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Visual investigation on effect of structural parameters and operation condition of two-phase ejector

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ABSTRACT

Based on shadowgraph technique, a visual research for an ejector in transcritical CO_2 refrigeration cycle has been conducted. The mixing process and the changes of the flow structure in suction chamber was recorded. A visualization test platform with rectangular ejector was builted to collect experiment data about the performance of ejector. And images of mixing process under different mixing cross-sectional area(A) and length of the divergent section of the motive nozzle also collected. The images displayed that there existed two symmetrically premixed vortexes in suction chamber in the mixing process of primary flow and secondary flow. With the increase of primary flow pressure, the diameters of these premixed vortexes become larger, and the location of premixed vortexes also trend from the exit to the entrance of the suction chamber. Particularly, the length of divergent section of the motive nozzle and the cross-sectional area(A) of mixing section had significant effect on the merging of primary flow and secondary flow. Moreover, too long or short length of the divergent section of the motive nozzle and too small mixing cross-sectional area(A) made the location of premixed vortexes obviously trend from the exit to the entrance of the suction chamber, and the mixing flow of these two flows would not be homogeneous for this condition, which would result in the deterioration of the performance of the ejector. Finally, some special phenomenons in the observing experiment was depicted.

1. INTRODUCTION

An ejector is used in a transcritical CO_2 refrigeration cycle to lower the compressor power and increase system efficiency by recovering the expansion process losses. Deng et al. (2007) performed thermodynamic analyses and found that the transcritical CO_2 ejector expansion refrigeration cycle (EERC) had better performance than that of conventional vapor compression refrigeration cycle. Elbel and Hrnjak (2014) also pointed out that the use of an ejector may reduce the pressure drop of evaporator and increase heat transfer coefficient of evaporator, resulting in the an improvement of system COP. Li and Groll (2007) showed that COP of EERC could be improved by more than 16% over the basic transcritical CO_2 refrigerant on cycle under their operation condition.

As the core component of the EERC, ejector has significant impact on the efficiency and stability of the system. Chaiwongsa and Wongwises (2005) carried out the experimental study to investigate the effect of throat diameter of the motive nozzle on the system performance. They found that there existed a best throat diameter of motive nozzle to make the highest system efficiency. Zhu et al. (2009) pointed out that the suitable motive nozzle exit position and converging angle of mixing section could improve the system performance. Nakagawa et al. (2010) (2011) built an experiment test facility, and designed a rectangular type ejector. They analyzed the flow characteristics of two-phase ejector by inserting thermocouples into the ejector interior. Zheng et al. (2016) conducted the numerical simulation and experimental study on the improved EERC and found that with the decrease of throat diameter of motive nozzle, the gas cooler pressure was increased while the pressure of separator and evaporator were all decreased.

With the development of photics and computer technology, the visualization research become an attractive method to investigate the inner flow structure of ejector. Compared with the conventional measurement techniques like pressure, temperature sensors, this method does not damage the flow regime and can capture the change of flow structure immediately. Dvorak and Safarik (2005) conducted visualization research on air ejector, and paid attention to analyze quantitatively the boundary layer separation and phenomenon of flow structure oscillates,and found schilieren images of the flow were in the entrance of the mixing section. Using X-ray tomography technology, Bouhanguel et al. (2011) captured images of shock wave structure and the mixing processing in air ejector. Zhu and Jiang (2014) captured the images of shock wave structures after the nozzle, and the influence of the first shock wave length on the ejector entrainment performance was analyzed.

However, the previous visualization research of the ejector concentrate mainly focus on the single-phase ejector. The opening publication on transcritical CO_2 two-phase ejector has not been seen, as we known. This paper utilizes the high-speed digital camera to capture images of inner flow structure in a rectangular CO_2 ejector. Besides the mixing process of primary flow and secondary flow, as well as the change of flow structure was observed under different operation condition and structural parameters.

2. EXPERIMENTAL APPARATUS

2.1 Experimental setup of this research

A schematic of the experimental setup and most of the measurement devices were presented in Figure 1. Experimental setup consists of three parts: circulatory system of CO_2, water system for heat exchange and high-speed data acquisition system.

