PERFORMANCE OF A SCROLL EXPANDER WITH AMMONIA-WATER

James Muye[1]*, Joan Carles Bruno[1], Rajagopal Saravanan[2], Alberto Coronas[1]

[1]Universitat Rovira I Virgili, Department of Mechanical engineering,
Tarragona, Spain

[2]Anna University, Department of Mechanical engineering,
Chennai, India

* jamesmuye.mwangome@urv.cat

ABSTRACT

This paper examines the performance of an open drive scroll compressor modified to work as an expander operating on ammonia-water working medium. The modelling and simulation of the scroll expander is carried out with EES program. In this study a simulation of the expander performance at various pressure ratios (2-4), expander speeds (2500-7500 rpm) and ammonia concentrations (0.8-0.99) at a constant supply pressure (5 bar) and temperature (105^{o}C) has been presented. The scroll expander produced a work output of 0.29 to 1.5 kW, with isentropic efficiencies of between 0.48-0.64. At the assumed in let conditions, the optimum expansion ratio for the expander is 3.

1. INTRODUCTION

Rankine cycles can use a variety of working fluids including mixtures. One of these mixtures is the ammonia-water mixture using absorption and desorption processes. In the ammonia-water mixture, the low boiling point of ammonia makes it attractive for low/medium grade heat utilization; and the tendency to boil and condense at a range of temperatures of the ammonia-water mixture provides a good match between the heat source and working fluid. Also the similar molecular weights of ammonia and water make it possible to utilize the standard steam turbine components (Ganesh and Srinivas, 2010). This binary mixture can find applications in the Kalina and Goswami cycles. The efficiency of the Kalina cycle can be as much as 1.9 times higher than that of the Rankine Cycle system, at the same border conditions (Kalina, 1984).

The expander plays a critical role in systems converting heat into power. It has been established that utilizing a scroll expander can be a viable option for small scale applications. Song *et al.* (2014) gave a comprehensive review on the application and research of scroll expanders. Synthetic refrigerants have been the common working fluid in organic systems integrating scroll expanders (Bracco *et al*., 2013; Twomey *et al*., 2013; Jradi *et al*., 2014). The scroll expander can also be useful in absorption power and cooling cycles. Ayou *et al*. (2013) provided an overview of the numerous combined absorption power and cooling cycles proposed in the literature. To investigate the viability of these cycles, Villada *et al*. (2014) modelled and simulated different solar absorption power-cooling systems that use ammonia based working fluid mixture to simultaneously produce cooling and mechanical power with a single system. They concluded that solar collectors could be used to drive combined absorption power and cooling cycles.

Demirkaya (2011) integrated a scroll expander in an absorptive power and cooling cogeneration system utilizing low temperature heat sources and performed a theoretical and experimental analysis. He modified an off the shelf open drive scroll compressor used in truck refrigeration units and warned that when using a scroll device for an absorption based cycle oil can be carried to the absorber and mix with the strong solution ammonia-water mixture by the vapor flow. The performance of the expander was between 30-40%. The investigation however did not include characterization of the scroll device.

Mendoza *et al*. (2014) experimentally characterized and modeled a scroll expander with air and ammonia as working fluid. They studied how the main operating variables (supply pressure and temperature, pressure ratio, rotational speed and lubrication) influence the performance of the scroll expander and used a semi-empirical model to determine the scroll expander performance. A constant lubrication mass fraction of 2% was determined as the optimum lubrication amount. The semi-empirical model could predict mechanical power, exhaust temperature and supply mass flow rate of the expander at accuracy levels of ±9%, ±4 K and ±5%, respectively.

The objective of this study is to investigate the performance of an open drive scroll compressor modified to work as an expander operating on ammonia-water working medium. In this paper a simulation of the expander performance for ammonia-water has been presented. Experiments to validate the model are being performed. The results of the complete study will be relevant in the future development of small capacity ammonia-water energy conversion systems driven at low/medium temperatures.

