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A New Thermally Driven Refrigeration System with Environmental Benefits

Charles A. Garris, Jr., Woo Jong Hong, Catherine Mavriplis, Jeremy Shipman
The George Washington University
School of Engineering and Applied Science
Washington, DC 20052
202-994-6749
garris@seas.gwu.edu, whong@seas.gwu.edu, mavripli@seas.gwu.edu, jshipman@seas.gwu.edu

ABSTRACT

The pressure-exchange ejector offers the possibility of attaining a breakthrough in the level of performance of ejectors by means of utilizing non-dissipative non-steady flow mechanisms. Yet, the device retains much of the mechanical simplicity of conventional steady-flow ejectors. If such a substantial improvement in performance is demonstrated, its application to ejector refrigeration will be very important. Such a development would provide significant benefits for the environment in terms of both CFC usage reduction and greenhouse gas reduction.

The current paper will discuss in detail the concept of pressure-exchange ejector refrigeration, compare it with existing technologies, and discuss the potential impact that might be derived if certain levels of ejector performance can be achieved. Since the limiting issue on the system performance is in the fluid dynamics of non-steady flow induction, research issues and recent progress will be discussed.

EJECTOR REFRIGERATION

Conventional reverse-Rankine cycle refrigeration has three major drawbacks, all of which are associated with the use of the compressor:

i. The compressor is usually driven by high quality mechanical power provided by means such as an electric motor, mechanical power extraction from an engine, and the like. When the electric power comes from fossil fuel powered plants, or the mechanical power comes from a combustion engine, greenhouse gases and other pollutants are generated, and fuel is consumed. There are many applications where usable waste energy is available and is discarded and lost. One such example application is in automobile air conditioning where, in the present state-of-the-art, a conventional reverse Rankine cycle refrigerator is used such that the compressor is powered directly by the engine, while thermal energy in sufficient quantity to power the air conditioning system is lost through the engine exhaust and the cooling system. The possibility of using automotive waste heat for air conditioning in an ejector refrigerator is discussed in Balasubramaniam[1], Hamner[2], Kowalski[3].

ii. Recent research has shown the chlorofluorocarbons (CFC's), the refrigerants of choice for the reverse Rankine cycle refrigeration system, have produced dire effects for the earth's ozone layer. Alternate refrigerants have been sought, particularly among the hydrochlorofluorocarbons (HCFC's), however, concerns have been raised about other environmental problems associated with these refrigerants. Besides their adverse effects on the ozone layer, Fischer[4] stated that " . . . CFC's have been implicated as a major anthropogenic cause of global warming.” Turiel[5] calculated that one pound of R-12 released to the environment has about 15,000 times the global warming effect of the same weight of CO_2.

iii. Conventional reverse Rankine cycle refrigeration is the complexity of the compressor. This complexity increases the cost of the unit, increases the maintenance required, and consumes excessive space or requires that the compressor be situated at inconvenient locations.

A possible remedy for all of these deficiencies is embodied in ejector refrigeration. A typical ejector refrigeration system is shown in Figure 1. Note that it operates in a manner commensurate with reverse Rankine cycle refrigeration with the modification that the mechanical compressor is replaced by a boiler-energized ejector and feed pump. A sketch of a typical steady-flow ejector is shown in Fig. 2. This device is

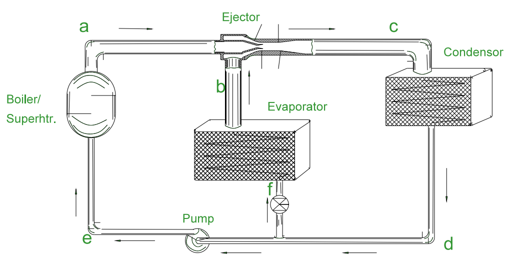

Figure 1 Ejector Refrigeration System

mechanically very simple, can directly convert thermal energy into refrigeration, and is compatible with environmentally friendly high specific volume refrigerants such as water.