Circulatory system of CO_2 consists of a compressor, a gas cooler, an ejector, an evaporator, a separator, an expansion valve, some stainless steel pipe and a safety valve. The compressor CD-300h whose air displacement is $1.46m^3/h$ and rated refrigerating capacity was 3.0HP is manufactured by Dorin. The gas cooler which is 10 meters and evaporator which is 6 meters are counter-flow type heat exchanger with concentric dual tubes, which are wound into spiral coils. In the heat exchanger, the refrigerant flows through the inner tubes and the water flows through the annulus counter-currently to the refrigerant. Volume of the separator was $7.4dm^3$.Mass flow meters FC-300 and MASS- 2100 manufactured by Siemens are used to measure the refrigerant mass flow rate of primary flow and secondary flow, whose accuracy is ±0.1% of the full scale. The temperature and pressure in the setup are measured using thermocouples, resistance temperature detectors (RTDs) and pressure transducers EJA-530A made by Henghe. The accuracy of the thermocouples and RTDs is ±0.5 °C and ±0.15 °C, respectively, while the accuracy of the pressure transducer is ±0.075% of the full scale. The data is acquired using a data acquisition system including a data acquisition instrument 2700 and a data acquisition card 7700 made by Keithley connected to a computer. In the circulatory system of CO_2 ,the CO_2 is compressed to a supercritical fluid by the compressor into the gas cooler and then the high pressure CO_2 expands through the motive nozzle and entrains the fluid from the evaporator. The two fluids mix in the mixing section of the ejector and leave the ejector for the separator. The liquid portion is directed to the evaporator through the expansion valve while the vapor portion enters the compressor. This is the cycle for these two flows. This experiment system was built to observe the flow structure in the ejector.

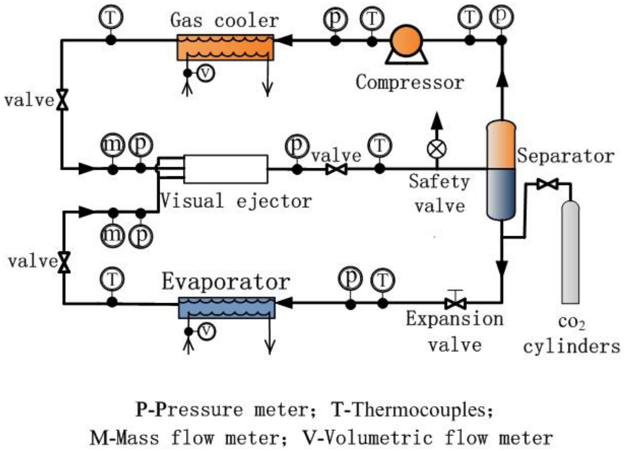

Figure 1: Schematic diagram of experimental setup

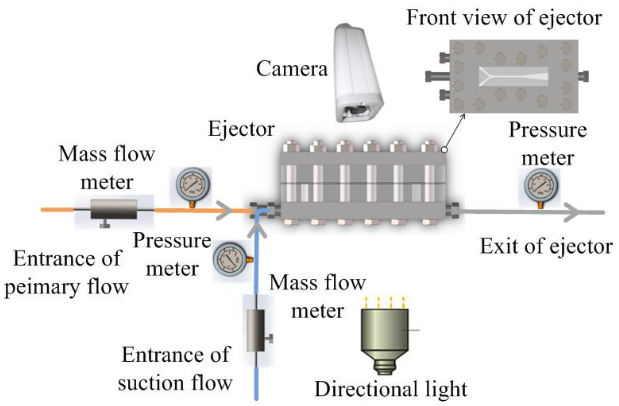

Figure 2: Schematic diagram of visualization research

2.2 Visualization system

The visualization system for the ejector has been designed and depicted in Figure 2. The AOS VITcam-CTC high-speed camera is used to capture images at a resolution of 512×1280 and a frame rate of 500 fps. A 150 W halogen lamp is used as a light source.

Due to distinct difference in density between the primary flow which was two-phase flow and secondary flow which was gas phase, the mixing process was captured by shadowgraph technique. There was a parallel beam of light into the window of the ejector and then was captured by the camera. Images were captured because of difference transmittance of light of two flows.

