

Influence of Nozzle Divergent Part Length and Throat Diameter on Vortex Control of Initially Subcooled Flashing Flow

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ABSTRACT

Expansion work recovery by two-phase ejector is known to be beneficial to vapor compression cycle performance. However, one of the biggest challenges with ejector vapor compression cycle is that the ejector cycle performance is sensitive to working condition changes which are common in many applications, including automotive AC systems. Different working conditions require different ejector geometries to achieve maximum performance. Slightly different geometries may result in substantially different COPs under the same conditions. Ejector motive nozzle throat diameter (motive nozzle restrictiveness) is one of the key parameters that can significantly affect COP. This paper presents the experimental investigation of a new motive nozzle restrictiveness control mechanism for two-phase ejectors used in vapor compression cycles, which has the advantages of being simple, potentially less costly and less vulnerable to clogging. The redesigned ejector utilizes an adjustable vortex at the motive inlet to control the nozzle restrictiveness on the flow expanded in the motive nozzle. Adjustable nozzles based on this new control mechanism were designed and manufactured for experiments with R134a. The influence of nozzle divergent part length and throat diameter on the vortex control of initially subcooled flashing flow is presented. Visualization results of the two-phase flow inside the nozzle are also provided.

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INTRODUCTION

Ejectors which can recover the kinetic energy released during the expansion process are known to be beneficial to vapor compression cycle performance (Elbel and Hrnjak [1]; Lawrence and Elbel [2]). Figure 1 shows the layout and pressure-specific enthalpy diagram of a two-phase ejector cooling cycle first proposed by Gay [3]. In this cycle, high pressure motive flow leaving the condenser enters the ejector through the motive inlet. The motive flow is expanded in the motive nozzle and creates a low pressure zone at the nozzle outlet, which entrains the suction flow from the evaporator. The two streams are mixed in the mixing chamber and kinetic energy is transferred from the motive flow to the suction flow. The mixed fluids leave the ejector through the diffuser. The fluid velocity is reduced in the diffuser which results in recompression of the mixed fluids by converting velocity energy back into pressure energy. Therefore, the ejector diffuser outlet pressure is higher than the suction flow pressure (that is, the evaporator pressure). The two-phase flow then gets separated in the separator. Saturated vapor enters the compressor while saturated liquid gets throttled and is fed into the evaporator via a metering valve. That way, kinetic energy released during expansion is utilized to compress the fluid from the evaporator. As a result, some compressor work is saved while the cooling capacity is increased if the heat rejection capacity remains constant.

Transcritical R744 cycles usually have larger expansion losses caused by throttling process than subcritical cycles under common working conditions. It is very beneficial to apply an ejector to transcritical

R744 cycles due to the large recovery potential. COP improvements of 20% over baseline cycle using a conventional expansion valve has been achieved by using an ejector (Ozaki *et al.* [4]).

Ejector cooling cycles using low-pressure refrigerants, such as R134a or R1234yf, can also have noticeable performance improvements. Lawrence and Elbel [2] experimentally investigated the performance of an alternate two-phase ejector cycle in which the pressure lift provided by the ejector was utilized in order to provide multiple evaporation temperatures. Low-pressure fluids R134a and R1234yf were used. The ejector cycle showed maximum COP improvements of 12% with R1234yf and 8% with R134a when compared to a two evaporation temperature expansion valve cycle. When compared to a single evaporation temperature expansion valve cycle, the ejector cycle showed maximum COP improvements of 6% with R1234yf and 5% with R134a.

However, ejector cycle performance is usually sensitive to working condition changes which are common in many applications, including automotive AC systems. Different working conditions require different ejector geometries to achieve maximum performance. Slightly different geometries may result in substantially different COPs under the same conditions. Therefore, it is desirable to introduce an adjustable feature to the ejector so that ejector cycle performance can be optimized under different working conditions, which could make ejector technology more suitable for real world applications (Sumeru *et al.* [5]).

