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Numerical modeling of two-phase supersonic ejectors for work-recovery applications

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ABSTRACT

An ejector is a fluid pumping device that uses the energy of a high pressure motive fluid to raise the pressure of a secondary lower-pressure fluid. Motive pressure is converted into momentum through a choked nozzle creating a high velocity jet which entrains the surrounding low-momentum suction flow. The two streams mix and finally pressure is recovered through a diffuser. There has been little progress on high fidelity modeling of the expanding supersonic two-phase flow in refrigerant expansion work recovery ejectors due to rather complex physics involving nonequilibrium thermodynamics, shear mixing, and void fraction-dependent speed of sound. However, this technology can be applied to significantly increase the efficiency of space cooling and refrigeration devices. The approach developed in this study integrates models for real-fluid properties, local mass and energy transfer between the phases, and two-phase sonic velocity in the presence of phase change into a commercial CFD code. The intent is to create a practical design tool with better fidelity than HEM CFD models yet with tractability lacking in current boundary tracking phase change CFD models. The developed model has been validated through comparison of key performance metrics against test data under certain operating conditions.

1. Introduction

Reduced environmental impact has become an important goal for environmental cooling. Global warming potential (GWP) of vapor compression cooling can come directly from leakage of fluorinated refrigerants and indirectly from emissions related to electricity use. Unfortunately, many refrigerants with lower direct GWP such as CO_2 offer reduced thermodynamic performance and thus greater indirect emission. Expansion work recovery is one means of improving the overall performance of vapor compression cycle devices thus enabling environmentally friendly refrigerants. Fig. 1 illustrates a transcritical CO_2 vapor compression cycle where expansion through a valve or orifice is an inefficient near-isenthalpic process. The potential work available to an isentropic expansion is shown as a shaded region. Application of an ejector to recover some of this expansion work and apply it to pre-compress evaporator outlet flow is illustrated by Fig. 2.

Fundamentally, ejectors operate by accelerating a high pressure fluid, mixing this high velocity motive flow with a low velocity suction flow to transfer momentum, and then diffusing the intermediate velocity mixed flow to recover pressure. Pressure rise and entrainment (defined as the ratio between suction and motive mass flows) are the primary performance metrics of this device. As seen in Fig. 2, the motive flow of our work recovery ejector will be supercritical fluid expanding into a low quality two phase region, the suction flow will be near-saturated vapor from the evaporator, and the ejector outlet flow will be moderate quality two phase fluid.

Fig. 3 illustrates some of the phenomena that occur in such a flashing two phase ejector and that complicate the analysis relative to common single-phase ejectors. Under the influence of the pressure boundary conditions imposed by the vapor compression system, the supercritical motive flow will accelerate through a nozzle until pressure drops below the equilibrium boiling point. Bubbles will begin to nucleate after some relaxation time or more promptly if the pressure drops below the homogeneous nucleation threshold. In either case, introduction of vapor causes a dramatic drop in the sonic speed and the flow chokes. If there is sufficient energy in the process, expansion to supersonic speeds is possible and desirable. Low pressure supersonic flow leaves the nozzle and shears against the subsonic suction vapor drawn into this low pressure region. In the best case momentum mixing occurs at the highest possible motive velocity but this ideal process can be adversely affected by poor radial momentum diffusion, suction choking, and shock losses which can be related not only to the hardware configuration but also to the local rate of void formation and the phase distribution within the two-phase fluid. At some point momentum mixing gives way to dissipation and the two phase fluid will then be diffused to recover pressure. Phase segregation in this region may reduce recovery or aggravate separation.

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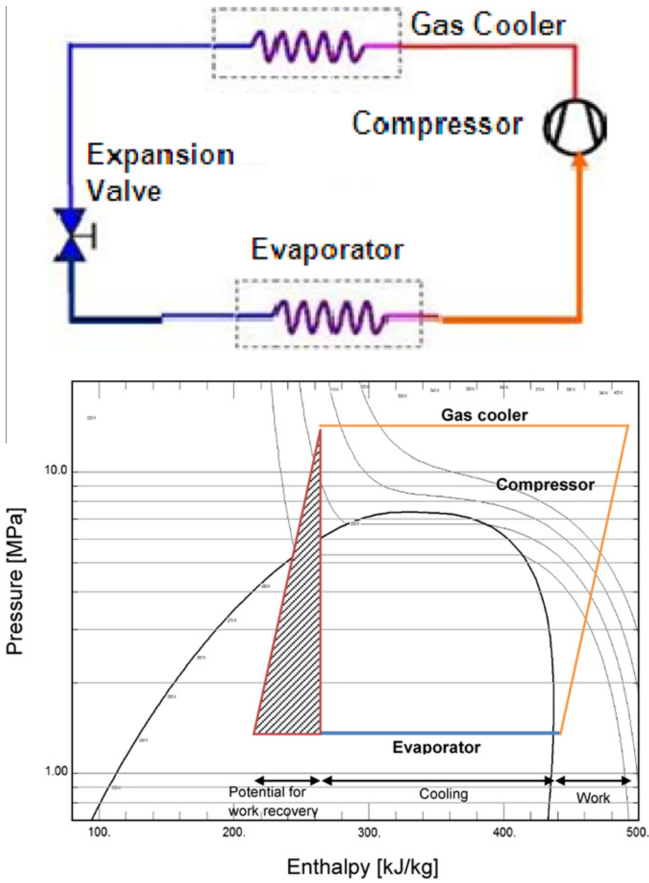

Fig. 1. Transcritical CO_2 vapor compression cycle.