2. METHODOLOGY

The expander model adopted by Mendoza *et al*. (2014) for ammonia working fluid uses four semi-empirical parameters. The semi-empirical parameters required for this model are: the swept volume of the compressor (obtained from manufacturer's data), built in volume ratio (obtained from geometrical measurements of the device), work loss (from no load tests) and the theoretical leakage area (deduced from experimental data). The input parameters for the model are pressure and temperature at the expander inlet, pressure at the outlet and the expander rotational speed. It then predicts mechanical power, exhaust temperature and supply mass flow rate of the expander. This model is similar to the one proposed by Lemort *et al.* (2009), the only difference is that in the present model heat transfer with the environment has been assumed adiabatic because of the small heat transfer area of the expander. For simplicity the current model also neglects the effects of lubrication.

Figure 1 shows the model outline of the expander. The working fluid stream supplied to the expander (m_{su}) is split into two: a work producing stream (m_{in}) and a non-work producing steam (m_{leak}) which leaks between the scrolls. The work producing stream is expanded in two stages: the first process is adiabatic and reversible (from su to int) then followed by a constant volume process (int to ex_2). After the expansion processes there is adiabatic mixing of the two streams (m_{leak} and m_{in}) at ex_1. The stream ex_1 then captures heat that was generated from mechanical losses such as friction to produce the exhaust stream ex.

The total work and actual work resulting from the two expansion stages can be calculated as:

$$W_{total} = m_{in}\{(h_{in} - h_{\text{int}}) + v_{\text{int}}(P_{\text{int}} - P_{ex})\} \tag{1}$$

$$W_{net} = W_{total} - W_{loss} \tag{2}$$

To calculate the isentropic efficiency of the expander, the actual work output is compared to the isentropic scenario. The isentropic efficiency of the expander can be expressed as:

$$\eta_{iso.\text{exp}} = W_{net} / \{m_{su}(h_{su} - h_{iso,\text{exp}})\} \tag{3}$$

The volumetric efficiency of the expander is the ratio between the theoretical mass flow rate and the actual mass flow rate as expressed in equation (4).

$$\eta_{v.\text{exp}} = (V_{swept} N \rho_{su}) / m_{su} \tag{4}$$

The mechanical efficiency of the expander is the ratio between the useful work and total work produced by the expander.

$$\eta_{m.\exp} = W_{net} / W_{total} \tag{5}$$

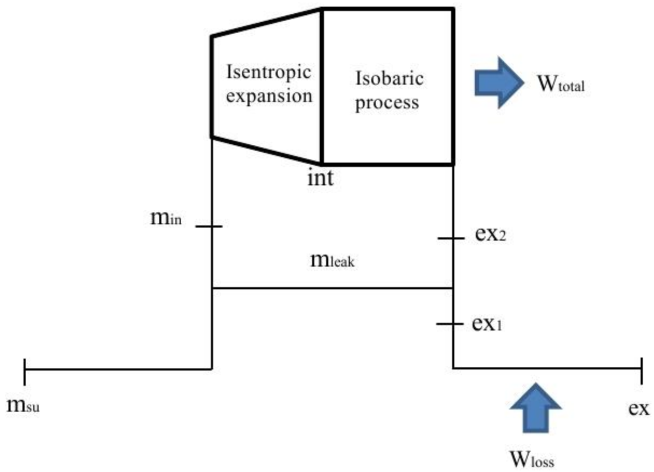

Figure 1: Model outline of the expander

Thermodynamic properties for the ammonia-water mixture are obtained from the (Engineering Equation Solver) EES (2014) external routines database. In a future study, a comparison will be made between the experimental data and simulated data. If the two sets of data do not agree, then the expander will need to be characterized specifically for ammonia-water.

