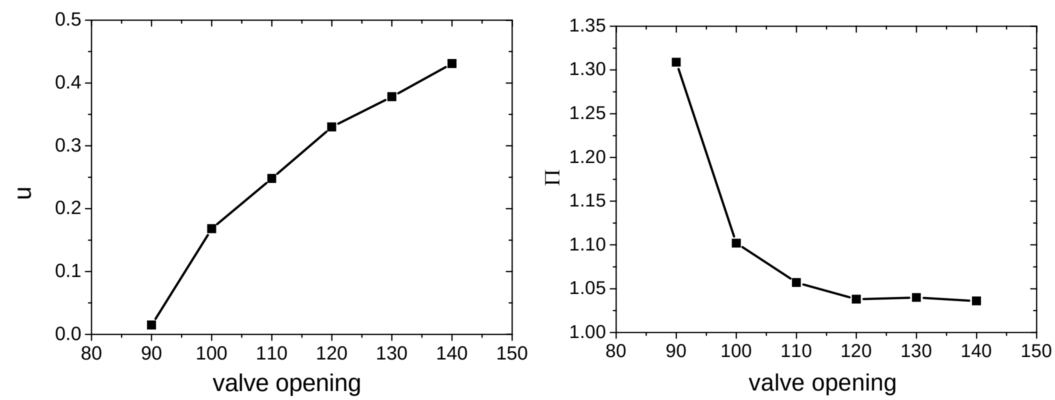
Fig 6a shows the effect of high and low evaporator temperature difference on the both two systems performance. The method to adjust high and low evaporator temperature difference of these two systems is through adjusting the on off valve position and the needle position respectively. The deeper as rotating the ejector needle or on off valve position, the lager temperature difference you gets. Referring to fig 6a and 6b, the cooling capacity for ejector system is higher about 4.3% than on off valve system and the EER is higher about 4.2% at the high and low temperature evaporator temperature difference of 9℃, while when the high and low temperature evaporator temperature increases to 16℃, the cooling capacity of ejector system is higher about 12.9% than on off valve system and the EER is higher about 9.5% than on off valve system.



(a) Cooling Capacity (b) EER

Fig 6: the variation of high and low temperature evaporator temperature with cooling capacity and EER

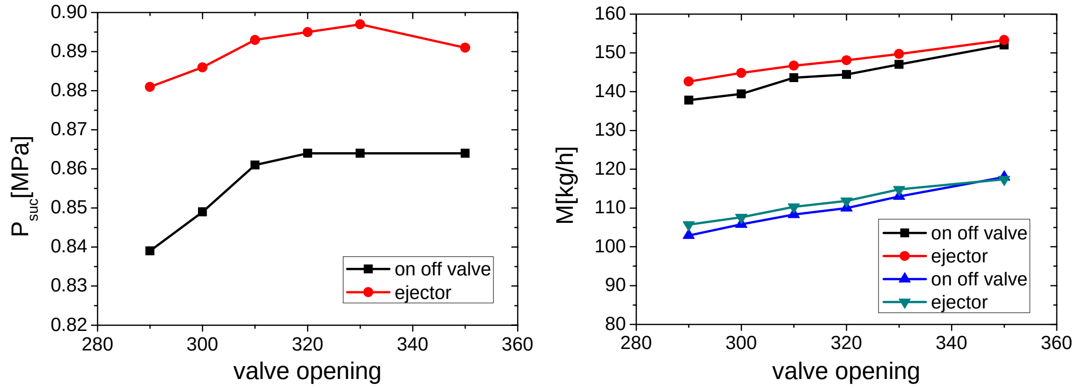
Fig 7a and fig 7b shows the effect of low temperature electronic expansion valve opening on ejector ratio and pressure ratio in single phase dual temperature ejector system, the ejector ratio is gradually increased with the increasing of low temperature electronic expansion valve opening whereas the pressure ratio is gradually dropping. When the valve opening is at 100 steps, the ejector ratio is nearly 0.16 and pressure ratio is around 1.1, however while the valve opening increases to 140 steps, the ejector ratio increases to 0.4 and pressure ratio reduces to about 1.04, this indicates that low temperature electronic expansion valve opening have much effect on ejector performance. Because the valve opening have strong relationship with suction pressure, thus the ejector ratio and pressure ratio changes greatly with the variation of low temperature electronic expansion valve opening.



(a) ejector ratio (b) pressure ratio

Fig 7: the variation of low temperature electronic expansion valve opening with ejector ratio and pressure ratio