Common water is an excellent refrigerant which has a high latent heat of vaporization, a high specific heat, good heat transfer characteristics, non-corrosive, and is totally in harmony with the environment. However, since for normal air conditioning applications, the specific volume of water vapor under operating conditions must be hundreds of times larger than that of a system using CFC’s under comparable environmental conditions and design requirements. Water refrigerant, when used with a positive displacement type compressor, therefore, requires a much larger compressor displacement volume. The need for a much larger compressor, and the associated increased cost, has rendered water to be less desirable as a refrigerant for conventional air conditioning. However, this problem can be overcome by the use of an ejector. Ejectors are capable of transporting large volumes of vapor within a relatively small space and at a low cost.

At the turn of the century when steam was more abundant than electricity, the patent literature reveals a plethora of inventions based on ejector refrigeration. In this era, steam from locomotives was used to provide air conditioning in passenger trains. Steam ejector refrigeration enjoyed considerable popularity in the 1930's for air-conditioning large buildings. It continues to be used in industrial applications where steam is abundant.

Despite its substantial advantages, steam-ejector air conditioning has not, in fact, been widely adopted because of the low Coefficient of Performance (COP) that has hitherto been attainable. Even when abundant waste heat is available, such as in automotive applications, a consequent result of the low COP is that not only must the evaporator heat absorbed by the refrigerant be rejected in the condenser, but also the thermal energy used to power the ejector. If the COP is low, large

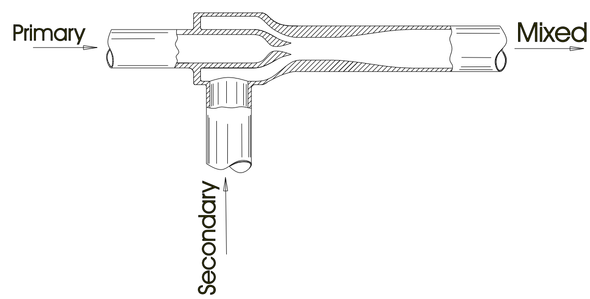

Figure 2 Steady-Flow Ejector

amounts of additional energy must be rejected at the condenser which requires a condenser of substantially increased size, weight, and cost. In automobiles, where space is a premium, this attribute would render steam ejector refrigeration unacceptable.

The efficiency of the ejector is a limiting factor in determining the performance of the refrigeration system. The physical principal upon which the steady-flow ejector functions is that of entrainment of a secondary flow by an energetic primary flow by virtue of the work of turbulent shear stresses. Thus, the relatively low energy secondary flow is “dragged” by the relatively high energy primary flow through tangential shear stresses acting at the interface between the two contacting streams. These turbulent stresses are a result of mixing that occurs between primary and secondary streams and the consequent exchange of momentum. While this mechanism is quite effective, and has been widely adopted in many applications, an inherent characteristic of mixing processes is to dissipate valuable mechanical energy. After mixing, these ejectors are designed[2,6] so as to produce a strong normal shock prior to passing through a subsonic diffuser section. This strong shock produces further dissipation of energy contributing to a loss of efficiency.

Huang et al[6] reports results which are typical of the state-of-the-art for ejector refrigeration with values of COP in the area of 0.20. Such levels of performance will render steam-ejector refrigeration non-competitive for all but the most specialized applications. Since the limiting factor on the COP is the ejector efficiency, it is clear that in the absence of a major breakthrough in ejector performance, the benefits of steam-ejector refrigeration will be unrealized on a large scale. Such a breakthrough with <u>steady-flow</u> ejectors is highly unlikely in view of their century old history of development.

One way in which the COP of the basic ejector refrigeration cycle can be increased is if the function of the ejector is replaced by a turbine-compressor equivalent as proposed by Rice[7]. However, such a system would be very expensive and would require excessively large components if water were to be used as the refrigerant.