The choked nozzle area of the expansion valve used in a simple vapor compression cycle is typically controlled to maintain a system parameter such as evaporator exit superheat or gas cooler pressure. This control allows the system to adjust to different thermal loads and environmental conditions. The ejector must also fulfill this system requirement so a useful ejector design will be robustly effective over a range of flow rates and pressure differences imposed by the system over its operational range. Published control schemes are primarily based on inserting needles in the ejector nozzle throat [1]. Any control scheme will have an effect on the fluid dynamics internal to the ejector and can substantially complicate analysis and design. Although researchers have demonstrated empirical development of controlled supersonic ejectors that give high performance in a narrow range of conditions [2] it is clear that robust design with this many degrees of freedom requires, at a minimum, multidimensional solutions that properly capture void growth rate and local sonic velocity.

Most of the physical phenomena present in work recovery ejectors have been modeled in different contexts. Many authors have described 1-D control volume models of work recovery ejectors, often paired with a system model [3,4]. Such models apply empirical correlations to represent complicated losses related to void growth and shear mixing and cannot be extended outside of their calibration space. CFD techniques have also been applied to single phase supersonic steam–air ejectors, readily capturing shocks and shear mixing [5,6], and even to supersonic non-equilibrium condensing humid air flows where droplets are nucleated and tracked as particles [7]. The phenomena observed when metastable fluid flashes to low quality two phase flow has been addressed experimentally for CO_2 ejector nozzles [8] and through high fidelity simulation for unconstrained fuel sprays [9]. The next step then is simulation of void growth and local sonic speed in the constrained ejector body to evaluate the coupling between the velocity field, pressure field, and shocks. Without accurate representation of these phenomena it is unreasonable to expect useful *a priori* prediction of the shear and momentum transfer that determine the ejector performance. However, high fidelity simulation of these complex phenomena is expensive or even intractable. The objective of this paper is to develop a practical, tractable ejector design tool through definition of local models for nucleation, void fraction, and sonic speed that are imposed upon an underlying commercial CFD simulation through user-defined functions.

2. Theory

To study the phase-change phenomena along with the mixing and pressure-recovery processes in the ejector, the following theoretical model is developed. The axisymmetric theoretical domain for a typical ejector consists of the motive nozzle, suction chamber, mixing region, and diffuser as illustrated in Fig. 4.

A nonhomogeneous mixture model is implemented for modeling the two-phase flow inside the ejector. The following equations constitute the conservation of mass, momentum, and energy in compact Cartesian notation,

$$\partial_t \rho + \partial_j \rho u_j = 0 \tag{1}$$

$$\partial_t(\rho u_i) + \partial_j(\rho u_i u_j) = -\partial_i P + \partial_j \tau_{ij} + \partial_j \alpha_k (\rho v_{idr} v_{jdr})_k \tag{2}$$

$$\partial_t E + \partial_j(u_j(\rho E + P)) = \partial_j(k_{\mathrm{eff}} \partial_j T) + \dot{Q} \tag{3}$$

where ρ and u, respectively, represent mixture density and mass-averaged velocity,

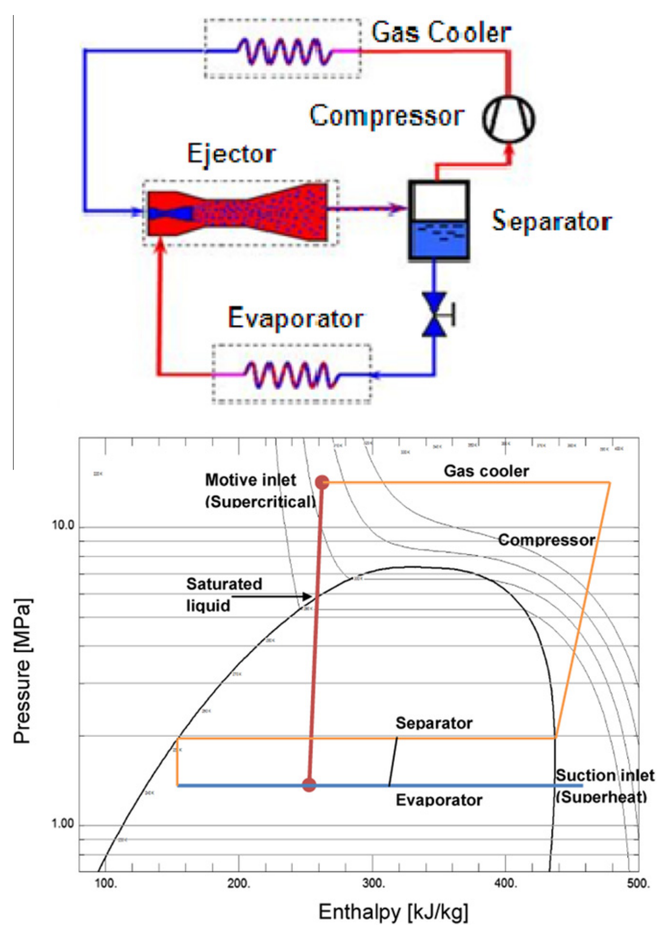

Fig. 2. Transcritical CO_2 cycle with ejector work recovery.