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Short Communications

EJECTOR POWERPLANT SYSTEM FOR LOW-ENTHALPY GEOTHERMAL HEAT SOURCES IN THE PHILIPPINES

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ABSTRACT

An ejector is a component which converts the available change in kinetic energy from a high pressure and/or high temperature and low velocity state to a low pressure and temperature but high velocity state into recompression energy that can be utilized for improvement in efficiency of a system. In the field of refrigeration and air conditioning, it is used to reduce the required compressor power in a vapor compression system or to aid in compression together with a heat source in a heat-driven cooling system. In our previous studies, a noble incorporation of the ejector into the organic Rankine cycle (ORC) has been established to obtain dramatically improved efficiency in using the modified ORC. This improvement is realized in the resulting ejector powerplant system by using the high-pressure liquid in the separator located after the evaporator in the conventional ORC that is just pumped back to the evaporator.

Geothermal energy is a good renewable energy source in countries that have high geothermal energy resource like the Philippines. However, current utilization of geothermal resources is focused on high temperature systems but small attention has been given to low-grade or low-temperature geothermal energy resources which are also abundant in the country. Most of these low-enthalpy sources are under-utilized or even unutilized at all.

In the current study, coupling of low-enthalpy geothermal sources in the Philippines into the ejector powerplant system has been investigated. Geothermal sources of 60 to 150 °C have been used. The geometric profile of the ejector, coupling of components and the overall system have been optimized for efficiency, economy and practicality of the system and operations. Computational techniques in our previous studies that incorporate two-phase flow, friction and shock waves have been incorporated.

Ammonia and propane, which are common in the ORC system, are used. With an ambient temperature in the Philippines at around 30 °C, a condenser temperature of 35 °C is considered. The computation using the working fluids considered resulted to having the turbine outlet temperature of 6 to 12 °C below the ambient, which can significantly enhance the powerplant efficiency. The range of the computed ejector efficiency is 90% to 98%. The geothermal-driven ejector powerplant system yields a maximum efficiency range of 10.5% to 17% which is way higher than the range of 6.25% to 10% of the conventional ORC. Ammonia shows superiority over propane in this case.

Keywords*: geothermal, low-enthalpy, heat sources, ejector, powerplant.*

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1. INTRODUCTION

Geothermal energy is a good renewable energy source in countries that have high geothermal energy resource like the Philippines. The country is located in the Western part of the Pacific Rim hosting several volcanic areas. Geothermal energy forms range from shallow ground hot water to extremely high pressure and temperature steam found in hot rocks and magma below the surface of the Earth. However, current utilization of geothermal resources is focused on high temperature systems but small attention has been given to low-grade or low-temperature geothermal energy resources which are also abundant in the country. Most of these low-enthalpy sources are under-utilized or even unutilized at all. From the data of the Department of Energy of the Philippines [1], there are 23areas in the country that can provide hot geothermal water or steam at temperature of 60°C and above, which can be tapped for power generation.

An ejector is a component that can efficiently recover expansion energy into recompression energy [2 – 3]. It is popular in the refrigeration system as it reduces the required compressor power by recovering the power in the expansion of the refrigerant from the condenser outlet for a compressor-driven system [4 – 7] and from the generator outlet for a heat-driven system [8].

In the current study, coupling of low-enthalpy geothermal sources in the Philippines into the ejector powerplant system has been investigated. Geothermal sources of 60°C to 120°C have been used. The geometric profile of the ejector, coupling of components and the overall system have been optimized for efficiency, economy and practicality of the system and operations. Computational techniques in our previous studies that incorporate two-phase flow, friction and shock waves have been incorporated. Comparison of the efficiency of the geothermal ejector powerplant system to that of a conventional organic Rankine cyle (ORC) has also been elucidated. The ORC system has been established in low-grade heat sources like ocean thermal energy conversion (OTEC) [9], solar-boosted OTEC (SOTEC) [10 – 11], solar-thermal, waste-heat driven, biomass and geothermal powerplantswhich were considered in the analysis

2. PERFORMANCE CHARACTERIZATION OF THE EJECTOR, THE EJECTOR POWERPLANT SYSTEM AND THE ORGANIC RANKINE CYCLE

The formulation for the general ejector powerplant cycle using one-dimensional flow with friction has been developed in our previous studies [12-14]. The formulation is used in this study to analyze the performance of the ejector and the ejector powerplant for the geothermal system. The performance of the ejector powerplant is compared to that of the conventional organic Rankine cycle (ORC), which is also described in one of our studies [12]. Essentially, the ejector enhances the performance of the modified powerplant by providing a turbine outlet pressure which is way lower than that of the condenser. Then, after passing through the mixing section, the flow is recompressed in the diffuser to make its pressure higher than that of the condenser so that the powerplant cycle is completed. This feature leads to an incrcased power output and efficiency of the new powerplant system compared to those of the conventional ORC.