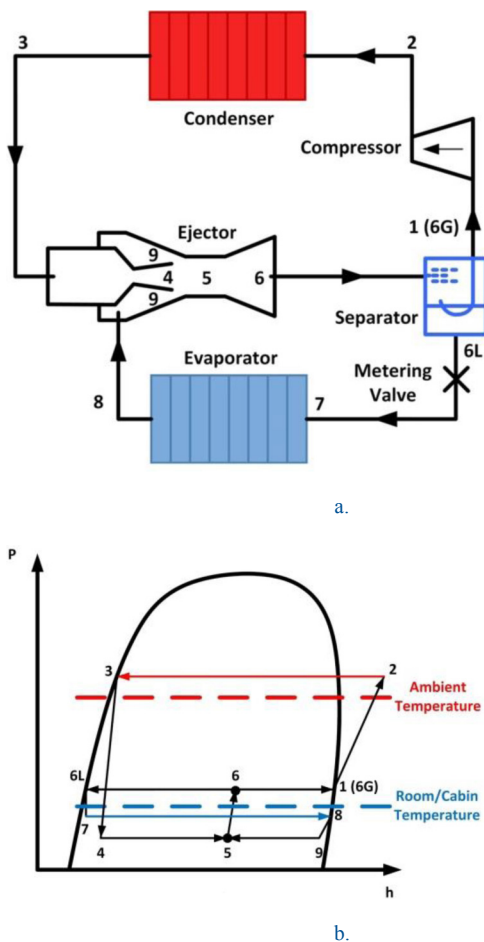


Figure 1. (a) Layout and (b) pressure-specific enthalpy diagram of the two-phase ejector cycle as proposed by Gay [3].

The ejector motive nozzle throat diameter (restrictiveness) is one of the key factors that affect ejector cycle COP. It has a direct impact on motive mass flow rate. One way to adjust the motive nozzle throat diameter in order to optimize ejector cycle performance according to the working conditions is by using a needle which moves in the axial direction so that the nozzle throat diameter can be varied, as illustrated in Figure 2.

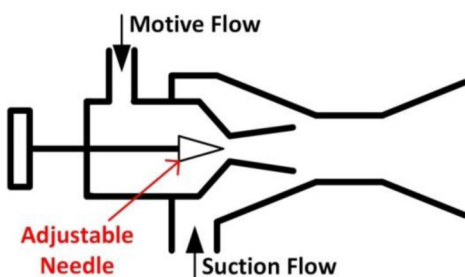


Figure 2. Variable ejector with adjustable needle in the motive nozzle.

Elbel and Hrnjak [1] were the first researchers to publish experimental results of introducing a variable two-phase ejector to a transcritical R744 system by installing a needle in the motive nozzle to control the motive nozzle throat diameter. The needle mechanism allowed control of gas cooler high-side pressure, which is an important task for a transcritical cycle to get optimum performance.

However, nozzle and ejector efficiencies were impaired because of the additional frictional losses introduced by the needle. It was found that the benefits of high-side pressure control offset the losses in nozzle and ejector efficiencies.

A variable geometry ejector with adjustable needle in the motive nozzle can optimize ejector cycle performance under different conditions, but this design is complicated and costly, and more frictional losses are incurred because of the additional surface area introduced which results in lower nozzle and ejector efficiencies. This provides motivation to develop a new technology to control the motive nozzle restrictiveness.

Zhu and Elbel [6] were the first to introduce vortex control to ejector for the control of ejector cooling cycles. A vortex ejector which employs the vortex control to adjust motive nozzle restrictiveness differs from a conventional ejector in that an adjustable vortex is generated at the ejector motive inlet, as shown in Figure 3. The motive inlet vortex can be created by injecting part of the motive flow tangentially. After injection the tangential flow is mixed with the axial motive flow. The total mass flow rate passing through the vortex nozzle is equal to the sum of mass flow rates entering through the nozzle's axial and tangential flow inlets. The ejector cooling cycle using a vortex ejector, as shown in Figure 4, is almost the same as the conventional ejector cooling cycle. The only difference is that the flow at the condenser outlet of the vortex ejector cooling cycle is separated into two streams. One stream enters the vortex ejector through the motive flow tangential inlet and another enters through the motive flow axial inlet. In such a way, a vortex is created at the ejector motive inlet. The ratio of mass flow rates through the two inlets can be adjusted by a valve installed at the motive flow tangential inlet, thereby changing the vortex strength. The pressure drop across the control valve is usually small. It can be assumed that the thermodynamic state at the motive nozzle inlet after the vortex is introduced (downstream of the tangential inlet valve) is the same as the refrigerant state at the condenser outlet.

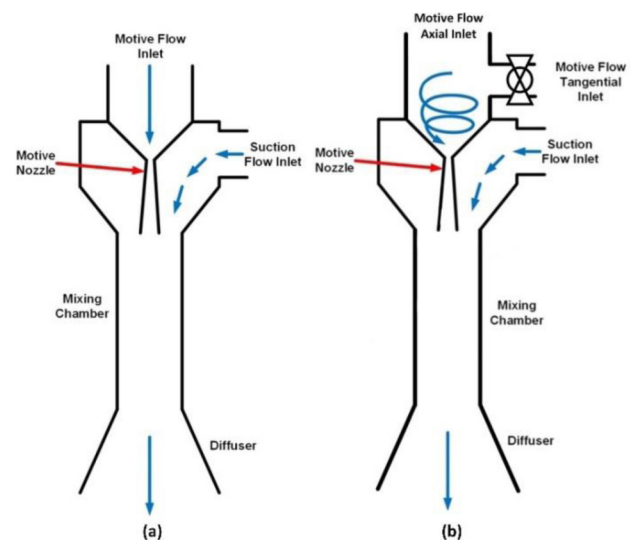


Figure 3. (a) Conventional ejector and (b) vortex ejector.