The structure of the visual ejector is shown in Figure 3A. The most middle stainless steel sheet of 0.8mm in thick provides a primary nozzle and part of the suction chamber, mixing section and diffuser. Then two pieces of high optical transmittance organic polymer plates A and B close to both sides of the stainless steel plate to adjust the dimensions of ejector with different thickness of 0.5 mm or 0.45mm. These two polymer plates enable the observation of the flow in the primary nozzle. Two pieces of transparent resin plate suffering the high pressure allow the visualization on the inner flow structure of the ejector. The whole device was fastened and sealed by two thick stainless steel plates with 16 bolts.

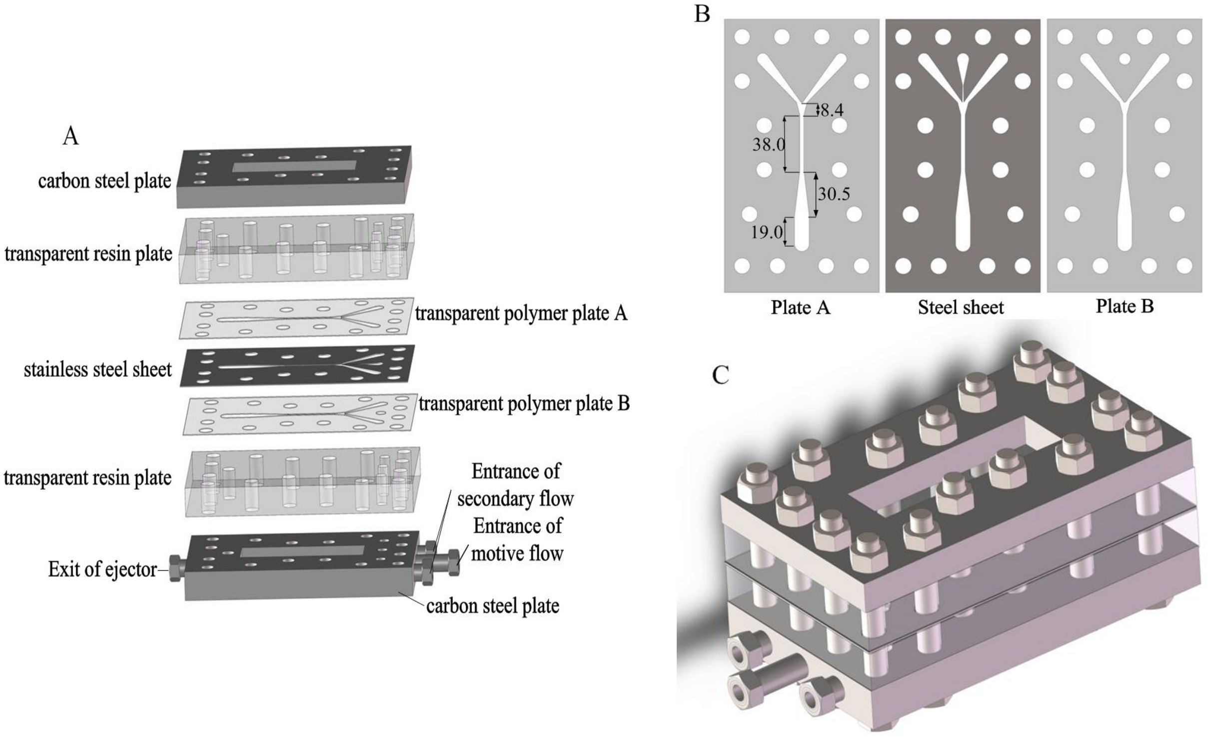

Figure 3: Schematic diagram of an ejector

Table 1: Some Parameters of the ejector

Length of suction chamber/mm	8.4	Length of mixing chamber/mm	38.0	Length of divergent chamber/mm	49.5
Width of motive nozzle exit /mm	0.94	Width of mixing chamber /mm	2.82	Width of throat/mm	0.49

3. RESULTS AND DISCUSSION

Experiments has been conducted under different operation conditions for varying mixing cross-sectional area(A) and length of divergent section of the motive nozzle. Firstly, in the case of the ejectors whose mixing cross-sectional area(A) was 4.79mm^2 and length of the divergent section in motive nozzle were 0mm（with no divergent section in motive nozzle）、5mm、11.5mm and 15mm were tested under different operation conditions. And then adjusting the primary flow respectively on 8.5MPa、9.0MPa、9.5MPa、10.0MPa、10.5MPa, the ejectors whose length of divergent section of the motive nozzle was 11.5mm and mixing cross-sectional area(A) were 3.94mm^2、4.79mm^2 and 5.07mm^2 were observed.