Those studies used one-dimensional analysis in single and two-phase flows incorporating friction and shock waves. Recommendations of ASHRAE [15], ESDU [16] and several other researchers [17 – 18] on the geometry of the mixing section and other component parameters were used in those studies.

The thermodynamic parameters of the working fluids used in those studies were obtained from Refprop [19] which is also used in this study.

3. SIMULATION RESULTS AND DISCUSSIONS FOR THE GEOTHERMAL EJECTOR POWERPLANT SYSTEM

The potential of geothermal resources in the country has been investigated. Geothermal sources of 60°C to 120°C have been considered; however, it was computed that the ejector has considerable energy recovery for temperature from 80°C above for ammonia and propane. Those working fluids are considered in this study as they are natural, do not contribute to ozone depletion and have very minimal contribution to global warming.

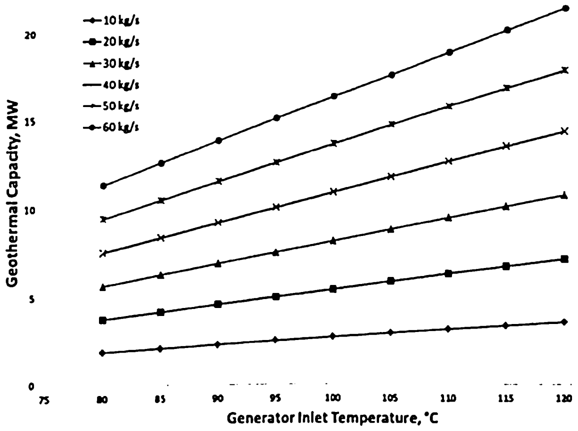

Figure 1. Thermal capacity of Philippine low-enthalpy geothermal sources

The heat that could be transferred to the vapor generator was primarily determined. Figure 1 shows the graph of the geothermal capacity as a function of the generator inlet temperature. The Philippine low-enthalpy geothermal sources can provide mass flow rate as high as around 60 kg/s [1, 8]. Different mass flow rates within this maximum are used in estimating the thermal capacity of sources at temperatures of 80°C to 120°C. Given an ambient temperature of 35°Cwhich is nominal in the Philippines, the sources can provide heat in the range of 2 – 21 MW. It is assumed here that the hot water is kept as liquid during the heat exchange.

Counterflow plate heat exchanger is selected for the heat recovery system as this device has been established to have a satisfactory performance for this situation [20] and offers practicality in terms of compactness, installation and maintenance [21]. The LMTD and Ɛ-NTU methods are combined [22] in determining the heat transfer performance of the generator containing plate heat exchanger in the ejector powerplant system.

Tables 1 and 2 show the ranges of temperatures of the ejector geothermal powerplant that are correlated to the generator or evaporator temperature of 80°C to 120°C for both ammonia and propane as the working fluids.

Table 1. Temperatures and mass flow rates for ammonia

AMMONIA

Temperature (°C)				Mass (kg/s)		
Evaporator	Turbine Outlet	TTD	Nozzle Exit	m_p	m_s	m_{tot}
120.00	24.00	96.0	19.00	20.26	14.30	34.55
115.00	26.00	89.0	21.00	20.77	15.22	36.00
110.00	28.00	82.0	23.00	21.61	16.36	37.97
105.00	29.00	76.0	24.00	22.41	17.43	39.84
100.00	31.00	69.0	26.00	23.87	19.07	42.94
95.00	32.00	63.0	27.00	25.30	20.68	45.97
90.00	34.00	56.0	29.00	27.66	23.15	50.82

Table 2. Temperatures and mass flow rates for propane

PROPANE

Temperature (°C)				Mass (kg/s)		
Evaporator	Turbine Outlet	TTD	Nozzle Exit	m_p	m_s	m_{tot}
90.00	28.00	62.0	23.00	86.86	77.25	164.12
85.00	31.00	54.0	26.00	95.17	87.34	182.51
80.00	33.00	47.0	28.00	102.77	96.30	199.06

3.1 Calculated ejector profiles and efficiency

A 3-MW powerplant for small-scale application is chosen for the simulation. Figures 2 – 3 show the geometry, pressure and Mach number profiles of the ejectors for ammonia and propane, respectively, at selected maximum evaporator temperatures and condenser temperature of 35°C. The nozzle inlet diameter was set at 0.2 m for both working fluids. The converging and diverging angles were set at 60° and 5°, respectively. The calculation shows that the throat diameter and other dimensions of the ejector for ammonia are larger than those for propane except for the length of the converging section.

