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Stefan Elbel *Creative Thermal Solutions*

Predrag Hrnjak University of Illinois at Urbana-Champaign

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Ejector Refrigeration: An Overview of Historical and Present Developments with an Emphasis on Air Conditioning Applications

Stefan ELBEL¹*, Predrag HRNJAK²

¹Creative Thermal Solutions, Inc. 2209 N. Willow Rd., Urbana, IL 61802, USA Phone: +1 (217) 344-7663, Fax: +1 (217) 344-7552, E-mail: stefan.elbel@creativethermalsolutions.com

> ²University of Illinois at Urbana-Champaign Department of Mechanical Science and Engineering 1206 W. Green St., Urbana, IL 61801, USA Phone: +1 (217) 244-6377, Fax: +1 (217) 333-1942, Email: pega@uiuc.edu

ABSTRACT

Ever since the renaissance of transcritical R744 systems in the late 1980s, ejectors have been considered to improve energy efficiencies. However, the invention of the ejector dates back far longer. This review paper gives an overview of historical and recent developments regarding air-conditioning and refrigeration systems that use ejectors. More than 150 ejector papers available in the open literature have been studied and important findings and trends were summarized. Included are the early beginnings starting with the invention of the ejector and major fields of use are outlined. Research on refrigeration cycles that utilize low-grade energy to produce a refrigeration effect is summarized. Another major field, expansion work recovery by two-phase ejector, is described next. This application appears very promising when used in transcritical R744 cycles. Less commonly encountered setups, such as systems in which ejectors are used to raise the compressor discharge pressure instead of the suction pressure are also introduced.

1. INTRODUCTION

Henry Giffard invented the condensing-type injector in 1858. The background of Giffard's invention was to find a solution to the problem of feeding liquid water to replenish the reservoir of steam engine boilers. Since then, ejectors have been studied intensively for a large number of different applications. This paper is the result of a detailed literature review conducted to give an overview of historical and present developments regarding ejector refrigeration systems. Typical applications are reviewed with a special emphasis on how ejectors can be utilized to improve the performance of air-conditioning and refrigeration systems. In the past, ejectors have mostly been used in two different cycles for refrigeration purposes. In 1910, Leblanc introduced a cycle having a vapor jet ejector. His setup allowed producing a refrigeration effect by utilizing low-grade energy. Since steam was widely available at that time, the so-called steam jet refrigeration systems became popular in air-conditioning of large buildings and railroad cars. Nowadays, such cycles are used to harness solar heat or other low-grade heat sources. The patent by Gay (1931) described how a two-phase ejector can be used to improve the performance of refrigeration systems by reducing the inherent throttling losses of the expansion valve. Typical performance characteristics, design studies, and recent developments regarding these two, as well as less commonly encountered ejector cycles have been reviewed and the results are presented in this paper. Special emphasis is put on how ejectors are currently being applied to improve the performance of transcritical R744 systems.

2. EJECTOR WORKING PRINCIPLE

As outlined in Figure 1, a typical ejector consists of a motive nozzle, a suction chamber, a mixing section, and a diffuser. The working principle of the ejector is based on converting internal energy and pressure related flow work contained in the motive fluid stream into kinetic energy. The motive nozzle is typically of a converging-diverging design. This allows the high-speed jet exiting the nozzle to become supersonic.



Figure 1: Schematic of a typical two-phase ejector design

Depending on the state of the primary fluid, the flow at the exit of the motive nozzle might be two-phase. Flashing of the primary flow inside the nozzle might be delayed due to thermodynamic and hydrodynamic non-equilibrium effects. The high-speed jet starts interacting with the secondary fluid inside the suction chamber. Momentum is transferred from the primary flow which results in an acceleration of the secondary flow. An additional suction nozzle can be used to pre-accelerate the relatively stagnant suction flow. This helps to reduce excessive shearing losses caused by large velocity differences between the two fluid streams. Depending on the operating conditions both the supersonic primary flow and the secondary flow might be choked inside the ejector. Due to static pressure differences it is possible for the primary flow core to fan out and to create a fictive throat in which the secondary flow reaches sonic condition before both streams thoroughly mix in the subsequent mixing section. The mixing section can be designed as a segment having a constant cross-sectional area but often has a tapered inlet section. Most simulation models either assume mixing at constant area associated with pressure changes or mixing at constant pressure as a result of changes in cross-sectional area of the mixing section. The mixing process is frequently accompanied by shock wave phenomena resulting in a considerable pressure rise. The total flow at the exit of the mixing section can still have high flow velocities. Thus, a diffuser is used to recover the remainder of the kinetic energy and to convert it into potential energy, thereby increasing the static pressure. Typically, the total flow exiting the diffuser has a pressure in between that of the primary and the secondary streams entering the ejector. Therefore, the ejector acts as a motive-flow driven fluid pump used to elevate the pressure of the entrained fluid. The two major characteristics which can be used to determine the performance of an ejector are the suction pressure ratio and the mass entrainment ratio. The suction pressure ratio is defined as the ratio of diffuser exit pressure to the pressure of the suction flow entering the ejector. The mass entrainment ratio is defined as the ratio of suction mass flow rate to motive mass flow rate. A well-designed ejector is able to provide large suction pressure ratios and large mass entrainment ratios at the same time.

