Compound ejectors with improved off-design performance

Dr M. Dennis[1], Dr K. Garzoli[2]
[1,2]Centre for Sustainable Energy Systems
School of Engineering
The Australian National University
Canberra, ACT 0200
AUSTRALIA
[1] Mike.Dennis@anu.edu.au
[2] Keith.Garzoli@anu.edu.au

ABSTRACT

Due to concerns over the environmental impact of refrigerants and the rising greenhouse gas emissions associated with building cooling, there has been a resurgence of interest in solar driven ejector cooling in recent times. Much of the research effort has concentrated on understanding the inner operations of the ejector using the approaches of thermodynamic modelling and computational fluid dynamics. Nevertheless several problems with ejector cooling persist. Amongst these are the constraints of constant cooling capacity at lower than design condensing temperatures and inability to operate at all above design condensing temperature remain. Compounding several ejectors in a series arrangement alleviates these two problems to some degree without requiring additional driving power, making the compound ejector design particularly suitable for dry re-cooling applications where condensing temperatures are elevated.

A modelling study was conducted for a two stage compound ejector arrangement. The study concludes that about 1/3 of the solar energy should go to the first (low pressure, upstream) ejector and 2/3 to the second ejector for best cooling yield. Furthermore, the mixing chambers of each ejector can have the same geometry which affords some economies of production.

The main outcomes of the study suggest that several persistent complaints over ejector operational characteristics and off-design performance can be alleviated using the compounding approach. Further work is warranted to determine the optimum number of compounding stages and degree of intercooling between stages.

Keywords *Air conditioning, Ejector, Refrigeration, Solar cooling*

INTRODUCTION

The solar driven ejector is a heat pump solar cooling device whereby vapour compression is achieved by a heat driven ejector rather than an electrical compressor.

Steam ejectors have been used for many years and are simple, cheap and reliable devices since they have no moving parts. For solar cooling applications, ejectors typically use high temperature refrigerants as working fluids for improved performance.

The outstanding problems with solar driven ejectors can be grouped into three areas:

1. Poor performance at high condensing temperatures
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.

Although the last problem may be overcome with the addition of auxiliary heat, a typical ejector has a COP of less than unity. This suggests that alternative approaches to the continued provision of cooling without solar energy are desirable.

Since an ejector design geometry is directly related to one set of operating conditions, the design is not optimal for off-design conditions. This is manifested by poor cooling performance at high condensing temperatures where the mixing chamber is too large in diameter and insufficient pressure can be recovered in the ejector. Also, at low condensing temperatures, the mixing chamber is too small in diameter to accommodate the larger flow from the evaporator.

In Australia, the lower latitudes have experienced prolonged drought conditions since 1999. Although evaporative cooling has been popular and suitable to these regions of low humidity, the need to reduce water consumption is contributing to reduced demand for evaporative coolers. Currently, the residential market is dominated by low cost imported electric heat pumps which is now creating severe peak demand problems for Australia's electricity grids.

Another trend is that wet cooling towers are being replaced by dry cooling towers. For all heat pumps, this implies a higher condensing temperature and thus lower performance for the heat pump. It is known that ejectors perform poorly at high condensing temperature with a sharp decline in performance when the condenser back pressure exceeds a critical value.

If one is to design an ejector with dimensions that allow it to continue to operate at high condensing temperatures, the performance at moderate condensing temperatures is compromised (figure 1) since the mixing chamber is necessarily small in diameter.