The distance from nozzle exit to mixing section was determined by using a flow aspect ratio of 4.72. This value of flow aspect ratio was used for all the ejectors. The diameter of the mixing section was determined by defining first the appropriate area ratio for the ejector based on fluid and flow properties. The length of the mixing section is thrice the diameter. The end of the mixing section is the inlet of the diffuser. The diverging angle of the diffuser was set at 7°.

The nozzle primary flow as shown in red lines in Figures 2 – 3 enters the nozzle at high pressure. Minimal pressure drop occurs at the converging section of the nozzle, but the flow accelerates into supersonic speed and rapidly decreases into very low pressure in the diverging section. The secondary flow, indicated by a dashed blue line, enters the nozzle at a pressure higher than the nozzle exit pressure in order for it to be entrained in the mixing section. The primary and secondary flows are assumed to start turbulently mixing at constant-pressure at a certain location downstream of the nozzle exit. The location at the start of mixing is not known, so it was assumed to occur at the mixing section inlet. The process of constant-pressure mixing is shown in horizontal line in the pressure profile. Shock wave is assumed to occur right after the two fluids become fully-mixed to decelerate the supersonic flow in the straight section to subsonic flow. The length of the mixing section is set to accommodate a shorter length between the back of the shock wave and the diffuser to ensure that subsonic flow will enter the diverging configuration of the diffuser. The diffuser then causes compression of the mixed flow to make it attain the pressure of and enter the condenser.

It can be seen from the Mach number profiles of the flows that the transition from sonic to supersonic flows in the nozzle occurs around the throat. The flow from nozzle exit to the start of mixing can be approximated. The Mach number of primary flow at the start of mixing can also be determined. Based on the graphs, there is a slight decrease in Mach number of primary flow from nozzle exit to the start of mixing, suggesting that kinetic energy is lost during the entrainment process. The entrained flow accelerates as it flows from the suction chamber to the mixing section before the two fluids start to turbulently mix.

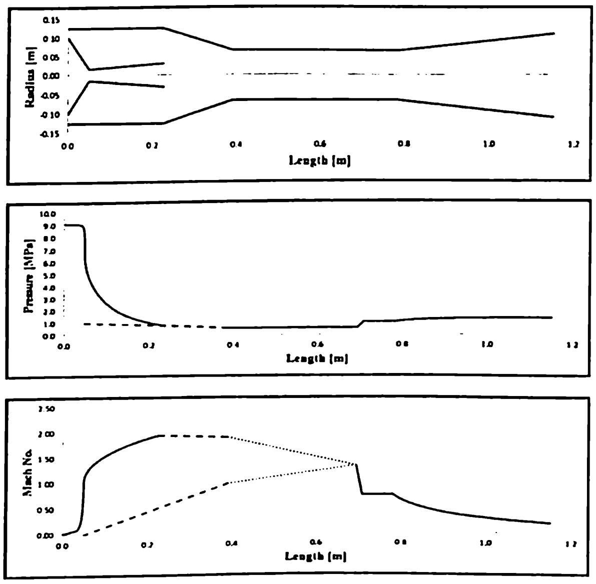

Figure 2. Geometry, pressure and Mach number profiles of the ejector at T_{con} = 35°C and T_{evap} = 90°C for ammonia

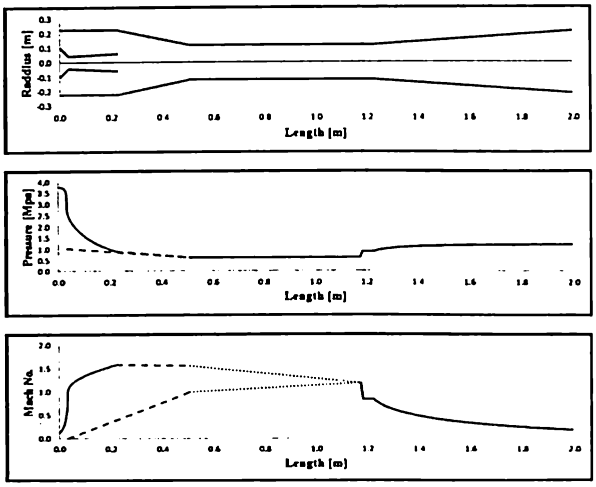

Figure 3. Geometry, pressure and Mach number profiles of the ejector at $T_{con} = 35°C$ and $T_{evap} = 90°C$ for propane