3. RESULTS AND DISCUSSION

Figure 2 shows the expander production and performance at various concentrations and pressure ratios. Pressure at the expander inlet (P_{su}), temperature at the inlet (T_{su}) and rotational speed (N) were kept constant at 5 bar, 105°C and 5000 rpm respectively. The expander output increases with pressure ratio due to the improving expansion ratio across the expander. For all the three pressure ratios considered, the expander output decreases by 32W as the concentration (X) improves from 0.8 to 0.99. There is slightly more work produced at lower concentrations as expected because water has a higher enthalpy than ammonia. The expander registered the best isentropic efficiency ($\eta_{iso,\exp}$) when operated at a pressure ratio of 3 ($\mathrm{Pr} = 3$). The relationship between isentropic efficiency and pressure ratio depends on the rate of increase of actual work and ideal work (no entropy generation) as pressure ratio increases. Both actual work and ideal work increase with pressure ratio but at different rates. Thus at $\mathrm{Pr} = 3$ actual work is closer in value to ideal work, this implies less entropy generation than at $\mathrm{Pr} = 2$. Increasing the concentration improves $\eta_{iso,\exp}$ at $\mathrm{Pr} = 4$, however improving the concentration diminishes $\eta_{iso,\exp}$ at $\mathrm{Pr} = 2$. Therefore in the $\mathrm{Pr} = 2$ case, improving the concentration increases irreversibilities however when $\mathrm{Pr} = 4$ the reverse is true.

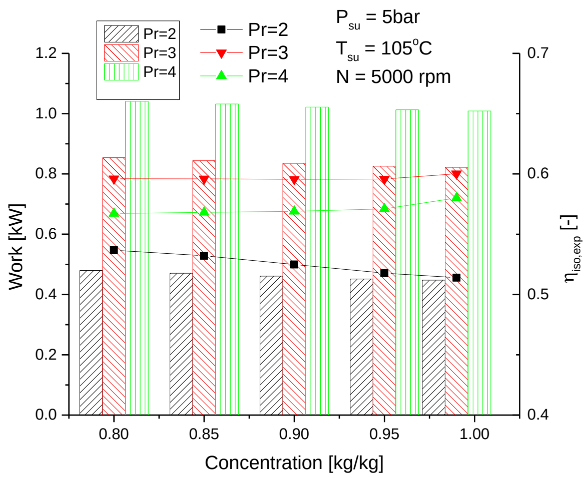

Figure 2: Expander work (bars) and isentropic efficiency (lines) at varying concentrations and pressure ratios

Figure 3 shows the expander work and isentropic efficiency at varying concentrations and expander speeds (P_{su} and T_{su} constant). At a speed of 2500 rpm, work output diminished by 16W as concentration improved from 0.8 to 0.99. It diminishes by 32W and 48W at 5000 rpm and 7500 rpm respectively. The best $\eta_{iso,\exp}$ was observed at $\Pr = 3$ for all the three rotational speeds considered. By design, the expander becomes more efficient and more productive as the rotational speed is increased since leakages are minimized at high speeds. The improvement in performance is more pronounced at $\Pr = 4$ than at $\Pr = 2$. Therefore high pressure ratios are not effective in low rotational speeds, the converse applies also. As depicted in Figure 2, increasing the concentration was found to improve $\eta_{iso,\exp}$ at $\Pr = 4$, however $\eta_{iso,\exp}$ diminishes as the concentration is improved for the $\Pr = 2$ case.
Figure 4 shows the expander exit temperature and mechanical efficiency at various concentrations and pressure ratios (P_{su}, T_{su} and N constant). A big pressure ratio implies a big expansion ratio across the scroll device which results to low expander exit temperatures because most of the enthalpy of the working fluid is harnessed by the expander. Therefore the expander exit temperature drops with increasing pressure ratio. The mechanical efficiency of the expander ($\eta_{m,\exp}$) improves with pressure ratio because the work loss becomes insignificant as more work is produced. Because water has a better enthalpy than ammonia, the exit temperature generally reduces as the ammonia concentration improves. We can predict that the expander exit temperatures will drop further when the rotational speed is increased. Nonetheless the exit temperature, T_{ex} will increase when the supply temperature (T_{su}) is increased. Therefore by taking into account T_{su}, the value of T_{ex} can indicate the productivity of the expander. For example if two similar expanders are subjected to the same conditions, the expander with a lower T_{ex} will be the most productive.