3.1 Characteristics of the premixed vortexes

It was observed in the experiments that the primary flow was subjective to phase change closely to the throat of motive nozzle, transforming from gas to vaporific two-phase flow. Vaporific two-phase flow from motive nozzle would intermingle with gas from motive nozzle, and then pass through the mixing channel together. Then two premixed vortexes were created due to the mixing of primary flow and secondary flow at the exit of the suction chamber. A premixed vortexes was shown in Figure 4A ,which was captured in an ejector with mixing cross-sectional area(A) was 5.07mm^2 and length of the divergent section in motive nozzle were 11.5mm. Figure 4A was processed into grayscale image with 256 gray levels by MATLAB, and then contrast enhancement and edge sharpening was help to get Figure 4B. It easy to recognize the premixed vortexes and it was found that the operation condition and structural parameters of ejector had significance impact on the location and diameter of these two premixed vortexes.

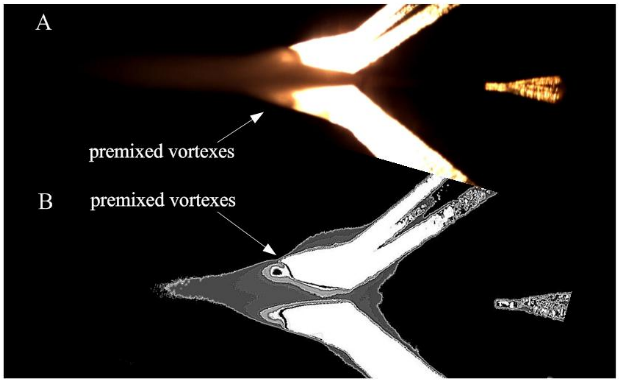

Figure 4: Premixed vortexes in ejector

Table 2: Operation condition of this experiment

	Group A					Group B				
Mixing cross-sectional area/ mm^2	4.79					5.07				
Pressure of motive flow/MPa	10.49	10.00	9.49	8.99	8.47	10.50	10.08	9.54	9.06	8.53
Pressure of primary flow/MPa	3.87	3.757	3.63	3.45	3.28	3.95	3.96	3.84	3.7	3.58
Primary mass flow/(g/s)	22.22	21.30	20.34	19.24	17.69	24.66	24.60	24.58	24.05	22.70
Suction mass flow/(g/s)	11.72	11.31	10.63	9.67	8.80	13.37	13.12	13.00	12.53	11.47
Entrainment ratio	0.527	0.531	0.523	0.504	0.497	0.542	0.533	0.529	0.521	0.505

As shown in Figure 5, the changes of structure of premixed vortexes were compared between Ejector A and Ejector B whose length of the divergent suction in motive nozzle was 11.5mm and mixing cross-sectional area(A) were

4.79mm^2 and 5.07mm^2 respectively under the operation condition of pressure of primary flow at 8.5MPa、9.0MPa、9.5MPa、10.0MPa、10.5MPa. With the drop of primary flow pressure, the speed of primary flow reduced and the diameter of the premixed vortexes declined, meanwhile the location of the premixed vortexes trended to the exit of the suction chamber. More specifically, for the pressure of primary flow decreasing from 10.5MPa to 9.5MPa, diameter of the premixed vortexes were lager, velocity difference between primary flow and secondary flow were more obvious. Entrainment ratio only decreased a little on this condition. The ejector was working on the choking station. With the pressure of primary flow decreasing from 9.5MPa to 8.5MPa, the location of the premixed vortexes trend to exit of the suction chamber more, the diameter of the premixed vortexes decreased a lot, and velocity difference between primary flow and secondary flow also decreased a lot. Entrainment ratio decreased obviously on this condition. The ejector was working on the subcritical choking station.