The fully mixed flow of the primary and the secondary fluids is supersonic, and then shock wave occurs. The shock results to rapid drop in flow speed from supersonic to subsonic. At the allowance length, there is only a slight change in the Mach number. The flow will reduce its speed further through the diffuser as the kinetic energy is converted to potential energy, leading to pressurization.

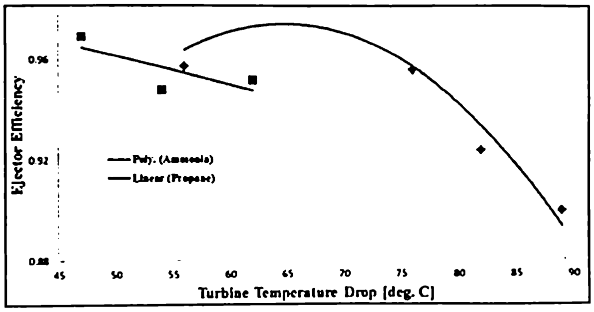

Figure 4. Ejector efficiency at $T_{con} = 35°C$ and $T_{evap} = 90°C$

Figure 4 shows the trend of ejector efficiency for both ammonia and propane. The ejector efficiency has an optimum value with turbine temperature drop (TTD). After reaching the optimum point containing the maximum efficiency, increasing the TTD would result to efficiency drop because the diffuser would have less kinetic energy to raise the temperature back to condenser condition. Propane in this case has already reached the optimum point at the beginning of the given TTD range and is already decreasing with further increase in TTD. The computed ejector efficiency is 90 – 98% for ejector using ammonia and 95 – 97% using propane.

3.2 Ejector powerplant efficiency

Figures 5 and 6 show the efficiency of the geothermal ejector powerplant. The ORC efficiency is 10% at an evaporator temperature of 120 °C. The efficiency is increased up to 17% for TTD of 55 – 95 °C. For propane, the ORC efficiency of 6.25% is increased up to 10.5% for TTD of 45 – 62 °C.

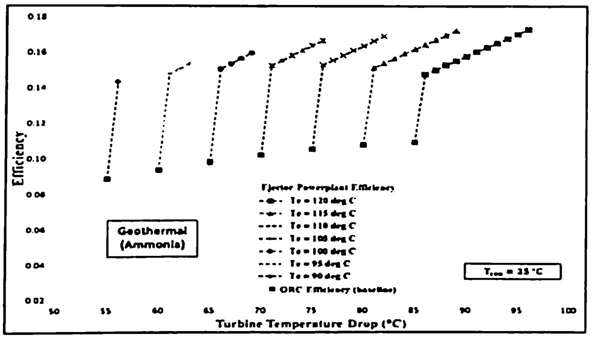

Figure 5. Powerplant efficiency for ammonia

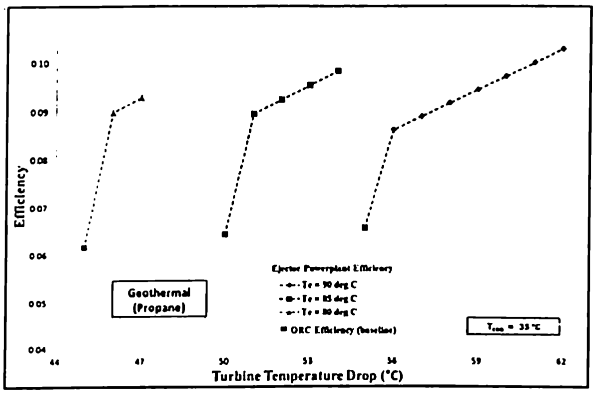

Figure 6. Powerplant efficiency for propane

4. CONCLUSIONS

Coupling of low-enthalpy geothermal sources in the Philippines into the ejector powerplant system has been investigated. Geothermal sources of 60 to 150 °C have been used. The geometric profile of the ejector, coupling of components and the overall system have been optimized for efficiency, economy and practicality of the system and operations. Computational techniques in our previous studies that incorporate two-phase flow, friction and shock waves have been used.