3. HISTORICAL BACKGROUND AND TYPICAL EJECTOR APPLICATIONS

Depending on the application, injector is synonymously used for ejector. The main difference in this case is the discharge pressure at the diffuser exit. While the diffuser exit pressure of the ejector is closer to that of the suction flow than that of the motive fluid, the term injector is sometimes used for applications in which the diffuser discharge pressure can actually reach the pressure of the driving fluid. Other synonyms encountered in the literature are eductor, diffusion pump, aspirator, and jet pump. In case the total flow exiting the diffuser consists of only a single component, the most commonly encountered ejector flows can be classified according to Table 1.

	Driving flow	Driven flow	Exit flow	Remarks	
Vapor jet ejector	Vapor	Vapor	Vapor	Two-phase flow can occur, shock waves possible	
Liquid jet ejector	Liquid	Liquid	Liquid	Single-phase flow without shock waves	
Condensing ejector	Vapor	Liquid	Liquid	Two-phase flow with condensation of driving vapor, strong shock waves	
Two-phase ejector	Liquid	Vapor	Two- phase	Two-phase flow, shock waves possible	

Table 1: Commonly encountered	l single-component flo	w ejector types
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Giffard invented the condensing ejector in 1858. Kranakis (1982) gave a very detailed overview of his groundbreaking work. The background of Giffard's invention was to find a solution to the problem of feeding liquid water to replenish the reservoir of steam engine boilers. Besides being not very reliable, mechanical pumps required the steam engine to move in order to provide water to the boiler. This inherent disadvantage could be overcome with Giffard's ejector, because the motive steam required to pump liquid water was also available during standstill. Although supersonic flow at the exit of the motive nozzle would have been preferable, Giffard and other early ejector designers used converging motive nozzles. The converging-diverging motive nozzle was not introduced until 1869 by an engineer named Schau. Interestingly, this appears to be even earlier than de Laval's work, who carried out his first supersonic steam nozzle experiments in 1890. Furthermore, in the case of Giffard's ejector, the condensation of steam in the mixing section caused a void as a result of the sudden increase in density. This effect might have created an even larger suction effect than that caused by the induced current theory. Giffard empirically decided to use small diffuser angles, because he was concerned with strong turbulence effects caused by too sharply diverging angles. He modified his original ejector design by integrating a spindle valve which could be axially moved to control the motive flow rate. This design is shown in Figure 2.

Ejectors have since been used in a variety of different applications. Chunnanond and Aphornratana (2004) mentioned that in 1901, Parsons first used an ejector to remove non-condensable gases from steam condensers by utilizing the ejector's vacuum capabilities. The relatively simple and maintenance-free design has made the ejector the preferred pumping device when high reliability is required. Water or steam driven ejectors are being used to provide emergency cooling water to nuclear reactors, as reported by Beithou and Aybar (2000). In fact, the advent of nuclear power technology resulted in a number of fundamental ejector research studies during the later half of the 20th century. Ejectors can be operated in harsh temperature and pressure environments. The chemical industry makes use of ejectors to pump hazardous or combustible substances, as pointed out by Power (1993). Elgozali et al. (2002) investigated a gas-liquid reactor with an ejector-type gas distributor. In this application, the ejector was basically used to enhance the desired mixing process of two different fluid streams. Bartosiewicz et al. (2005) reported about multi-stage ejectors being used to simulate aerospace altitude testing of equipment by reducing test chamber pressures. These facilities house some of the largest ejectors ever built, as shown in Figure 3. Bartosiewicz et al. (2005) further mentioned the use of ejectors in aircraft propulsion systems for thrust augmentation purposes and to reduce the thermal signature of the exhaust gases. Addy et al. (1981) conducted research on ejectors used in high energy chemical lasers. ASHRAE (1983) pointed out the utilization of ejectors in direct contact evaporative cooling applications used for drying medical drugs and food items.