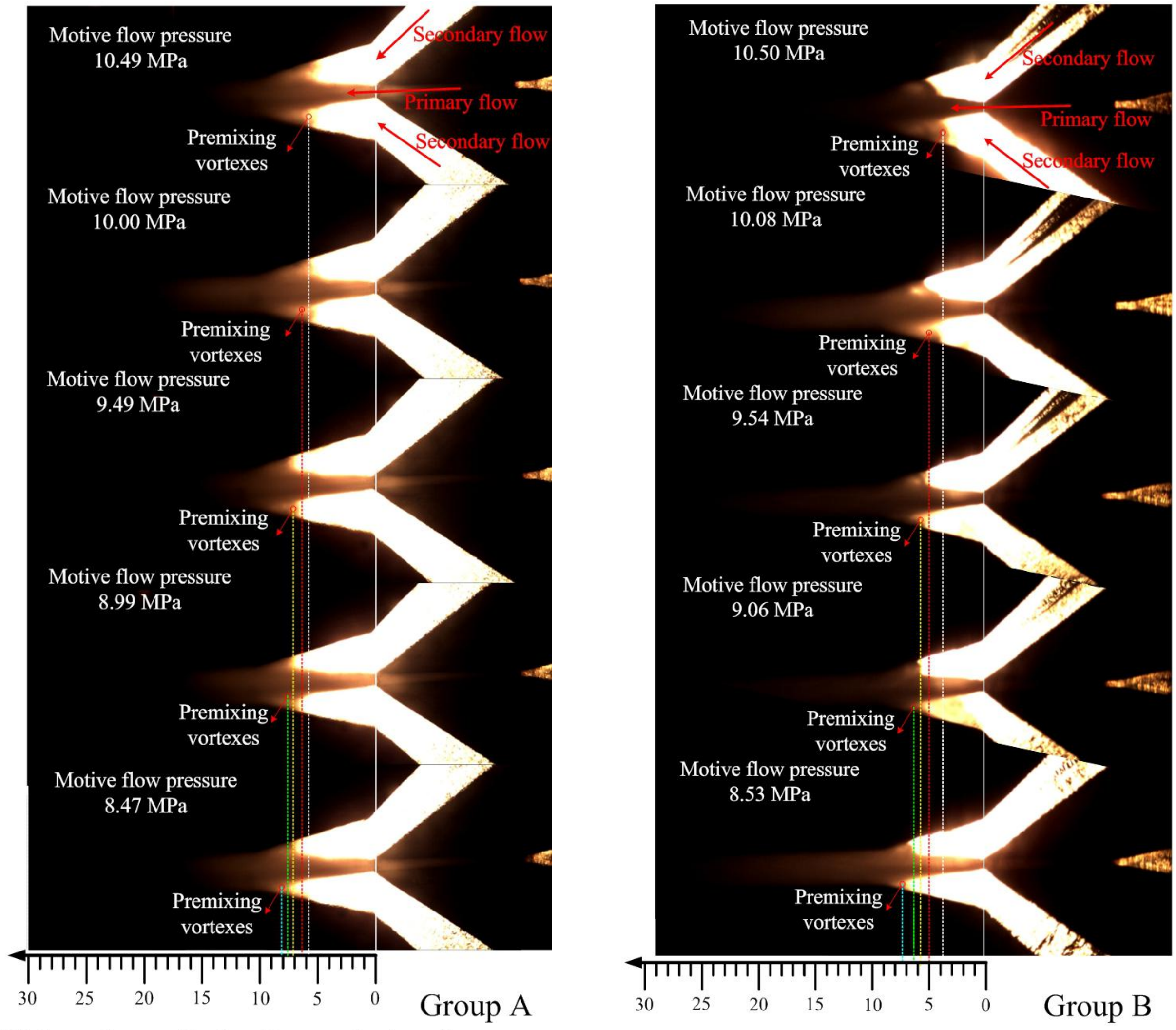

Figure 5: Flow structure under different operation and structural parameters of ejector

3.2 The effect of length of the divergent section in motive nozzle on entrainment ratio

In the case of the ejectors with mixing cross-sectional area(A) was 4.79mm^2 and length of the divergent section in motive nozzle were 0mm（with no divergent suction in motive nozzle）、5mm、11.5mm and 15mm , inner flow structure images of the ejector and entrainment ratio curve chart at different operation conditions were shown as Figure 6A and 6B.