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5. REFERENCES

1. Ulgado, A., Gular, M.T., 2005, "Status of Direct Use of Geothermal Energy in the Philippines," Proceedings World Geothermal Congress, Antalya, Turkey.
2. Berana, M.S., Characteristics of supersonic two-phase flow of carbon dioxide through a converging-diverging nozzle of an ejector used in a refrigeration cycle, Master's Thesis, Toyohashi University of Technology, Toyohashi, Aichi, Japan (2005).
3. Nakagawa, Berana, M. S, Kishine, A., Supersonic two-phase flow of CO2 through converging-diverging nozzles for the ejector refrigeration cycle. Int. J. Refrigeration 32(6), 1195–1202 (2009).
4. Sarkar, J., Optimization of ejector-expansion transcritical CO2 heat pump cycle. Energy 33, 1399–1406 (2008).
5. Deng, J., Jiang, P., Lu, T., Lu, W., Particular characteristics of transcritical CO2 refrigeration cycle with an ejector. Applied Thermal Engineering 27, 381–388 (2007).
6. Elbel, S., Hrnjak, P., Experimental validation of a prototype ejector designed to reduce throttling losses encountered in transcritical R744 system operation. Int. J. Refrigeration 31, 411–422 (2008).
7. Nakagawa, M., Takeuchi, H., Performance of two-phase ejector in refrigeration cycle. Proceedings of the 3rd International Conference on Multiphase Flow, Lyon, France, 382: 1–8, June 8-12, 1998.
8. Redo, M. A. B., Design and experiment alanalysis of heat-driven ejector refrigeration system, Master'sThesis, University of the Philippines Diliman (2014).
9. Avery, H., Wu, C., Renewableenergyfrom the ocean: A guide to OTEC, Oxford Press: NY (1994).
10. Yamada, N., Hoshi, A, Ikegami, Y., Performance simulation of solar-boosted ocean thermal energy conversion plant. Renewable Energy 34, 1752–1758 (2009).
11. Straatman, P.J.T., vanSark, W.G.J.H.M., A new hybridocean thermal energy conversion–Offshore solar pond (OTEC–OSP) design: A cost optimization approach. Solar Energy 82, 520–527 (2008).
12. Berana, M. S., Bermido, E. T., Design and Analysis of Ejector Powerplant System, Proceedings of the ASME 2013 International Mechanical Engineering Congress and Exposition (IMECE2013), San Diego, California, USA, November 15-21, 2013.
13. Berana, M. S., Bermido, E. T., Ejector Modelling for Powerplant Application, Proceedings of the 8th International Conference on Multiphase Flow (ICMF 2013), Jeju, Korea, May 26 - 31, 2013.
14. Bermido, E. T., Berana, M. S., Design of Converging-Diverging Nozzle of an Ejector for Powerplant Application using Natural Working Fluids, Proceedings of the Sustainable Future Energy Conference 2012, Brunei Darussalam, November 21-23, 2012.
15. ASHRAE, Steam-jet refrigeration equipment, equipment handbook, vol. 13, pp. 13.1-13.6 (1979).
16. ESDU, Ejectors and jet pumps, design for steam-driven flow, Engineering Science Data Item 86030, Engineering Science Data Unit, London (1986).
17. Huang, B.J., Chang, J.M., Petrakos, V.A., Zhukov, K.B., A solar ejector cooling system using refrigerant R141b, Solar Energy (64), pp. 223–226 (1998).
18. Chen, X., Omer, S., Worall, M., Riffat, S., Recent developments in ejector refrigeration technologies. Renewable and Sustainable Energy Reviews 19, 629-651 (2013).

19. Lemmon, E. W., Huber, M. L., McLinden, M. O., NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties - REFPROP, Version 8.0, National Institute of Standards and Technology (2007).
20. Dagdas, A., 2007, "Heat Exchanger Optimization for Geothermal District Heating Systems: A Fuel SavingApproach," RenewableEnergy, 32, pp. 1020-1032.
21. Gut, J., Pinto J., 2004, "Optimal Configuration Design for Plate Heat Exchangers," International Journal of Heat and Mass Transfer, 47, pp. 4833-4848.
22. Espeña, G. D., Heat-driven ejector refrigeration system for hot-springresorts application, Master's Thesis, University of the Philippines Diliman (2014).