The present paper offers hope that a major breakthrough in steam-ejector refrigeration performance may be possible through a newly patented non-steady flow ejector which utilizes reversible means to achieve flow induction, while retaining much of the mechanical simplicity of conventional ejector refrigeration. Moreover, the device should be low in cost and compact in size. If such a breakthrough in ejector performance can be achieved, steam ejector refrigeration will have to be considered in an entirely new light in view of its outstanding environmentally friendly attributes as well as its high potential for energy conservation through waste-heat utilization.

THE PRESSURE EXCHANGE EJECTOR

A detailed description of the pressure-exchange ejector is given in Garris[8], Garris and Hong[9] and Garris et al[10]. A sketch of a pressure exchange ejector is shown in Fig. 3. In the configuration under study, it is a simple radial-flow turbomachine with one moving part: a free-spinning rotor. Integral with the rotor is a multiplicity of canted supersonic nozzles. Primary flow leaving the nozzles drive the rotor to free-spin, attaining angular speeds possibly exceeding 50,000 rpm. The secondary flow is directed towards the interaction space between adjacent fluid jets, between which it is trapped and driven outward toward the periphery by virtue of the work of interface pressure forces. The work of pressure forces is inherently reversible and does not incur the detrimental dissipation caused by the mechanism of turbulent entrainment used in conventional ejectors. Furthermore, due to the radial geometry, the need for a strong normal shock in the diffuser, a further source of dissipation in steady-flow ejectors, may be obviated. Since pressure exchange ejectors operate through an entirely different principal than steady-flow ejectors, there is a possibility that a major improvement in performance can be obtained. Garris and Hong[9] reviewed previous research on pressure-exchange ejectors designed for thrust augmentation applications, and the use of pressure exchange in wave engines. However, the idea of using it for ejector-compressor applications, as well as ejector refrigeration applications, is new.

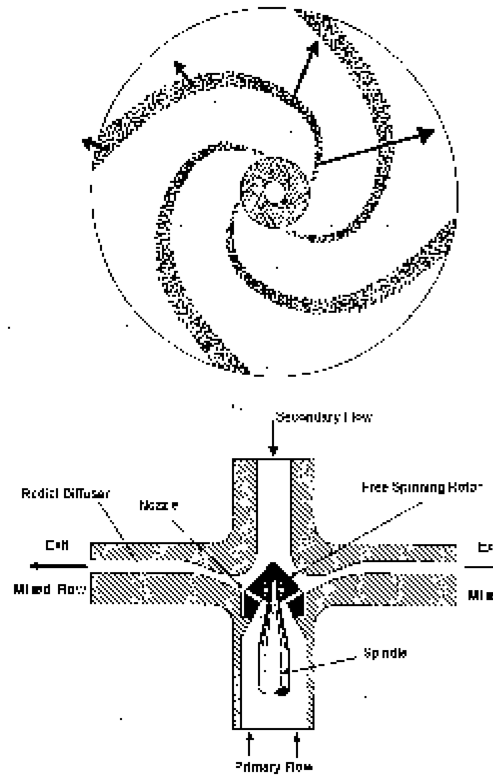

Figure 3 Radial-Flow Pressure-Exchange Ejector

EJECTOR REFRIGERATION CYCLE

In the discussion that follows, we will attempt to place the performance of ejector refrigeration equipment within the context of alternate technology.

Huang et al[6] showed both theoretically and experimentally what levels of performance might be expected using real steady flow ejectors as characterized in detail via their experimental results. In their very thorough investigation, the COP's reported for a basic system, using R-113 rather that steam, were in the range of 0.06 - 0.25.

Since the ejector refrigeration system is directlyenergized by thermal energy, it is appropriate to compare it with absorption cycle refrigeration which is also thermally energized. Herold et al[11] report typical values of COP from 0.5 to .75 for absorption chillers. While the current state-of-the-art ejector refrigeration system is much simpler, carries a lower initial capital cost, lower maintenance, and a wider choice of refrigerants, absorption cycle refrigeration is substantially more energy efficient.

