Characteristics of high performance cooling systems using ejectors

Dr Mike Dennis
School of Engineering, The Australian National University
Canberra, ACT 0200, AUSTRALIA
P: +61 2 6125 9856 F: +61 2 6125 0506 E: Mike.Dennis@anu.edu.au

Abstract

Much of the research effort on ejectors examines the steady state performance of the ejector component using approximate analytical models or more recently using CFD models. So far, the performance of ejector solar cooling systems has not been sufficient to warrant uptake by commercial entities. Until the performance of ejector systems rivals that of absorption chillers, their advantages of simplicity, reliability and low cost have little value. By collating the best published research proposals for improvement to ejector system design in these areas of greatest performance sensitivity and by directing whole of system integration, a technology design suite for a high performance ejector cooling system is proposed. It is hoped that these ideas may inform research direction for ejector practitioners.

1. Introduction

The solar driven ejector is a heat pump solar cooling device whereby vapour compression is achieved by a heat driven ejector rather than electrical or thermo-chemical compression. In addition to the benefits of any solar cooling system, the ejector solar cooling technology has potential for low cost and excellent reliability.

Despite the growing understanding of the ejector component design and operation, ejector system performance is not improving very much and there are no commercially available systems. There is a need for researchers to build upon best practice and focus on designing better systems. A number of research priorities are suggested in this paper for future research in ejector cooling systems.

2. Characteristics and Short-comings of Gas Ejectors

Since ejector geometry is derived from one set of operating conditions, the design is not optimal for off-design conditions. At high condensing temperatures, the mixing chamber diameter is too large such that insufficient pressure can be recovered in the ejector, resulting in ejector malfunction. Conversely, at low condensing temperatures, the mixing chamber diameter is too resulting in a limiting constant capacity constraint although reducing the generator temperature can help.

The outstanding problems with solar driven ejectors can be grouped into three areas:
1. Poor thermal efficiency, particularly at high condensing temperatures. This implies that a large solar collector will be required and this makes the system expensive
2. A limiting constant cooling capacity effect at low condensing temperatures
3. Inability to operate into the evening when cooling is required but solar energy is not available.

Such a holistic perspective on ejector system performance implies a systems engineering approach is preferable to a focus on the ejector component itself.

3. Improvements to the Ejector Component

3.1 Variable Geometry

Many researchers have conducted multi-variable optimisation of the ejector component and produced geometry best suited to a particular operating point defined by generating, evaporating and condensing temperatures. However, the condensing temperature changes with ambient temperature throughout a day and generating conditions are subject to changes in insolation. Evidently, variable geometry would be a desirable feature of a high performance ejector. The primary nozzle throat diameter, the primary nozzle axial position relative to the mixing chamber, the mixing chamber diameter, the mixing chamber length and the diffuser length should be variable. Such a device should demonstrate increased capacity at low condensing temperatures and smooth drop of capacity at increasing condensing temperatures (Sun, 1996). However, no such device has been noted in the literature and to some degree the challenge is to retain the ejector's advantages of simplicity and reliability in doing so. This challenge remains one of the key outstanding priorities in ejector research.

3.2 Elimination of Supersonic Shocks

A step improvement in ejector performance was noted by Eames (2002) in the Constant Rate of Momentum Change (CRMC) design methodology. This design avoids the losses associated with the normal shock that theoretical models predict to occur near the end of the mixing chamber. The CRMC design predicts greater pressure recovery but there appears to be no mechanism by which ejector entrainment might be improved. It should be noted that numeric models and experimental data sometimes dispute this prediction. Indeed no studies have been found on the off-design performance of the CRMC ejector. Nonetheless, the principle of improving ejector compression efficiency through gradual compression rather than through a compression shock is a design imperative.

3.3 Improved Mixing Efficiency

The energy losses due to the highly turbulent viscous shear layer at the mixing between primary and secondary ejector flows is the major source of inefficiency in the ejector, evidenced by high degree of superheat observed in the ejector exit flow. Promising efforts have been made to reduce the velocity mismatch between the flows and by changing the primary nozzle shape (Chang, 2000), thus to improve mixing efficiency. Coupled to improved mixing is the location of the primary jet relative to the mixing chamber entry and the strength of the primary jet. Clearly, both of these parameters must be varied to suit the operating conditions to provide optimal ejector entrainment and optimal pressure recovery.

3.4 Refrigerant Selection

Up till the 1980s most ejector systems used water as the working fluid perhaps reflecting the heritage and application of the ejector whereby efficiency was not the prime concern. In a solar cooling application, the low efficiency of the steam ejector implies that a large and costly solar collector is required. More recently, researchers improved ejector performance by switching to working fluids of higher molecular mass and improved low temperature thermodynamics. Concerns over environmental impact, flammability and toxicity severely limit choices for ejectors and this is a key challenge for future ejector designers. The thermodynamic suitability of refrigerants in ejector systems is challenging due to the wide range of temperatures the refrigerant is exposed to. However, there is no need for a lubricant in an ejector system and thus ejectors do not suffer from lubricant compatibility issues.

4. Improvements to Ejector Systems

4.1 Hybrid Designs

Many of the proposed ejector designs specify a low evaporating temperature suitable for dehumidification in an air conditioning application. However, this condemns the ejector system to operating at a high compression ratio and thus low COP. Substantial improvements in ejector cooling system performance have been demonstrated for hybrid ejector systems whereby the ejector's role is to assist the operation of a primary heat pump. The ejector circuit might typically do this by cooling the heat pump condenser or pre-cooling the heat pump evaporator feed. Such designs improve the COP of the heat pump and the ejector COP simultaneously and naturally provide a backup cooling service when solar radiation is not available without additional cold or hot storage.