It can be observed that the location of the premixed vortexes were nearer to the middle of the suction chamber for the ejector with length of the divergent section in motive nozzle were 15mm and 0mm. The mixing flow was not very homogeneous at the exit of the suction chamber, especially for the ejector with no divergent section in motive nozzle whose primary flow and secondary flow could even be distinguished clearly. It indicated that primary flow and secondary flow did not merged very well. However for the ejector with length of the divergent section in motive nozzle were 5mm and 11.5mm the location of the premixed vortexes were closer to the exit of the suction chamber. The mixing flow was more homogeneous at the exit of the suction chamber, indicating that this two flows merged better in this condition. Obviously, the ejector with length of the divergent section in motive nozzle were 5mm and 11.5mm presented better performance in entrainment than the ejector with length of the divergent section in motive nozzle were 15mm and 0mm. We drew a conclusion that whether this two flows merged well played an important role to guarantee good performance of an ejector.

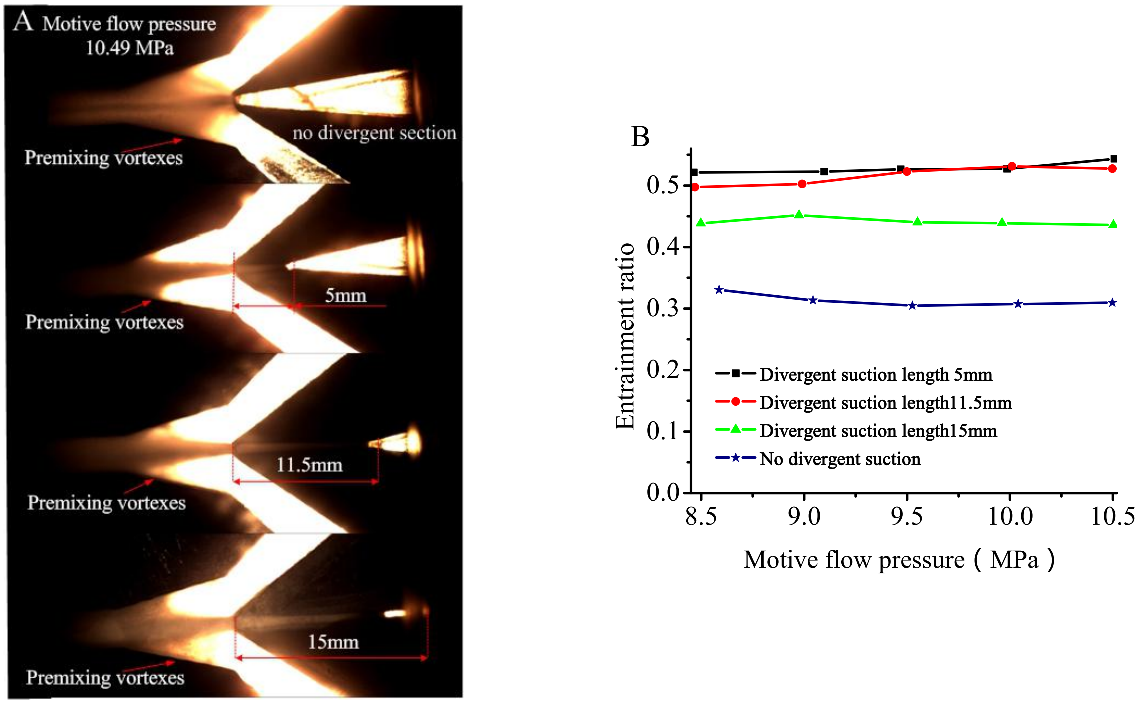

Figure 6: Flow structure and entrainment ratio for ejectors with different length of the divergent section in motive nozzle

3.3 Fluid characteristics of mixing process

It has been found in the experiment that flow pattern presented significant difference as a result of different structural parameters of ejector and operation conditions. However, there were following common characteristics in the mixing process of primary flow and secondary flow. Vaporific two-phase flow from motive nozzle passed the suction chamber keeping trace on a certain cone angle θ until merged with the premixed vortexes. This is an important approach for the mixing of primary flow and secondary flow. The direction of these two flows had been changed after this merging. The change of the angle created by vaporific two-phase flow from motive nozzle distributed symmetrically along with center axis of the ejector could been seen in the suction chamber.