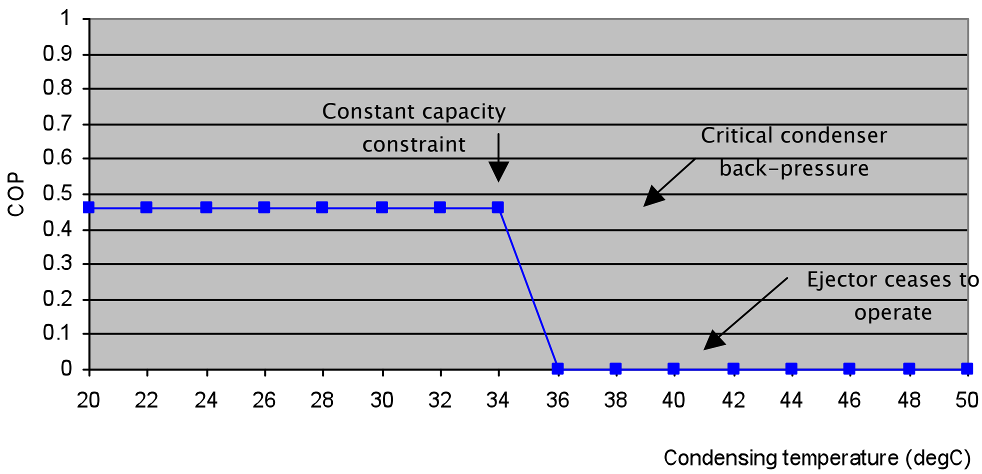

Fig.1. Typical operating characteristics of ejectors designed for fixed condensing temperatures

Using a fixed geometry ejector, the ejector performance increases with decreasing condensing temperature and the ejector is able to operate at a lower solar collector temperature. However, this decreases the primary jet massflow and thus the ejector cooling capacity remains fairly constant. Thus the fixed geometry ejector is not able to take full advantage of the cool ambient conditions in the morning.

Sun (1996) analysed a theoretical variable geometry ejector and showed that such a device would demonstrate increased capacity at low condensing temperatures and smooth drop of capacity at increasing condensing temperatures. However, no such device has been built. Although many examples of ejector-absorption and ejector-vapour compression systems can be found in the literature, there is a remarkable absence of ejector-ejector based hybrid systems.

This paper uses computer modelling to investigate the design and operation of a compound ejector to achieve some of the effects of a variable geometry ejector but in an easily realisable form.

The compound ejector is compared to a family of ejectors designed using a conventional approach described by Huang et al (1999) for operation over a range of condensing temperatures using refrigerant R141b.

THE COMPOUND EJECTOR

A compound ejector couples two ejectors such that the generator flows are in parallel but the evaporator flows are in series (figure 2). The diffuser of the first ejector feeds the secondary port of the second ejector.

A number of questions arise with such a design:

1. For a given power input from a solar collector, what proportion should be diverted to each ejector?
2. What temperatures should be provided by each generator?
3. How does one optimally set the intermediate pressure (p_i) between ejectors in order to meet a target condensing pressure (P_{co})?
4. What are the operational advantages of the compound ejector?
5. How many ejector stages should be used?

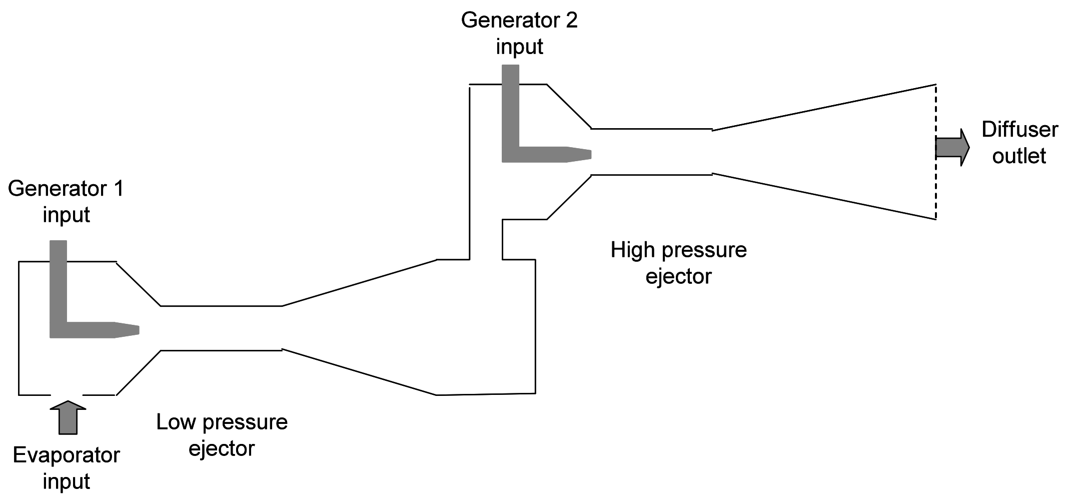

Figure 2. Schematic of a compound ejector

In the analysis, a comparison is made between a standard ejector and a compound ejector designed for condensing temperatures of 30ºC, 40ºC and 50ºC.