For comparison with reverse Rankine cycle refrigeration, one must also factor in the efficiency of generating mechanical motive power for the compressor from a fuel source. In the case of electrically driven compressors that receive their electrical power from fossil fuel powered plants, one must consider that the thermal efficiency of modern fossil-fuel fired plants is around 35%-40% (Decher[12]). Transmission losses must also be taken into account. If one defines COP as the energy removed from the cooling space divided by the thermal energy expended at the source in order to effect that energy removal, reverse Rankine cycle refrigerators would have a COP in the vicinity of 1-1.5. For automotive applications[13] where the maximum efficiency of gasoline spark ignition engines is less than 30%, and for Diesels between 35%-40%, the overall COP for conventional automotive air conditioning systems would be on the order of 0.75-1.0. It is the hypothesis of this paper that if the COP of ejector refrigeration could be brought up to about 0.75, it could be a cost-effective alternative to vapor compression refrigeration in many domestic, automotive, and commercial applications. It would further provide immense benefits in reducing the release of hazardous fluorocarbon-based refrigerants to the environment, reduce the emission of greenhouse gases by using waste heat or low greenhouse gas emitting fuels such as natural gas, and provide low maintenance, safety, and low initial investment.

Huang et al[6] stated succinctly that: "It is obvious that the ejector is the heart of the jet refrigeration system". Although they did not correlate their results with adiabatic efficiency of the ejector, sufficient data were provided to permit such a calculation. Three representative COP's were extracted from the performance charts reported by Huang et al.[6] : 0.23, 0.125, and 0.05. The corresponding adiabatic ejector efficiencies are computed to be 21.4%, 15.4%, and 8.4%, respectively. The result suggests the very strong correlation of COP with ejector efficiency.

The efficiency of an ejector is closely connected with the entropy generation processes occurring within. The operating principles of a conventional steady-flow ejector result in two major sources of entropy generation: turbulent mixing and strong normal shock waves. The Mollier chart of Fig. 4 suggests how entropy generation

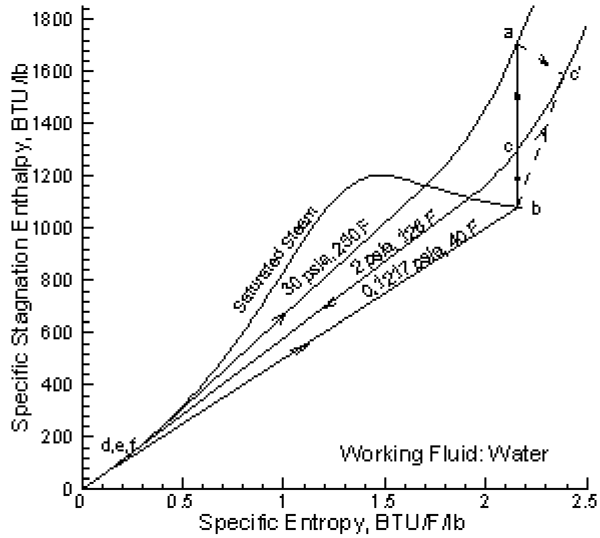

Figure 4 Mollier Chart of Steam-Ejector Refrigeration Cycle

in the ejector affect the thermodynamic cycle. The processes indicated by **ac** and **bc** are reversible isentropic processes as would occur in an ideal turbomachinery analog of the ejector with no shocks and no mixing. The processes indicated by **ac'** and **bc'** represent the irreversible processes that occur in the primary and secondary, respectively, of the ejector and include entropy generation from both mixing and shocks. Depending on the amount of entropy generated, one can compute the resulting COP of the cycle and the mass flow ratio. One should remember that in performing these exercises, energizing primary mass flow rate is adjusted to compensate for the dissipative processes so as to enable the operating temperatures and pressures to remain the same.