Ejector A, B and C whose length of the divergent section in motive nozzle was 11.5mm and mixing cross-sectional area(A) were 3.94mm^2、4.79mm^2 and 5.07mm^2 were tested with pressure of primary flow was 10 MPa. As shown in Figure 7, flow structure of these ejectors displayed distinct differences. Vaporific two-phase flow from motive nozzle passed the suction chamber keeping trace on different cone angle θ until merged with the premixed vortexes. For Ejector A, the mixing flow is not very homogeneous at the exit of the suction chamber after the merging of primary flow and the premixed vortexes. It was easy to recognize primary flow and secondary flow in the suction chamber on this condition. This manifested that the two flows did not merge well. Diameter of the premixed vortexes also relatively small for this ejector. For Ejector C, mixing flow is more homogeneous than Ejector A at the exit of the suction chamber after the merging of primary flow and the premixed vortexes under this experiment operation condition. Diameter of the premixed vortexes was also the largest one of all these three ejectors. For Ejector B, mixing flow was almost as homogeneous as Ejector C at the exit of the suction chamber after the merging of primary flow and the premixed vortexes under this experiment operation. However, the size of diameter of the premixed vortexes in Ejector B was between Ejector C and A. Experiment data showed that entrainment ratio of Ejector A, B and C were 0.314, 0.531 and 0.533. It got a conclusion that the performance of ejector a deteriorated because of decrease of mixing cross-sectional area(A) compared with Ejector B and C. We could see that the images from the experiment agreed well with the experiment data.

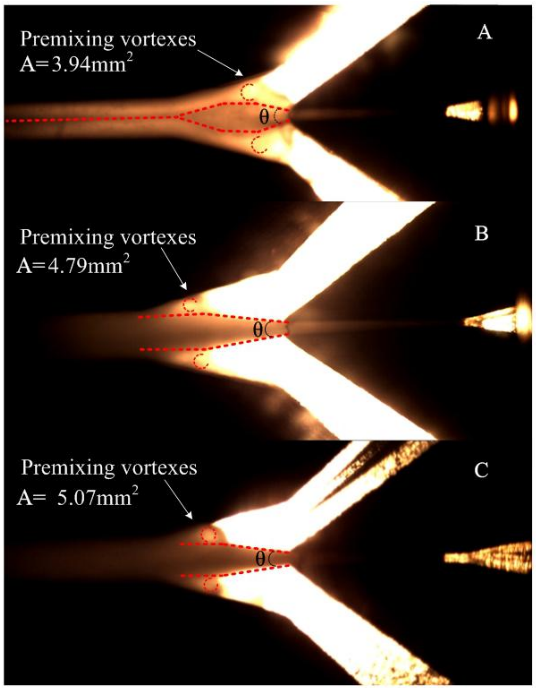

Figure 7: Flow structure for ejectors with different mixing cross-sectional area(A)

3.4 Special phenomenons in the observing experiment

For this part, some special phenomenons which help to analyze the flow structure was described, but it, as yet, can not be explained well.

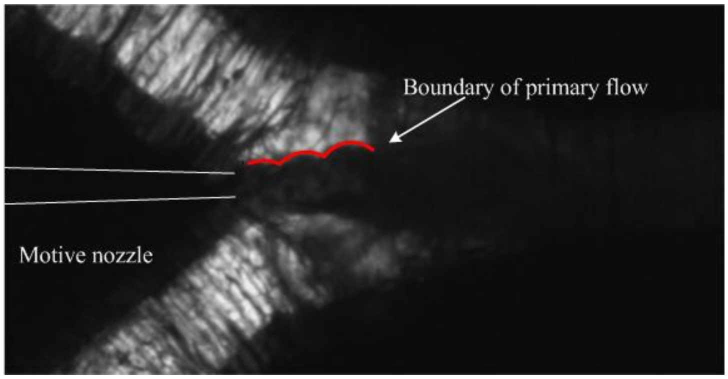

Figure 8: Flow structure for primary flow

It was shown in Figure 8 that on account of the aging of the resin plate, the images was not very clear, but the boundary of primary flow was recognized. The primary flow eject from motive nozzle demonstrated that the boundary of primary flow was curve instead of straight on certain operation condition.