In each case, the total collector power was maintained constant at 10 kW. The evaporating temperature was also maintained at 8ºC.

Description of the model

Two models were constructed – one for a standard ejector and one for a compound ejector. Additionally, two versions of each of these models were constructed. The first version is used as an ejector design model. Its purpose is to determine the geometry of an ejector optimally designed for a steady a single set of operating conditions specified by the generating temperature, generating power, evaporating temperature and condensing temperature. The second version of each model is an ejector operational performance model.

With reference to the ejector modelling methodology proposed by Huang, the distinction between each version is that the design model iterates by altering the mixing chamber diameter until the condensing pressure criteria is met whereas the operational model (using fixed geometry) does not iterate since the geometry is fixed and thus the evaporating massflow becomes the dependent variable.

The reference ejector design model assumed that the generator was able to provide motive energy over a range of temperatures from 70-100ºC, but limited in power to 10 kW. The model produced ejector designs suitable for condensing temperatures ranging from 20-50ºC. Saturated vapour conditions were assumed to exist at the evaporator inlet and the generator inlet. For all ejector designs, the isentropic efficiency of the primary nozzle was fixed at 0.91, the mixing momentum efficiency at 0.87 and the secondary flow isentropic efficiency at 0.90. The optimal ejector design was the one that provided the greatest evaporating effect at a given condensing temperature.

The reference ejector designs give rise to a family of optimal ejector geometries represented by the primary and secondary throat diameters as shown in figure 3.

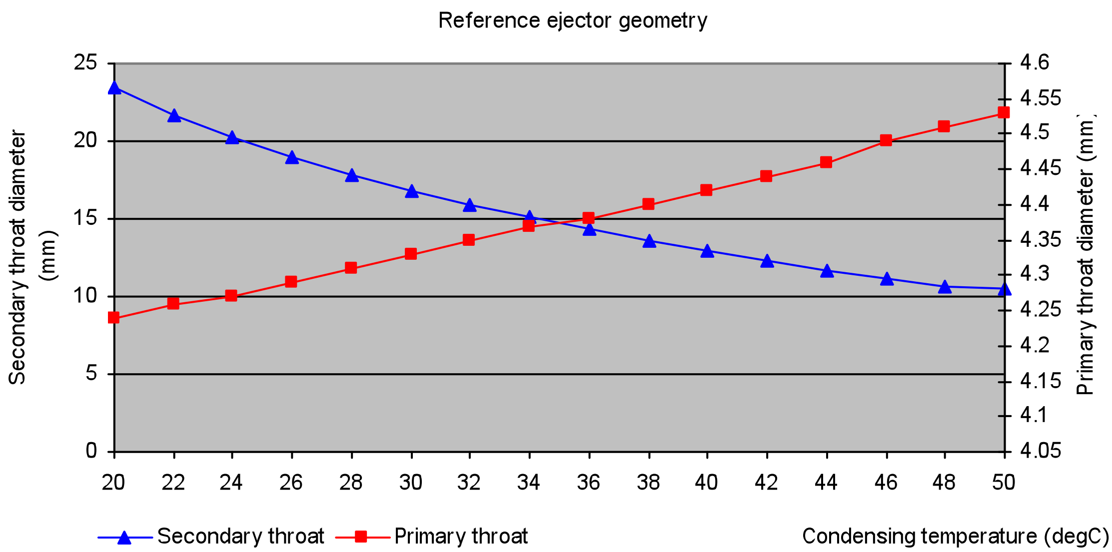

Figure 3. Design geometry for the reference family of ejectors, each optimised for a given condensing temperature

At first it seems counter-intuitive that the generator massflow can increase with constant collector power. Since the increasing condensing temperature effectively provides generator pre-heat, this offsets additional collector energy, thus allowing a small increase in design primary throat diameter.