Figure 2: Henri Giffard's ejector from 1864 with integrated spindle valve for control of motive flow rate (Kranakis, 1982)



Figure 3: Multi-stage ejector facility used to create high altitude testing environments (Northrop Grumman, 2007)

4. EJECTORS USED IN AIR-CONDITIONING AND REFRIGERATION SYSTEMS

In the past, ejectors have mostly been used in two different cycles for refrigeration purposes. In 1910, Leblanc introduced a cycle having a vapor jet ejector. His setup allowed producing a refrigeration effect by utilizing low-grade energy. Since steam was widely available at that time, the so-called steam jet refrigeration systems became popular in air-conditioning of large buildings and railroad cars. The patent by Gay (1931) described how the two-phase ejector can be used to improve the performance of refrigeration systems by reducing the inherent throttling losses of the expansion valve.

4.1 Ejector for Utilization of Low-Grade Energy

Figure 4 shows the layout of a transcritical R744 vapor jet ejector cycle which utilizes a low-grade energy source to produce a refrigeration effect. The corresponding pressure-specific enthalpy diagram visualizes the processes involved. In an ideal cycle, a fraction of the liquid coming from the condenser is isentropically pumped to a higher

pressure before it enters the generator. A low-grade energy source can be used to isobarically heat the fluid in the generator. For subcritical systems, the liquid entering the generator is vaporized. The heated flow enters the motive nozzle where it isentropically expands to the mixing pressure. The motive vapor jet entering the mixing chamber has a high kinetic energy. Depending on the fluid temperature at the generator exit, it is possible that the motive stream is expanded into the two-phase region. The suction flow exiting the evaporator is entrained into the suction chamber by momentum transfer from the motive to the suction flow. A suction nozzle can be used to isentropically preaccelerate the secondary flow before it is mixed with the primary flow. Depending on the specific geometry of the ejector, the mixing process is often assumed to occur at constant pressure or at constant cross-sectional area. The mixing process is not fully reversible unless the two fluid streams enter the mixing section at equal velocities. This is not possible, because a velocity difference is needed in order to transfer momentum. The pressure of the total flow is increased in the subsequent diffuser by isentropically converting the remainder of the kinetic energy into potential energy. The vapor exiting the diffuser is condensed at constant pressure before a fraction of the liquid is sent again to the pump. The pressure of the remainder of the liquid flow is isenthalpically lowered before it enters the evaporator where heat is isobarically absorbed to provide the desired refrigeration effect. The main advantage of the vapor jet ejector cycle is that it can produce a refrigeration effect by utilizing low-grade energy sources. Most vapor jet ejectors utilize waste heat to energize the motive flow in the generator. Chunnanond and Aphornratana (2004) also mentioned research carried out on solar-powered vapor jet ejector systems. Huang et al. (1985) and Garris et al. (1998) cited work carried out on automotive air-conditioning systems using the hot exhaust gases from the combustion engine as an energy source.

Ouzzane and Aidoun (2003) explained that in the vapor jet cycle a liquid pump, a vapor generator, and an ejector replace the compressor. As a side effect, the liquid pump requires less work than a compressor for the same pressure increase, because the process follows a steeper isentrope in the pressure-specific enthalpy diagram. Huang and Chang (1999) further pointed out that the vapor jet cycle does not require any lubrication, thereby reducing the negative impact on performance caused by lubrication oil in conventional vapor compression systems. In comparison to absorption refrigeration systems, which also utilize low-grade energy, the vapor jet ejector system does not require working fluid mixtures, as pointed out by Cizungu et al. (2001). Both the vapor jet cycle and the absorption system achieve relatively low COPs. Garris et al. (1998) pointed out that consequently, oversized condensers are required for these systems. A large number of studies regarding vapor jet ejector cycles used for airconditioning and refrigeration are available in the open literature. The majority of these studies are numerical simulations, outnumbering the experimental investigations by far. Chunnanond and Aphornratana (2004) contributed a comprehensive review paper in which they gave a detailed overview of vapor jet ejector refrigeration systems. They summarized basic theories regarding fundamental ejector flow features and discussed important design issues. Huang et al. (1985) experimented with an R113 vapor jet ejector system. Their cooling capacity ranged between 0.4 kW and 2.2 kW with COPs between 0.02 and 0.26. They presented ejector performance maps and placed special emphasis on investigating flow choking inside the ejector. In a subsequent study, Huang et al. (1998) were able to show experimentally that the COP of a vapor jet ejector cycle is comparable to that of absorption systems. Their R141b solar-powered system had a COP of 0.5 at a cooling capacity of 10.5 kW. The generation, condensation, and evaporation temperatures were 90 °C, 28 °C, and 8 °C, respectively. They also showed that the ejector performance decreased for unchoked flow conditions.