Garris et al.[14] showed that as the entropy rise increases, the system COP decreases precipitously. It was demonstrated that the COP can be improved dramatically if the entropy rise can be controlled effectively. By means of the pressure-exchange ejector which utilizes physical mechanisms which produce modest entropy rises, a substantial improvement over conventional technology is possible. This study also showed that when the entropy rise is small, only a small amount of energetic superheated primary fluid is needed in order to drive the refrigeration system. However, when the entropy rise in the ejector increases, there is a rapid drop in the mass flow ratio indicating that much more fluid is needed in the primary circuit in order to drive the system. By reducing the entropy rise in the

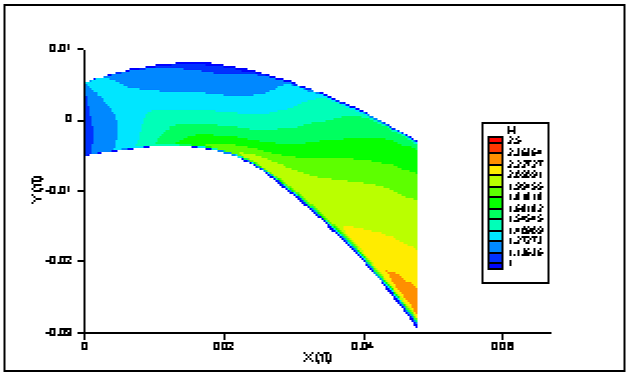

Figure 5 TASCflow Solution for Curved Supersonic Nozzle

ejector, the pressure-exchange ejector minimizes the energy requirement in the boiler/superheater while minimizing the amount of heat to be rejected in the condenser leading to a more cost-effective and space conserving system.

EXPERIMENTAL PROGRAM

The experimental program has the near-term goal of understanding the behavior of the pressure-exchange ejector, and the long-term goal of implementing it in a refrigeration system. Recent work has concentrated on the former.

The current test rig consists of a radial-flow pressure-exchange ejector having a 3.0" diameter rotor with nine planar minimum-length Mach 2.5 supersonic nozzles canted at an angle of 20^o from the radius. Air is provided through a blow-down air supply. The system is instrumented and pressures, temperatures, and flow rates are measured in the primary and secondary flow circuits. As indicated in Fig. 3, the discharge flow is released to the atmosphere through a vaneless diffuser. Static pressure taps are placed at many radial locations in the diffuser to monitor diffuser performance. The rotor is mounted on a shaft with precision high- speed ball-bearings. Laser-fiber optic probes are used to measure angular speed, and a piezoelectric pressure transducer is placed near the nozzle discharges to measure fluctuations in static pressure. A hot wire anemometer is employed to measure velocity and turbulence in the diffuser. Vibration is also monitored. Data is compiled via a computerized data acquisition system.

It must be appreciated that this type of ejector is completely new and that there is not any previous design experience upon which to build. Before experiments can be conducted, the ejector must satisfy unforgiving mechanical design constraints including bearing design, structural design, and dynamic sealing. The operating parameters that must be studied include primary/secondary stagnation pressure ratio, primary/secondary stagnation temperature ratio, ejector discharge back pressure, and working fluid (air, steam, etc.). In order to obtain an optimum configuration, the geometrical parameters that must be studied include: Area ratio of supersonic primary nozzle (Mach Number), configuration of nozzle (planar, axi-symmetric, minimum-length, curved, etc.), number of nozzles, spin angle of nozzles (peripheral speed), diffuser spacing (distance between vaneless diffuser surfaces), diffuser angle, secondary to primary throat area ratio, and aerodynamic design configuration.