A further design initiative that is beginning to receive attention, in the form of Combi+ systems from Europe, is the hybridisation of thermal services. A solar cooling system with low thermal efficiency requires a large solar collector so it would make sense for that collector to provide winter space heating and water heating in addition to summer cooling. Thus the costs of the collector are spread over three thermal services.

4.2 Internal Heat Recovery

Internal heat recovery has been proposed and sporadically adopted in ejector designs. There are several obvious opportunities to recover heat in an ejector system. Firstly, the ejector diffuser outlet vapour may be desuperheated and this heat recovered to pre-heat condensate being fed by the circulating pump to the generator. The second opportunity for heat recovery is to use cool vapour from the evaporator outlet to sub-cool liquid passing to the expansion valve. Provided that the heat exchangers have low pressure loss, and depending upon the refrigerant used, the gains in COP can be in the order of 10-20%.

4.3 Control Systems

The application of ejectors to solar cooling exposes ejectors to transient conditions whereby the system dynamics become an important consideration. The ejector has a large number of degrees of freedom in design but rather less in operation since its geometry is fixed during manufacture. Optimisation studies have noted that the greatest gains in ejector performance come from elevating the evaporating temperature, followed by decreasing the condensing temperature. The generator temperature should then be reduced as much as possible to allow the ejector to operate near its critical point. In determining the optimal setpoints for actuated variables, model based control might be adopted. However, neither analytical nor numeric models are sufficiently accurate and robust. Presently, the most reliable approach would be to conduct a comprehensive set of experiments to map the operational space of the ejector and subsequently generate an empirical performance table for control purposes. The basis for control then becomes the ambient temperature from which all other operational control variables are derived. For advanced control, solar radiation (or a proxy) will need to be sensed.

4.4 Improved Models

Although analytic models have improved greatly resulting in a better understanding of ejector operation, real improvements in ejector design over the last 50 years have been few. Refinements to analytic are all limited by treating the fluid flows with bulk properties, usually those of an ideal gas. While they model the observed large scale behaviour and may enable simple ejector design, they do not provide insights that may allow improvement to ejector design. It would seem that the highly turbulent processes and the non-equilibrium thermodynamics of ejectors preclude any further insights to be gained from further work on analytical ejector models and that the path forward is to improve Computational Fluid Dynamics (CFD) models.

The application of CFD to ejectors is complicated by the nature of the ejector mixing process. The ejector research community is yet to agree on a set of guidelines for CFD ejector modelling. It would appear that as a minimum, the following should be adopted: real gas models; appropriate turbulence models; high quality, dynamic 3-D meshing; second order or hybrid solvers. It is also probable that time-varying CFD will provide more useful information than static CFD. Research effort in this area should focus on improving the quality and consistency of the CFD process. This involves examination of the sensitivities of the CFD process as applied to ejector analysis, coming up with and sharing a recommended set of guidelines to best practice amongst ejector researchers through publication.

4.5 Design for the Climate

The ejector system must be designed to suit the climate in which it is to operate. Since an ejector designed to condense at high ambient temperatures will have low COP, it's annual cooling yield may be less than one designed to operate at higher COP but over a narrower range of condensing conditions. Furthermore, a humid climate may require the ejector to operate at low evaporating temperatures. Such a tradeoff can only be evaluated using software models simulated over a range of conditions indicative of typical operation. Such a study is yet to be presented in the literature.

5. Dealing with Intermittency of Solar Radiation.

An ejector system driven by solar heat alone is subject to intermittent operation and hence may not be able to satisfy a cooling load effectively. The three obvious means of overcoming this problem are:

1. Run the ejector from stored solar heat
2. Store coolth wherever possible for later use
3. Use a hybrid cooling system.

The addition of auxiliary heat is not attractive since a typical ejector has a COP of less than unity. Also, cold storage is presently problematic. The cooling system must typically evaporate at very low temperatures to freeze water or to overcome temperature losses in the heat exchange process with the cold store. A solution to the cold storage problem would be beneficial to all comfort cooling systems in an effort to reduce peak electricity consumption.

6. Measures of Performance

A review of ejector literature reveals a range of methods of assessing ejector performance at a range of reference conditions. These inconsistencies make it difficult to compare various designs and can be misleading. Also, researchers commonly abstract ejector system performance to COP and then to ejector entrainment ratio. This abstraction results in a narrow focus on improving the ejector component with lesser regard to the ejector system performance as a whole. Perhaps the most useful and direct indicator of annual performance is the annual specific cooling yield, measured relative to solar collector area. This can then be extrapolated to annual energy savings, greenhouse gas savings and cost savings relative to a given reference system in a given geo-political climate. This measure, and its derivatives, has the advantage of capturing the local context and presenting the most important system performance parameters of relevance to commercial promotion of ejectors.

Conclusion

Ejector solar cooling systems have a number of potential advantages over incumbent cooling systems, but this potential has not been realised since it is masked by the low thermal efficiency of the ejector and thus its requirement for a large and costly solar collector. In this paper, a number of research directions are recommended in a hope that the performance of ejector solar cooling systems can be improved through a more coordinated effort in areas of high performance potential. A worthy performance target would be demonstrating equivalent specific cooling yield as an absorption chiller, whereupon the other advantages of the ejector should make a compelling case for its commercial uptake.

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