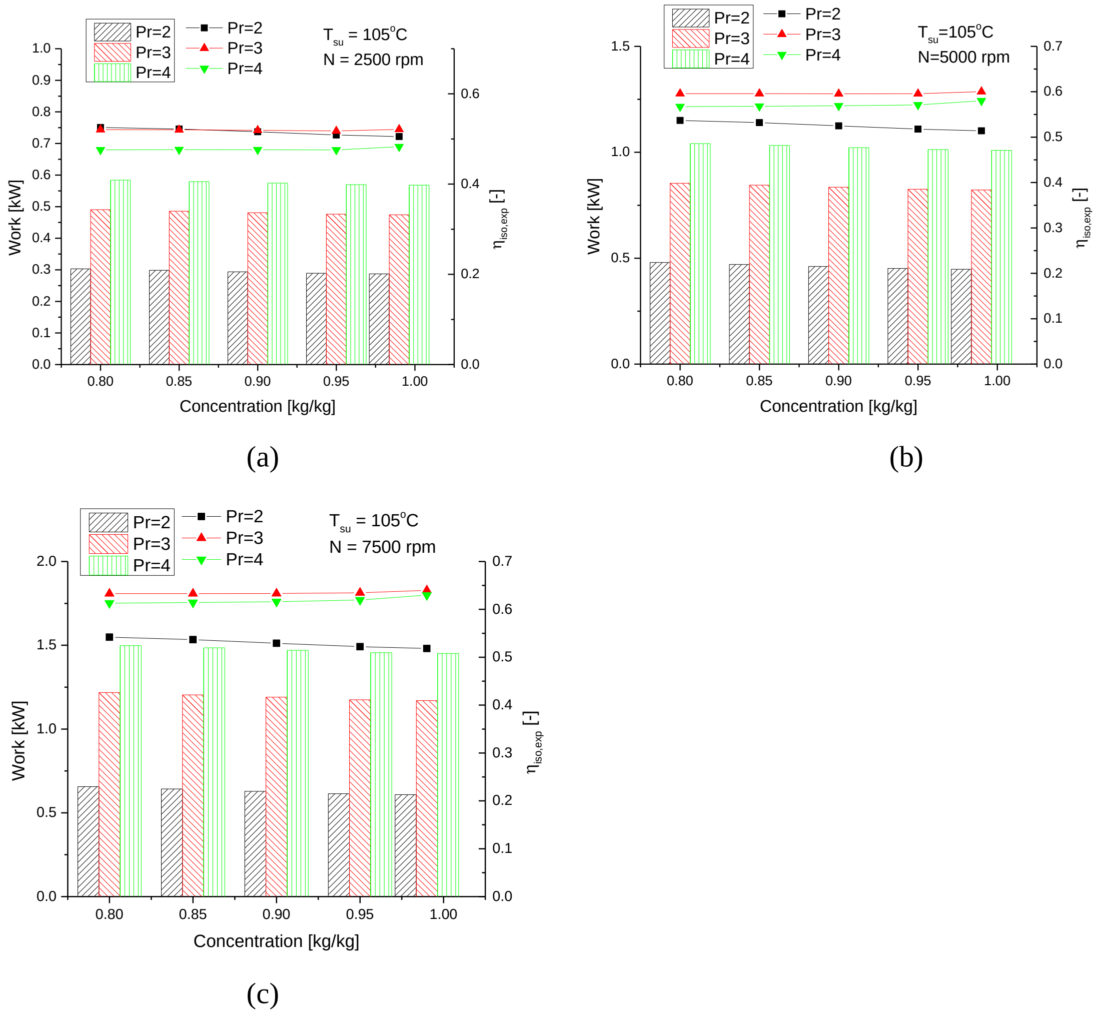

Figure 3: Expander work (bars) and isentropic efficiency (lines) at varying concentrations and expander speeds: (a) 2500 rpm (b) 5000 rpm and (c) 7500 rpm