4.2 Ejector for Recovery of Expansion Work

As already mentioned, a two-phase ejector can be used to improve the performance of a refrigeration system by reducing the throttling losses associated with the use of an expansion valve. The layout of such a transcritical R744 cycle and the corresponding pressure-specific enthalpy diagram are shown in Figure 5. It should be noted that the mass flow rate through the gas cooler is not identical to the evaporator mass flow rate. For this reason, Lorentzen (1983) suggested to use a temperature-entropy diagram rather than a temperature-specific entropy diagram.

In an ideal cycle, saturated vapor coming from the vapor port of the vapor-liquid separator enters the compressor and is isentropically compressed to a high pressure and temperature. Heat is isobarically rejected in the gas cooler. In the motive nozzle, the supercritical motive fluid is isentropically expanded to the mixing pressure. During the expansion process the motive fluid gains kinetic energy. Furthermore, as the fluid crosses the saturated liquid line the refrigerants starts to flash, becoming a two-phase flow. In reality however, the expansion process might occur too rapidly for the two-phase mixture to maintain hydrodynamic and thermodynamic equilibrium. Consequently, these metastability effects might cause a delayed flashing of the flow which could potentially influence the performance of the ejector. The high-speed two-phase flow transfers momentum during the entrainment of the secondary fluid exiting the evaporator. A suction nozzle can be used to isentropically pre-accelerate the suction flow before it mixes with the primary stream. Depending on the specific geometry of the ejector, the mixing process is often assumed to occur at constant pressure or at constant cross-sectional area. As in the case of the vapor jet ejector, irreversible shearing occurs when the two fluid streams enter the mixing chamber at different velocities. Under certain conditions, complex shock wave phenomena accompany the mixing process. In the subsequent diffuser, kinetic energy is converted into potential energy which causes an isentropic compression of the two-phase flow before it enters the vapor-liquid separator. While the vapor portion of the separated flow is returned to the compressor, the pressure of the liquid is isenthalpically reduced before it enters the evaporator. The evaporator isobarically absorbs heat to provide the desired refrigeration effect. It should be noted that some of the models available in the open literature neglect the fact that the pressure at the inlet of the mixing chamber has to be lower than at the evaporator exit. This pressure differential is needed for the entrainment of suction flow.





Figure 4: Transcritical R744 vapor jet refrigeration cycle for utilization of a low-grade energy source and corresponding pressure-specific enthalpy diagram

Figure 5: Transcritical R744 refrigeration cycle using a two-phase ejector for expansion work recovery and corresponding pressurespecific enthalpy diagram

There are two main advantages of Gay's (1931) refrigeration cycle using a two-phase ejector. First, the cooling capacity increases, because the ideally isentropic processes inside the ejector result in larger specific enthalpy differences across the evaporator in comparison to a system having an isenthalpic expansion valve. Second, the COP of the ejector system is improved, primarily because the compressor work is reduced. The suction pressure of the compressor is increased due to the compression effect provided by the ejector. The compressor work is further reduced by higher compressor efficiencies as a result of reduced compression ratios. As in the case of airconditioning and refrigeration systems using a vapor jet ejector, the available literature contains far more numerical two-phase ejector studies than experimental investigations. Kornhauser (1990) presented a one-dimensional iterative model for an R12 system with two-phase ejector. He defined efficiencies for the individual ejector components, namely the primary nozzle, the suction nozzle, and the diffuser. These efficiencies were introduced to represent deviations from isentropic processes. He showed a theoretical COP improvement of up to 21% over the conventional cycle with expansion valve. By variation of the constant mixing pressure, he showed that mixing losses caused by shearing can be reduced when both streams enter the mixing chamber with similar velocities. Many of the two-phase ejector models available in the open literature are based on this numerical approach. Kornhauser's study triggered intensive ejector research effort in his workgroup. Several of his students worked on improving the ejector after initial experimental results obtained by Menegay (1991) showed COP improvements of only a few percent. He observed that for higher mass flow rates the pressure rise caused by the ejector decreased. He thought that excessive frictional pressure drop and delayed flashing of the motive flow were responsible for the observed trends. Even though the ejector system was investigated experimentally, the results were only compared to a theoretically determined performance of a hypothetical baseline system with expansion valve. Kornhauser's iterative modeling approach was used by Nehdi et al. (2007) to numerically investigate the performance of a vapor compression system using a two-phase ejector instead of an expansion valve. All of the different working fluids tested were characterized by subcritical heat rejection. Among the fluids considered, R141b yielded the highest COP improvements, 22%, over a comparable baseline system with expansion valve.