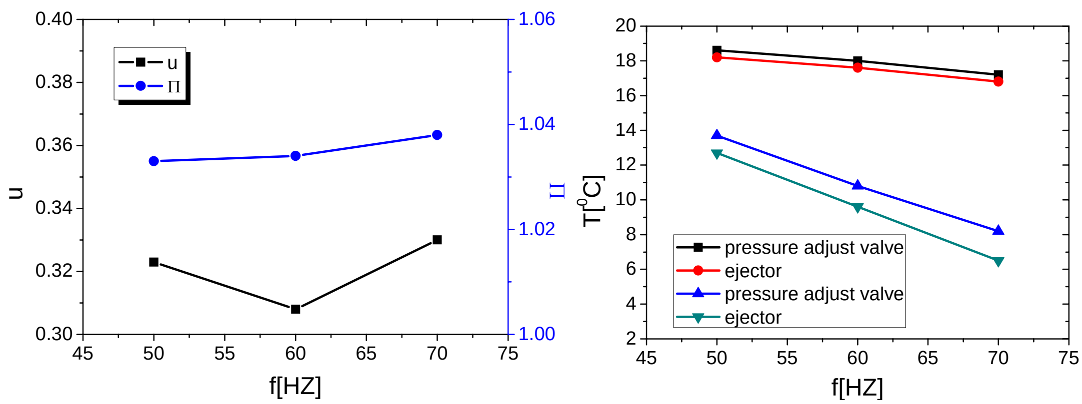
Fig 8a shows the effect of high temperature electronic expansion valve opening on compressor suction pressure and refrigerant mass flow rate. Referring to fig 8a, the suction pressure of ejector system is about 30 to 40 kPa higher than on off valve system when the valve opening varies in the range of 290 steps to 350 steps. Fig 8b shows that the total refrigerant mass flow of ejector system is about 4.8 kg/h a little higher than on off valve system for higher suction pressure at the valve opening of 290 steps. At the same time high temperature side refrigerant mass flow rate difference is around 2.8kg/h. The advantage of mass flow increase is gradually weakened with the increase of high temperature electronic expansion valve opening.



(a) compressor suction pressure (b) refrigerant mass flow rate

Fig 8: the variation of high temperature electronic expansion valve opening with compressor suction pressure and refrigerant total and high temperature side mass flow rate

Fig 9a shows the effect of compressor frequency on ejector ratio and pressure ratio in single phase dual temperature ejector system. Referring to fig 9a, it is found that the ejector ratio and pressure ratio almost remains unchanged as the compressor frequency changes from 50HZ to 70HZ. The reason for such result is that compressor frequency mainly impacts on total refrigerant mass flow rate and two branch mass flow rate at one scale. Hence, the ejector ratio changes a little when the compressor frequency varies in a wide range. Moreover pressure ratio mainly relies on ejector ratio, so pressure ratio almost remains constant with slight ejector ratio variation. Fig 9b shows the outlet water temperature of high temperature side and low temperature side respectively. The outlet water temperature is linearly reducing with the increase of compressor frequency for both two systems. Further more the water temperature for ejector system is slightly lower than on off valve system because of better cooling capacity at same water mass flow rate.



(a) ejector ratio and pressure ratio (b) outlet water temperature

Fig 9: the variation of compressor frequency with ejector ratio, pressure ratio and high temperature side and low temperature side outlet water temperature

5. CONCLUSIONS

In this paper an adjustable ejector was designed according to dynamical function method, analyzing the impaction of flow distribution coefficient, high and low temperature evaporator temperature on ejector designed dimension, using CFD software to simulate the ejector flow field and validate with experimental result. Setting up the on off valve and single phase ejector dual temperature experimental apparatus and comparing the two systems performance, major conclusions are summarized as follows:

- Flow distribution coefficient influence much on ejector diameter. However, high and low temperature evaporator temperature impact much less on ejector diameter.
- The comparison of CFD simulated and experimental result indicates that the CFD software can predict single phase ejector performance well.
- The simulated result shows that when ejector outlet flow pressure increases, the ejector ratio remains constant until reaching a critical valve Po*, then drops sharply with the increase of ejector outlet flow pressure. When suction pressure increases, the ejector ratio is gradually increases, there exists an optimal ejector primary pressure makes the ejector ratio ultimate.
- The cooling capacity and EER of single phase ejector is higher about 12.9% and 9.5% higher than on off valve dual temperature system as high and low temperature evaporator temperature difference reaches 16℃ respectively. However, when the temperature difference reduces to 8℃, the cooling capacity and EER raises only 4.3% and 4.2% respectively. This indicates that the bigger temperature difference between the high and low temperature sides, the more benefits when comparing the two systems.
- The low temperature electronic expansion valve have great influence on ejector ratio and pressure ratio, the ejector ratio can rang from 0.1 to 0.4 and pressure ratio range from 1.3 to 1.04 with the low temperature electronic expansion valve opening rang from 90 steps to 140 steps.
- The compressor suction pressure difference between ejector system and on off system varies within 30 to 40 kPa as high temperature electronic expansion valve opening range from 290 steps to 350 steps. The total refrigerant flow rate of ejector system is higher than on off system, this enabled the ejector system cooling capacity and EER is higher than on off system.
- The compressor frequency doesn't impact much on ejector ratio or pressure ratio, however, the outlet water temperature have strong relationship with compressor frequency because of higher compressor frequency means higher cooling capacity.

NOMENCLATURE

Q	cooling capacity
$\dot{V}$	volume
T	temperature
△T	temperature difference
P	pressure
△P	pressure difference
η	efficiency
V	velocity
d	diameter
x	flow distribution coefficient
A	area
u	ejector ratio
EER	energy effiency
Π	pressure ratio
M	mass flow rate
f	frequency

Subscripts

e	evaporator
dis	displacement
c	condenser
eh	high temperature evaporator
el	low temperature evaporator
sc	sub cooling
shh	high temperature superheating
shl	low temperature superheating
suc	suction
p	primary flow
s	suction flow
*	critical
exp	experiment
cal	calculation
1	throat
2	nozzle outlet
3	mixing chamber
4	diffuser outlet

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ACKNOWLEDGEMENT

This work has been supported by Gree Electric Appliances, Inc. of Zhuhai and Chinese National Engineering Research Center of Green Refrigeration Equipment.