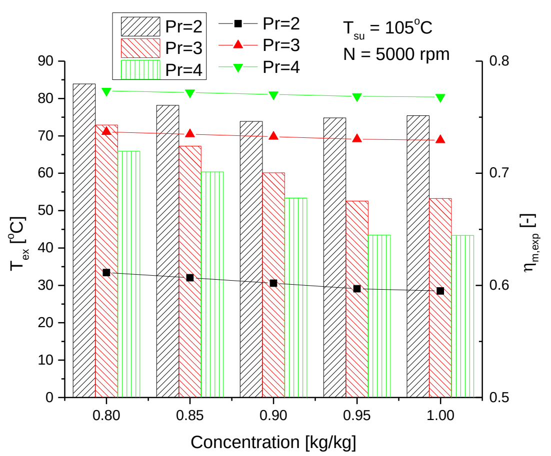

Figure 4: Expander exit temperature (bars) and mechanical efficiency (lines) at various concentrations and pressure ratios

At constant P_{su}, T_{su} and N the variation of volumetric efficiency and mass flow rate at various concentrations and pressure ratios is shown in Figure 5. The mass flow is fairly constant (at a particular pressure ratio) with regard to changes in ammonia concentration however improving the pressure ratio increased the mass flow. The scroll expander is a fixed volume device therefore a high mass flow rate translates into a low volumetric efficiency as indicated in Figure 5.

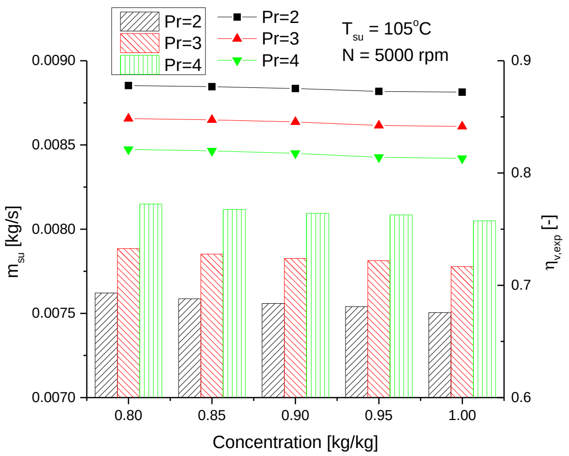

Figure 5: Volumetric efficiency (lines) and the mass flow (bars) through the expander at various concentrations and pressure ratios.

4. CONCLUSIONS

A simulated performance study of a scroll expander working with ammonia-water working fluid has been presented. The effects of pressure ratio, ammonia concentration and expander rotational speed on the performance of the expander was investigated. Generally the work output improved by increasing the pressure ratio and rotational speed or by reducing the ammonia concentration. When considering the expander isentropic efficiency, a pressure ratio of 3 ($\mathrm{Pr}=3$) was found to be ideal for the expander with a supply pressure and temperature of 5 bar and 105°C respectively and at rotational speeds of between 2500-7500 rpm. Also it is important to remark that high pressure ratios are not ideal at low rotational speeds and vice versa. At a supply pressure and temperature of 5 bar and 105°C respectively, the maximum $\eta_{iso,\exp}$ is 63.96% achieved at $X=0.99, \mathrm{Pr}=3, N=7500$ and the maximum work output is 1.5 kW attained at $X=0.8, \mathrm{Pr}=4, N=7500$. The lowest $\eta_{iso,\exp}$ is 47.59% at $X=0.8, \mathrm{Pr}=4, N=2500$ and the minimal work produced is 0.29 kW when $X=0.99, \mathrm{Pr}=2, N=2500$. A low expander exit temperature can imply either: a high expansion ratio (pressure ratio), a high rotational speed or simply a low supply temperature. Because the scroll expander is a fixed volume device, a high mass flow rate transforms into a low volumetric efficiency.