A major goal of this research program is to explore all of these aspects. However, to date, we have dedicated much of our effort towards satisfying the mechanical design constraints. In the process, we have encountered difficulty with bearing failures, vibration instability, structural failure, and sealing problems. We have made much progress in this connection and are now able to conduct experiments in order to explore the behavior of the ejector subject to varying operating parameters. The results to be presented constitute our first attempt for one set of geometric parameters. Thus far, no study of the important effects of the geometric parameters has been performed. The results to be presented in the present paper, therefore, should in no way be construed as representative of the capabilities of the pressure-exchange ejector. We expect to be able to provide such information in future publications.

Test results, as reported in Garris et al.[10], determined that rotor speeds exceeded 40,000 rpm. In practice, the rotor experiences bearing friction and windage torque. Considerable effort was made to reduce bearing friction and work on designing special air bearings is being conducted in parallel with the aerodynamic investigation of the ejector.

Figure 5 shows how the ejector suction (secondary pressure) varies with primary pressure for three different secondary flow conditions ranging from no-flow to maximum flow. The former is obtained by shutting the secondary flow valve, and the latter is obtained by opening it wide. The third condition shown is intermediate. It may be seen that the no-flow condition corresponds to maximum suction.

COMPUTATIONAL SIMULATION PROGRAM

To model the characteristics of this novel pressure exchange concept computationally, the commercial fluid flow analysis code TASCflow was acquired. TASCflow solves the three dimensional Navier-Stokes equations by utilizing a finite element based finite volume method over structured hexahedral grids. It was chosen over other software packages primarily for its ability to handle time periodic boundary conditions and rotating frames of reference, making it well-suited for modeling rotating machinery. Other features particularly suitable to this research include the abilities to accurately model real gas compressible flows, turbulence, heat transfer, shocks resulting from transonic and supersonic flows, and special fluids such as wet steam and refrigerants.

To date, TASC flow has been used to model the two dimensional flow through the supersonic nozzles of the rotor used in the experimental rig. The current rotor configuration involves a plurality of minimum-length, Mach 2.5 nozzles canted at 20° with respect to the radius of the rotor. In the previous work of Divinis[15], these minimum-length nozzles were designed with a method of characteristics FORTRAN code developed by NASA[16].

The TASCflow predictions of the boundary layer growth were compared to that predicted with the NASA Code[16]. It was seen that both computations predict comparable values of boundary-layer thickness and are consistent.

TASCflow was further validated by comparison of the work on curved nozzles of Divinis[15] who utilized the method of characteristics for planar nozzles with different degrees of curvature. These nozzles are of interest to the project because of their ease of packaging in the confines of a rotor . An efficient ejector will depend on the ability of these nozzles to provide uniform, shock free flow. TASCflow is currently being used to investigate the flow in these nozzles. Figure 6 shows the solution for a Mach 2.5 nozzle with a 20° angle of curvature. While the flow is shock free, it is less than perfectly uniform and reaches the design Mach number only at a small region.

CONCLUDING REMARKS

It is the hypothesis of this research program that, through the work of interface pressure forces, a major improvement in performance over conventional steady-flow ejector technology may be possible. Unfortunately, the results herein reported do not exhibit this. However, considering that this constitutes our first attempt, we are satisfied that the pressure-exchange ejector does function, and future efforts at optimization should yield substantial improvements. Future plans include designing and testing a pressure-exchange ejector refrigeration system when sufficient information is learned on optimal ejector design.

Steam-ejector refrigeration, known for generations, may finally come of age in the 21st Century as a result of the need for environmentally friendly refrigeration coupled with a breakthrough in ejector technology: the pressure-exchange ejector. Much work is needed in order to bring this vision to fruition. Current performance levels are far below those of ideal turbomachinery and, to date, improvements over steady-flow ejectors have not yet been demonstrated. While the pressure-exchange ejector is far simpler than turbomachinery, being a direct fluid-fluid flow induction device, optimization is quite a daunting task. The number of geometrical and design parameters is substantial and the device in unforgiving in terms of sealing and bearing requirements. Once an understanding of this complex ejector is obtained, experiments and analysis on a complete pressure-exchange refrigeration system will be performed.

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