The design of the compound ejector is complicated by the need to specify an intermediate pressure that exists at the diffuser exit of the low pressure ejector. It is also complicated by the need to divide the collector power between the two ejectors.

The compound ejector design model works by concatenating two reference design models in series, whereby the diffuser outlet conditions of the low pressure ejector are preserved as secondary inlet conditions for the high pressure ejector.

The variables for this design model are the two generator temperatures (70-100ºC), the intermediate pressure (0.4Pco-0.9Pco) and the generator power apportioned to the low pressure ejector (0.2-0.8). The model worked through all combinations of variables these variables and selected the best design by maximising the evaporating effect at a given condensing temperature.

The apportioning of power between the two ejectors was studied over a range of condensing temperatures. There is a wide optimum coefficient of performance (COP) (figure 4) indicating that a simple rule of thumb may be established, suggesting that around 1/3 of the collector power should go to the low pressure ejector, while the remaining 2/3 goes to the high pressure ejector regardless of condensing temperature.

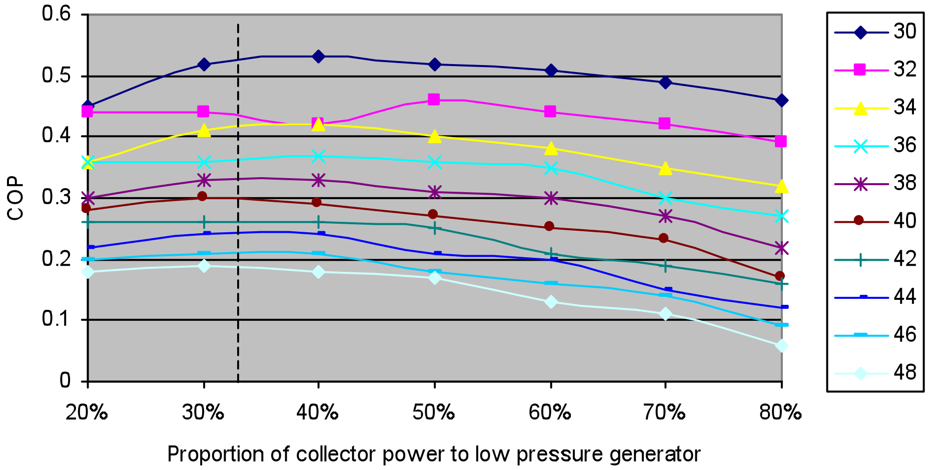

Figure 4. Proportioning of the collector power between the low and high pressure ejectors shows a broad optimum COP

Once the available power for each ejector's generator has been determined, the optimum intermediate temperature can also be fixed. It would be expected that the compression produced by each ejector is in proportion to the power supplied to it. Figure 5 shows that this is indeed the case and that for a given power split, one may prescribe a simple linear function to determine the intermediate pressure as a proportion of the condensing pressure, or fix that proportion. This information would be used to optimally control the compound ejector operation.