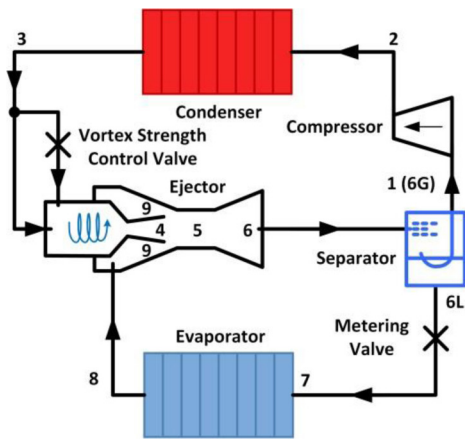


Figure 4. Vortex ejector cooling cycle.

Zhu and Elbel's experiments [6] on vortex nozzle with initially subcooled R134a show that the strength of the nozzle inlet vortex can change the restrictiveness of the two-phase nozzle without the need of changing the nozzle geometry. The nozzle becomes more restrictive as the strength of the vortex increases. The mass flow rate can be reduced by 36% with vortex control under the same inlet and outlet conditions. The control range of inlet pressures and mass flow rates that can be achieved by vortex control appears to be large enough to be applicable for real world applications.

This paper is a continuation of the previous experimental investigation of vortex control by Zhu and Elbel [6]. In the following sections, the influence of nozzle divergent part length and nozzle throat diameter on the vortex control of initially subcooled flashing flow will be presented. Visualization of initially subcooled flashing flow in the nozzle will also be provided.

EXPERIMENTAL FACILITY AND METHODS

Several transparent nozzles with controllable vortex at the nozzle inlet have been designed and manufactured for experiments, as shown in Figure 5. Important dimensions of the tested vortex nozzles have been summarized in Table 1 and these dimensions are shown with corresponding letters in Figure 5. Nozzles 1 and 2 are different in throat diameter, while nozzles 2, 3, and 4 have different divergent part lengths but the same convergent part, throat diameter and divergent angle (1 degree full divergent angle). Nozzle 4 is a nozzle that has almost no divergent part. It should be noted that the nozzle is only part of a vortex ejector. Experimental investigation of vortex ejectors in ejector cooling systems will be conducted in the future. The vortex nozzle is composed of three components: a tee-shaped part made of brass, a sleeve and a nozzle, as shown in Figure 6, both made of an optically clear resin called Waterclear Ultra 10122 from SOMOS and manufactured with a Stereo Lithography Apparatus (SLA) from 3D SYSTEMS.

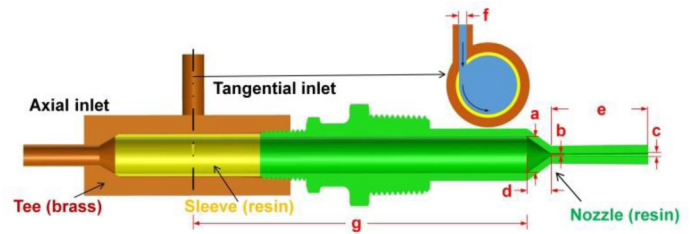


Figure 5. Vortex nozzle composed of tee, sleeve and convergent-divergent nozzle.

Table 1. Geometric parameters of tested vortex nozzles.

Nozzle #	1	2	3	4
(a) Nozzle inlet diameter (mm)	15.0	15.0	15.0	15.0
(b) Nozzle throat diameter (mm)	1.00	1.03	1.03	1.03
(c) Nozzle outlet diameter (mm)	1.74	1.77	1.07	1.03
(d) Nozzle convergent part length (mm)	9.9	9.9	9.9	9.9
(e) Nozzle divergent part length (mm)	40.0	40.0	2.1	0.3
(f) Tangential inlet inner diameter (mm)	2.0	2.0	2.0	2.0
(g) Vortex decay distance (mm)	168.0	168.0	168.0	168.0



Figure 6. 3D printed transparent convergent-divergent nozzle.

The layout of the experimental facility for the vortex nozzle tests is shown in Figure 7. A pumped-refrigerant-loop was used for adjustment of test conditions to investigate the influence of nozzle divergent part length and nozzle throat diameter on the vortex control. The working fluid was R134a. A visualization chamber was built from clear PVC pipe. The temperature readings were all obtained from ungrounded Type-T immersion thermocouples. The measured temperatures are regarded as total temperatures. Also, the pressures were read by piezo-electric pressure transducers. Pressures and