For ejectors with small mixing cross-sectional area(A), it was found that a path line exist in mixing chamber for special operation condition, followed by the performance deterioration of ejector. It was shown in Figure 9, path line which symbolize the non-homogeneous of the mixing flow was found. The entrainment ratio was 0.252 on this operation condition.

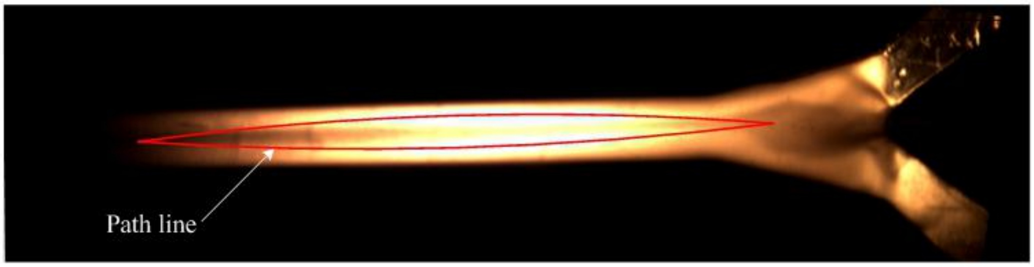

Figure 9: Path line in mixing chamber

As shown in Figure 10, multi-phase transformations were found in the divergent section of the motive nozzle. For an ejector with length of the divergent section of the motive nozzle was 11.5mm， alternately dark and bright faculae were observed in the divergent section of the motive nozzle. These faculae maybe indicate the phase transition was more complex than simply translate from supercritical phase to vaporific two-phase flow.

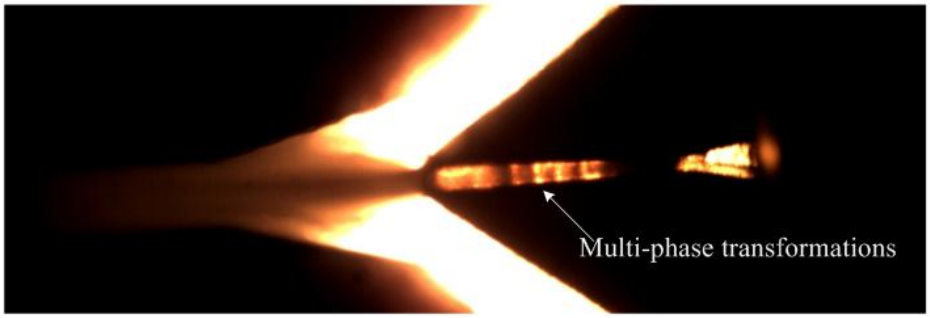

Figure 10: Path line in mixing chamber

4. CONCLUSIONS

Based on high-speed photography technology, a visualization research for an ejector in transcritical CO_2 refrigeration cycle was performed to record the mixing process of primary flow and secondary flow as well as the changes of the flow structure in the ejector. The results showed the conclusion as follow:

1) A test platform with visual ejector in transcritical CO_2 refrigeration cycle was built, and the inner flow process was recorded by high-speed photography. By analyze the mixing process of two-phase flow, it helps to optimal design of ejector. As an important component of refrigeration cycle, the optimal design of ejector helps to the performance improvement of refrigeration cycle.
2) With the increase of pressure of primary flow, the diameter of the premixed vortexes increased meanwhile the location of the premixed vortexes trended to the exit of suction chamber. Moreover, the larger of mixing cross-sectional area(A), the bigger the diameter of the premixed vortexes, and the cyclic structure of premixed vortexes was more complete.
3) Too long or too short length of divergent section of the motive nozzle or too small mixing cross-sectional area made the mixing flow no-homogeneous after the mixing of primary flow and secondary flow, resulting in the entrainment ratio of ejector was deteriorated.
4) Some special phenomenons which were unusual but meaningful like boundary curve of primary flow, path line in mixing chamber and multi-phase transformations were described.

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