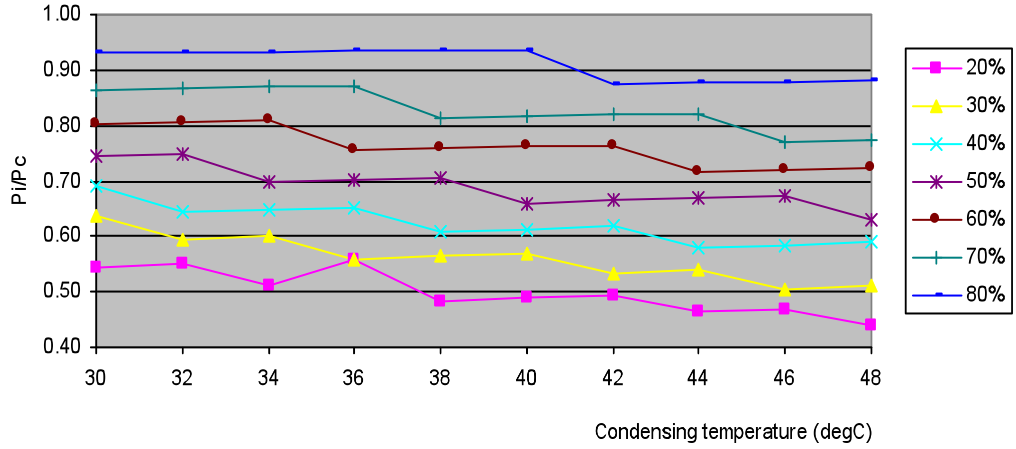

Figure 5. Determining the operational intermediate pressure Pi as a proportion of the condensing pressure Pco and condensing temperature.

The ejector design geometry, partly described by the primary jet diameters and mixing tube diameters, is shown in Figure 6. The primary jet diameters must increase with increasing condensing temperature since the ejector must work harder to build condensing pressure on hot days, effectively operating at elevated compression ratio. Conversely, the design mixing tube diameter becomes smaller with increasing condensing temperature to nullify the effects of increasing backpressure on the ejector.

From an operational perspective, the ejector designer must select one design condensing temperature for the compound ejector from figure 6 and realise that the compound ejector will operate best at that design condition. Figures 4 and 5 offer further design detail, culminating in several designs shown in Table 1.

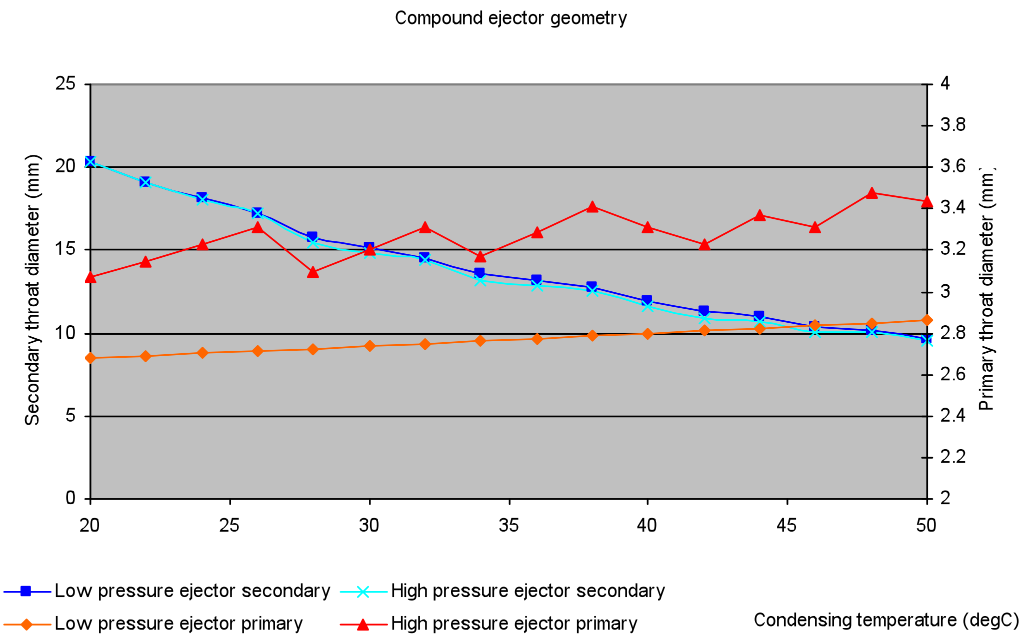

Figure 6. Design geometry for the compound family of ejectors, each optimised for a given condensing temperature.

For the study of the operational characteristics of the ejectors, three ejector designs were chosen. Each ejector is designed for a given condensing temperature.