Butrymowicz (2003) chose a different approach in his efforts to model two-phase ejector systems. He argued that the iterative one-dimensional modeling routine suggested by Kornhauser (1990) did not explicitly take into account mixing shock waves. Therefore, he constructed an ejector performance curve by relating the suction pressure ratio to the mass entrainment ratio. He used the same coordinates to model the remainder of the refrigeration system. The intersection of the two curves then yielded the operating performance of the entire system including the ejector. This

approach appears to be somewhat similar to the commonly used selection process for pumping equipment, in which the system characteristics are intersected with the fan or pump curves on a pressure-volumetric flow rate diagram.

More research on two-phase ejector systems was reported by Takeuchi *et al.* (2004). For the transportation refrigeration system investigated, it was claimed that the use of a two-phase ejector simultaneously improved the cooling capacity and COP by 25% to 45% and 45% to 65%, respectively. Even though these improvements appear to be very high, no other specific details were given, not even which working fluid was used. Furthermore, nothing was said whether these values were determined computationally or experimentally. It was also mentioned that the integration of a two-phase ejector should result in less additional cost and lower weight penalties in comparison to systems using turbo-expander machinery to recovery expansion work. Ozaki *et al.* (2004) presented more details related to the same two-phase ejector research efforts. Their study included the presentation of limited experimental results showing COP improvements of 20% over conventional transcritical R744 automotive systems with expansion valve at an outdoor temperature of 35 °C. Potentially easier implementation of a high-side pressure control mechanism was mentioned as another advantage of the ejector in comparison to transcritical R744 heat pump with two-phase ejector to the Japanese market. A patent search containing the keywords "Ejector" and "Denso" returned more than 50 US patents granted to the company between mid-2002 and mid-2007. Takeuchi *et al.* (2002) were named as inventors on the first patent of this series.

Li and Groll (2004) and Li and Groll (2005) presented simulation results of transcritical R744 air-conditioning systems with a two-phase ejector. Their analysis was also based on Kornhauser's approach. COP improvements of up to 16% were reported. No internal heat exchangers were included in the systems investigated. They offered a potential solution to a problem they foresaw in regard to controlling the system. A cycle was suggested in which part of the vapor coming from the vapor-liquid separator was injected to the liquid entering the evaporator. They claimed this was necessary to relax the existing constraint between the entrainment ratio and the vapor quality at the exit of the diffuser. In a subsequent publication by Li (2006), experimental R744 ejector data were presented as well, although the emphasis of the work was on modeling a transcritical R744 two-phase ejector system and to study the effects of different geometries and operational conditions. Interestingly, it was concluded that for ambient temperatures of more than 49 °C, the ejector would not be capable of improving the performance in comparison to that of the baseline system with expansion valve. Li (2006) reasoned that at these high ambient temperatures the entrainment ratio would drop significantly. This finding appears somewhat counter-intuitive, because the expansion work recovery potential should actually increase with increasing ambient temperature for otherwise unchanged conditions.