NOMENCLATURE

h	specific enthalpy	(kJ/kg)
m	mass flow rate	(kg/s)
N	rotations per minute	(rpm)
P	pressure	(bar)
Pr	pressure ratio	(-)
T	temperature	(°C, K)
V	volume	(m^3)
v	specific volume	(m^3/kg)
W	work	(kW)

X	concentration	(kg/kg)

Subscripts

ex	exiting the device
exp	expander
in	in to the device
int	internal
iso	isentropic
leak	leakage
loss	lost
m	mechanical
net	net
su	supply
swept	swept volume of device
total	total
v	volumetric

Greek symbols

η	efficiency
ρ	density

REFERENCES

Ganesh N.S., Srinivas T., 2010, Thermodynamic properties of binary mixture for power generation systems, *ARPN Journal of Engineering and Applied Sciences*, vol.5, no. 10: p.49–54.

Kalina A. I., 1984, Combined cycle system with novel bottoming cycle, *J Eng Gas Turbines Power*, Vol.106, no. 4: p.737–742.

Song P., Wei M., Shi L., Danish S. N., Ma C., 2014, A review of scroll expanders for organic Rankine cycle systems, *Applied Thermal Engineering*, vol.75 : p. 54-64.

Bracco R., Clemente S., Micheli D., Reini M., 2013, Experimental tests and modelization of a domestic-scale ORC (Organic Rankine Cycle), *Energy.*, vol.58: p. 107-116.

Twomey B., Jacobs P. A., Gurgenci H., 2013, Dynamic performance estimation of small-scale solar cogeneration with an organic Rankine cycle using a scroll expander, *Applied Thermal Engineering*, vol.51, no.1-2: p.1307-1316.

Jradi M., Li J., Liu H., Riffat S., 2014, Micro-scale ORC-based combined heat and power system using a novel scroll expander, *International Journal of Low-Carbon Technologies*, vol. 9: p. 91–99.

Ayou D. S., Bruno J. C., Saravanan R., Coronas A., 2013, An overview of combined absorption power and cooling cycles, *Renew. Sust. Energy Rev.*, vol. 21: p. 728–748.

Villada J. L., Ayou D. S., Bruno J. C., Coronas A., 2014, Modelling, simulation and analysis of solar absorption power-cooling systems, *International Journal of Refrigeration*, Vol. 39: p. 125–136.

Demirkaya G., 2011, *Theoretical and Experimental Analysis of Power and Cooling Cogeneration Utilizing Low Temperature Heat Sources*, PhD thesis, University of South Florida

Mendoza L. C., Navarro-Esbrí J., Bruno J. C., Lemort V., Coronas A., Characterization and modeling of a scroll expander with air and ammonia as working fluid, *Applied Thermal Engineering*, vol. 70, no.1: p. 630 – 640.

Lemort V., Quoilin S., Cuevas C., Lebrun J., 2009, Testing and modeling a scroll expander integrated into an Organic Rankine Cycle, *Applied Thermal Engineering*, Vol. 29, no.14–15: p. 3094–3102

EES, Engineering Equation Solver, 1992-2014. F-Chart Software. www.fchart.com.

ACKNOWLEDGEMENT

The authors acknowledge the support of Spanish Ministry of Economy and Competiveness (DPI2012-38841-C02-01) and the Government of India-Department of Science and Technology (DST/TM/SER1/2K12/74(C)). James Muye thanks Universitat Rovira i Virgili for the Martí i Franquès Predoctoral Research Staff Programme grant (2013PMF-PIPF-85).
.