Table 1. Summary of ejector design parameters

	Condensing temperature	**(ºC)**	**30ºC**	**40ºC**	**50ºC**
Single Ejector	Primary nozzle diameter	(mm)	4.33	4.42	4.51
	Mixing chamber diameter	(mm)	16.83	12.95	10.60
Compound Ejector	Low pressure ejector primary nozzle diameter	(mm)	2.74	2.80	2.85
	Low pressure ejector mixing chamber diameter	(mm)	15.12	11.96	10.15
	Intermediate pressure	(kPa)	65.0	84.5	104.7
	High pressure ejector primary nozzle diameter	(mm)	3.20	3.31	3.47
	High pressure ejector mixing chamber diameter	(mm)	14.87	11.65	10.01

Furthermore, the design model predicts a performance envelope represented in figure 5 by the COP. Note that this should not be confused with the operational performance of a single ejector. The plot suggests that a compound ejector design might have performance advantages at high condensing temperatures.

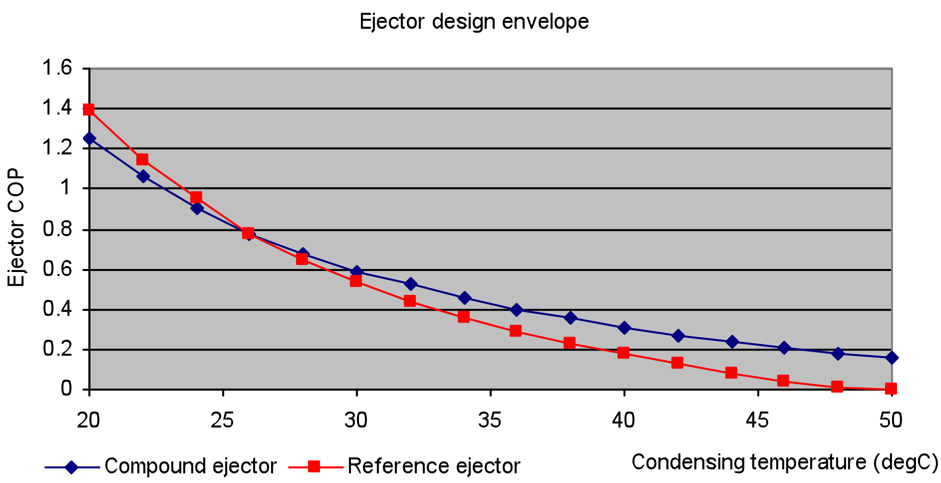

Figure 7. Performance limits are defined by a design envelope shown for the reference and compound ejectors at condensing temperatures.

RESULTS

Having determined the optimal design of a reference and compound ejector to suit various condensing temperatures, the second versions of each model will be used to determine the operational characteristics of the ejector designs.

For simplicity, three reference ejector designs and three compound ejector designs will be compared. The designs are optimised for condensing temperatures of 30ºC, 40ºC and 48ºC.