Elbel and Hrnjak (2004a) also used Kornhauser's approach to numerically investigate the effect of using an IHX on the performance of a transcritical R744 ejector system. They showed that the highest COPs can be achieved with ejector and IHX, even though both devices compete in the reduction of throttling losses. Another finding of their numerical study was that the high-side pressure of the transcritical ejector system can still be used to maximize system performance. Later, Elbel and Hrnjak (2006a) and Elbel and Hrnjak (2008) were able to verify their numerical predictions by experimental results. Their prototype was equipped with a needle extending into the throat of the motive nozzle, allowing for high-side pressure control. In comparison to the expansion valve system, their ejector setup simultaneously improved the COP and cooling capacity by 7% and 8%, respectively. They also pointed out that the use of an ejector may result in reduced evaporator pressure drop, increased evaporative heat transfer coefficient, and an improved refrigerant distribution in the evaporator, in accordance with their earlier results they obtained with a concept they called Flash Gas Bypass (Elbel and Hrnjak, 2004b). Elbel and Hrnjak (2006b) used temperature-specific entropy diagrams to visualize the interference between expansion work recovery and internal heat exchange. They showed that both of these mechanisms are in competition for the same temperature difference. They predicted that an ejector having 70% efficient nozzles and diffuser can replace an IHX with 60% effectiveness to achieve the same COP at a given cooling capacity. Elbel and Hrnjak (2007) presented the first high-side pressure control equation used to maximize the COP of a transcritical R744 two-phase ejector system. Furthermore, they identified the existence of mixing shock waves which they detected through static wall pressure distributions along the axis of the ejector. Images of the ejector mixing section were obtained through high-speed flow visualization. The images were taken under realistic operating conditions by using a semi-transparent ejector.

4.3 Other Ejector Cycles

This section presents less commonly encountered ejector cycles for air-conditioning and refrigeration purposes. While some of the concepts presented are solely theoretical, others have been built and tested successfully. Lorentzen (1983) presented a refrigeration cycle in which expansion work recovered by an ejector was used to drive a liquid recirculation loop to improve the evaporator performance. The cycle layout is shown in Figure 6. Kozinski (1996) basically used the same principle in his patent in which he described a method to improve automotive air-conditioning systems. Tomasek and Radermacher (1995) numerically investigated how an ejector can be utilized to improve the performance of a domestic household refrigerator-freezer having two evaporators. In this system, the flow exiting the high-temperature evaporator was used as ejector motive fluid to entrain flow coming from the exit of the low-temperature evaporator. Their analysis resulted in a COP improvement of up to 12% over conventional refrigerator-freezer systems. Riffat and Holt (1998) presented a numerical study to simulate the performance of a heat pipe with an integrated ejector. Their cycle was actually a modification of the vapor jet ejector cycle, but instead of using a pump, capillary action and a wick were used to transport the liquid to the vapor generator. A basic one-dimension modeling approach yielded COPs of up to 0.7 with environmentally friendly working fluids such as methanol.

Another interesting ejector concept was recently introduced by Bergander (2005). In this innovative approach, the ejector is used to raise the compressor discharge pressure rather than the suction pressure as in the case of two-phase ejector systems. The layout for such a system using transcritical R744 and the corresponding pressure-specific enthalpy diagram are shown in Figure 7. A liquid pump and an ejector can be used to act as a compressor stage. COP improvements can be achieved, because for the same pressure rise, the isentropic pump work is far less than that of a compressor. However, ejector inefficiencies can easily annihilate these potential improvements. In this particular setup, strong condensation shock waves are expected to take place inside the ejector. The pressure rise associated with shock waves represents a non-isentropic compression process. Theoretically it would be possible to eliminate the compressor from the system shown in Figure 7 in case all of the required pressure rise would be provided by the liquid pump. Such a cycle would have the advantage of not requiring any lubrication oil to circulate through the refrigeration system. Kemper *et al.* (1966) received a patent for this invention. They explicitly mentioned R744 as a potential working fluid for their setup.



Figure 6: Ejector cycle using expansion work to drive liquid recirculation through evaporator (Lorentzen, 1983)



Figure 7: Transcritical R744 refrigeration cycle using a condensing ejector to increase the compressor discharge pressure and a corresponding pressure-specific enthalpy diagram

5. CONCLUSIONS

The majority of the available literature concerned with ejectors used in air-conditioning and refrigeration describes numerical simulations of vapor jet ejectors. A number of established ejector flow theories point out the importance of flow choking and shock wave phenomena. However, significantly less literature is available on the topic of two-phase ejectors which can be used instead of an expansion valve to recover expansion work. In the particular case of R744, some numerical work on two-phase ejectors has been published in the open literature, but the availability of experimental R744 ejector data appears to be extremely limited. While many of the flow theories and design guidelines developed for single-phase ejectors should be transferable to two-phase ejectors, a number of significant differences exist. Metastability effects caused by delayed flashing of the primary nozzle flow as well as supersonic two-phase flow are believed to add more complexity to the task of designing efficient two-phase ejectors.

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