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Review

Review of recent developments in advanced ejector technology

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ABSTRACT

Previous reviews on ejectors for expansion work recovery have provided detailed discussions of operating characteristics and control of ejector cycles, zero-dimensional ejector modeling, ejector geometry effects, and alternate ejector cycles. However, important advances in the field of ejector technology have occurred since previous reviews were written. Several focuses of recent ejector research are the development of multi-dimensional CFD ejector models, investigation of alternate ejector cycles and uses of the work recovered by the ejector, implementation of effective control strategies for ejector cycles, and application of ejectors in real systems. The objective of this paper is to present a review of developments in the use of ejectors for expansion work recovery in vapor-compression systems focusing on the past several years. Although the first commercial applications are being introduced to the market, it is suggested that future works continue in these areas in order to make ejectors more suitable for additional applications.

Synthèse des récents développements dans la technologie de pointe des éjecteurs

Mots clés : Éjecteur diphasique ; Récupération du travail de détente ; Synthèse de la littérature ; Simulation; Expérience

1. Introduction

In vapor-compression refrigeration cycles, throttling devices such as capillary tubes, short tube orifices, and expansion valves are used as robust and cost-effective solutions for expanding the refrigerant from the higher condensing or gas cooling pressure to the lower evaporation pressure. However, the physical process during throttling is irreversible. The isenthalpic pressure reduction inflicts a dual penalty on the system in the form of reduction in cooling capacity as well as increase in required compression work. This results in lower COP of the actual

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Nomenclature

CFD	computational fluid dynamics
COP	coefficient of performance [–]
DEM	delayed equilibrium model
DX	direct expansion
h	specific enthalpy [kJ kg^{-1}]
HEM	homogeneous equilibrium model
IHX	internal heat exchanger
L	characteristic length [m]
LT	low-temperature
$\dot{m}$	mass flow rate [kg s^{-1}]
MT	medium-temperature
P	pressure [kPa]
Oh	Ohnesorge number [–]
s	specific entropy [kJ kg^{-1} K^{-1}]
UA	overall heat transfer coefficient–area product [kW K^{-1}]
$\dot{W}$	power [kW]

Greek symbols

η	component efficiency [–]
μ	liquid viscosity [Pa s]
Π_s	suction pressure ratio [–]
ρ	liquid density [kg m^{-3}]
Φ_m	mass entrainment ratio [–]
σ	surface tension [N m^{-1}]

Subscripts

diff	diffuser
ejec	ejector
in	inlet of component
max	theoretical maximum
mn	motive nozzle
out	outlet of component
rec	recovered by ejector
sn	suction nozzle

vapor-compression refrigeration cycle compared to an ideal Carnot refrigeration cycle. COP reduction due to the isenthalpic process in the expansion valve can be lessened by many different methods. One of the simplest methods is internal heat exchange that reduces the generation of flash gas during expansion by introducing more subcooling at the inlet of the expansion device. However, methods that involve expansion work recovery are known to be more beneficial in terms of cycle efficiency and cooling capacity. A common feature of methods that involve work recovery is that they attempt to utilize the kinetic energy released during the pressure reduction of the fluid as it passes from the high- to the low-pressure side to save compressor work instead of dissipating it in a throttling process. Meanwhile, an isentropic expansion process is approached rather than isenthalpic throttling. This increases cooling capacity because the specific enthalpy at the evaporator inlet is reduced. Therefore, devices that can approach expansion closer to isentropic process are worth exploring.

Commonly used refrigerant expanders are of the positive displacement-type including scroll, rotary vane, rolling piston, as well as free piston designs. Turbo-machinery designs exist as well, although they are less commonly found in refrigeration. Many expander designs are built to share the same drive shaft as the compressor. Even though these units are highly integrated, several problems can result. If there is only one compressor in the system, and both the compressor and the expander are of the positive displacement-type, the volumetric flow rate through the expander is fixed by its volume displacement rate since the compressor and the expander are operated on the same shaft. Other expander design challenges include thermodynamic losses caused by heat conduction through the shared housing, which can severely reduce the desired work recovery effect, and the possibility of two-phase flow damaging the equipment surfaces by erosion. Cost-wise, expanders are comparable to compressors and seem therefore not very attractive for mass produced HVAC and refrigeration systems, especially for smaller capacities.

Because of the described shortcomings that are associated with expanders and the desire of engineers to design and implement less complex devices capable of achieving the same goal, refrigerant ejectors are receiving much increased attention. An ejector is a device that uses the expansion of a high-pressure (motive) fluid to entrain and compress a low-pressure (suction) fluid by means of momentum transfer between the two streams of fluid. A diagram of an ejector can be seen in Fig. 1. The motive fluid is expanded through a usually converging–diverging (though sometimes converging-only) nozzle to high velocity and low pressure. This high velocity and low pressure is used to entrain the suction fluid through the suction nozzle; the motive and suction fluids are then mixed in the mixing section. The high-speed mixed flow is then decelerated in the diffuser and static pressure is recovered, resulting in a pressure increase provided to the suction stream across the ejector.

Fig. 2 shows the exponentially increasing interest in ejector technology, as revealed by the number of yearly publications in the *International Journal of Refrigeration* since 1995 that contain the keyword "ejector". It should be noted that the number of ejector papers for 2015 has been estimated based on the data available in the month of June. Interestingly, a total of only 23 ejector papers have been published in the same journal prior to 1995. Because of this trend, this review paper focuses on the most recent developments in advanced ejector technology. Fig. 2 also shows the number of *International Journal of Refrigeration* publications on ejectors for work recovery; the number for 2015 has been estimated based on the data available in the month

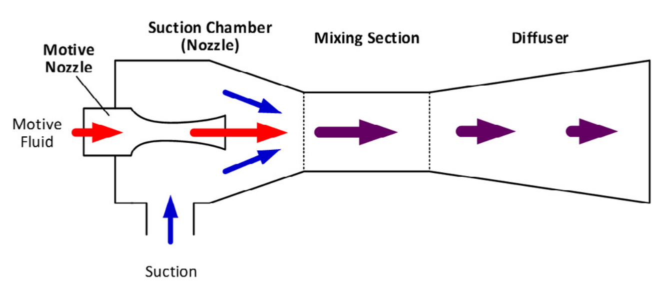

Fig. 1 – Main components and fluid flows through ejector.