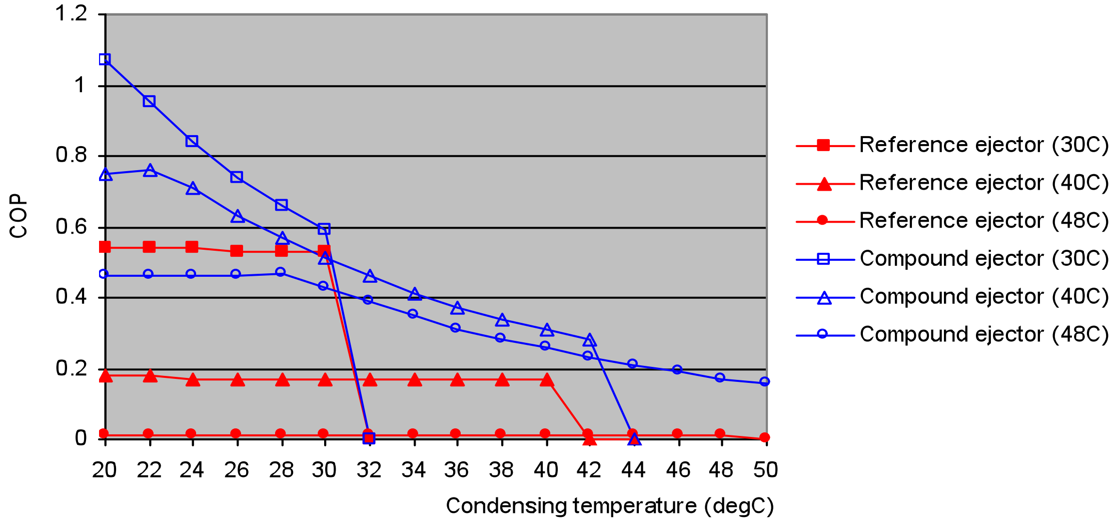

Figure 8. Comparison of operating performance of reference and compound ejectors designed for condensing temperatures 30ºC, 40ºC and 48ºC.

For ejectors designed for condensing temperature of 30ºC, the compound ejector shows no greater ability to operate at elevated condensing temperatures than the reference ejector. However, it does demonstrate a marked improvement in COP at condensing temperatures below and up to the design condensing temperature, apparently eliminating the constant capacity constraint of the reference ejector. Since this cool condensing condition does not directly coincide with the need for provision of cooling, this result is of greater interest when a system has the ability to store cold and thus take advantage of the greater performance available. It is also noteworthy that the compound ejector performs within 10% of the design envelope COP at lower than design condensing temperatures whereas the reference ejector is not capable of this.

For a more realistic condensing temperature of 40ºC, the compound ejector is able to continue to operate at a slightly higher condensing temperature and with much greater COP at all temperatures than the reference ejector. The performance of this design at very low condensing temperatures suggests that the compound ejector also has a constant capacity effect but this occurs at lower condensing temperature and higher COP than the reference ejector. Each ejector is operating closer to its design conditions and thus performance of the compound ejector as a whole is improved over the reference ejector.

The constant capacity effect for the compound ejector is more clearly visible for the ejectors designed to operate at very high condensing temperatures. The reference ejector is unable to build sufficient condensing temperature to operate effectively. The compound ejector continues to operate and once again shows advantages in COP across all condensing temperatures. The constant capacity characteristic is more evident.

DISCUSSION

The compound ejector modifies the reference ejector operating characteristics in three ways:

1. The COP is improved at all but very low condensing temperature designs
2. The critical condensing temperature is higher, particularly at high condensing temperatures
3. The constant capacity effect at low condensing temperatures is relieved

This indicates that the compound ejector would be suitable for applications requiring high condensing temperatures. This is typical of systems incorporating dry re-cooling as would be suitable for domestic application. It is also advantageous where cold storage is available such that cold generated with high COP when the condensing temperature is low (and cooling is not required) may be utilised to supplement cooling supply later.

The design results for the compound ejector suggest that the low and high pressure ejector mixing chambers have very similar diameters. This affords the design a cost saving since only the internal diameter of the primary jets differ between the low and high pressure ejector stages.

A further design improvement is possible by connecting the two ejectors directly in series such that the evaporator flow is conducted coaxially (figure 7). Since the low temperature flow typically has a high specific volume, such a design will tend to reduce viscous friction pressure losses to which ejectors are sensitive.

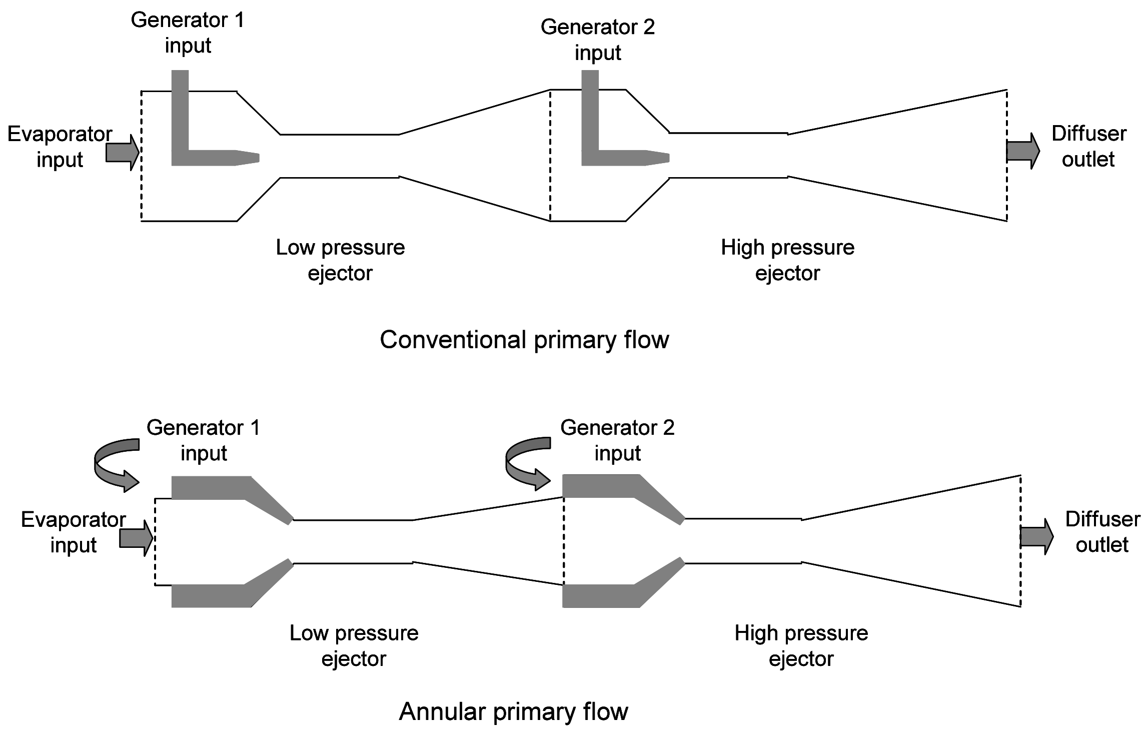

Figure 9. Coaxial designs for compound ejector

The control of the compound ejector is no more complex than for a reference ejector since the proportion of power going to each generator is fixed and the intermediate pressure is fixed by the compound ejector geometry.

The design of the compound ejector differs from a double effect design in that the two generators operate in parallel. This allows some of the benefits of true double effect operation while limiting the maximum collector temperature to levels similar to those required for single effect operation. Thus non-concentrating collectors may still be used.

In this study, only two ejectors working together were considered. Further work may consider more than two ejectors operating in compound fashion. It is also possible to consider intercooling between the ejector stages, cautioning that the ejectors are very sensitive to secondary flow pressure loss.

CONCLUSION

This study indicates that the compound ejector design has potential to improve ejector performance compared to conventional ejector design and is particularly well suited to high condensing temperatures typical of dry re-cooling. The design of a compound ejector is straight forward, offering no new challenges. Furthermore, the solar collector temperature does not need to be elevated to drive the compound ejector and so conventional evacuated tube collectors are well suited to compound designs.

REFERENCES

Huang B., Chang J., Wang C., Petrenko V., A 1D analysis of ejector performance, International Journal of Refrigeration 22 (1999), 354-364.

Sun D., Variable geometry ejectors and their applications in ejector refrigeration systems, Energy 21 (1996), No. 10, 919-929.

BRIEF BIOGRAPHY OF PRESENTER

Dr Mike Dennis is a senior research fellow with the Centre for Sustainable Energy at the Australian National University. He has ten years of international experience with large scale industrial process control and information systems. After returning to University to complete a PhD in predictive control of solar water heaters in 2004, he has continued to develop renewable energy technologies for residential applications and lecture in solar technologies. His chief interest is in solar air conditioning and hybrid residential solar thermal solutions.