Development of Scroll Expander for Utilization of Waste Geothermal Heat Through Organic Rankine Cycle

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Abstract: The demand for energy is increasing rapidly and the need for energy resources is in demand. The increase in energy generation and consumption has led to the production of large amounts of waste heat. This waste heat, while holding enormous potential as an energy source, is simply rejected into the atmosphere, contributing to the inefficiency of energy generation processes as well as thermal pollution on the environment. As a solution to this, the Organic Rankine Cycle (ORC) is an environmentally-friendly approach to power generation by utilizing waste heat energy from geothermal power plants. Among waste heat sources, geothermal heat holds the most potential because of the stability and abundance of its source. By being directly installed in locally existing plants in the Philippines, the ORC can increase their working efficiency by enabling them to capture heat energy at low temperatures, which conventional steam power cycles cannot otherwise utilize, while further minimizing thermal impact.
The study covers the development of a low-cost, small-scale ORC system simulating the heat capture from geothermal plants, at a temperature range of 80-85 °C. The mechanical design, control system, and software interface are all included in the construction of the system. A scroll expander converted from a scroll compressor is chosen as the type of power generator. The researchers conducted three trials to characterize the effectiveness of the converted scroll expander with the ORC test bench. A Carnot efficiency ranging from 11.8-13.2% was achieved by the system. Using R-134a as the working fluid, the expander reached an isentropic efficiency of 48-50%. Though the isentropic efficiency attained was quite low compared to other previous studies of similar nature, the ORC system managed to achieve a maximum power efficiency of 10.25%, with an average overall power efficiency ranging from 3.8-7.3%, presenting the viability of the ORC for utilizing low-temperature waste heat as energy.

Key Words: up to five key words/terms; separated by semicolons

1. INTRODUCTION

According to the report of the Geothermal Congress 2000 held in Beppu, Ōita Prefecture of Japan held from May to June 2000, the Philippines was billed as the largest consumer of electricity from geothermal sources [1]. Geothermal energy is a reliable source of power that can greatly reduce the need for importing fuels, a relief especially relevant for an import-dependent country like the Philippines. It is also renewable because its primary resource is natural heat recovered from within the earth. But as with all processes involving the conversion of thermal energy, it is only limited to achieve a certain degree of efficiency because of its inherent limitations and losses. The most notable of which is the Carnot efficiency that dictates the highest thermodynamic efficiency a power generation system can achieve. It is because of this principle that geothermal plants remain largely inefficient in successfully converting the constantly available heat into other forms of usable energy.

Yet, unlike other conventional and renewable energy sources, geothermal energy remains preferable because of its unique characteristics, namely being abundant, stable throughout the year in terms of quantity and availability, independent of weather conditions, and having an inherent energy storage capability [2]. Distinct from fossil-fuelled power generation, geothermal power generation is also considered to be a clean technology and environmentally friendly power source which could significantly contribute to the reduction of GHG emissions by replacing fossil fuels and other non-clean energy sources used for power generation [3].

As a way to potentially increase their operating efficiencies, geothermal plants then become ideal targets for small-scale power generation applications because they have hot water loop systems that operate at low temperatures. An ORC system can extract this latent heat energy from these geothermal sources and utilize it as mechanical or electrical energy. For this specific study, an Organic Rankine Cycle for geothermal heat will be explored, by virtue of being a low-temperature (100-150 °C) source with large potential as a renewable energy source. The amount of energy available is huge, but due to the low temperature, the work conversion efficiency becomes very low as well.

In addition, there is also a relatively larger production of waste heat energy in geothermal systems compared to other sources, and as such, it needs to be dissipated in an environmentally acceptable way. In an ORC-based low temperature geothermal power system, its thermal impact can be greatly reduced by reusing the waste geothermal heat in another power cycle so that the environmental contribution of the waste heat becomes insignificant [4].

The study holds potential in the improvement of the efficiency of geothermal plants by integrating a low-cost, small-scale power generation solution to work alongside the dry steam Rankine cycle to be able to harness additional energy and consequently, reduce operational energy wasted and released to the environment.

2. INSTRUMENTATION

The Organic Rankine Cycle (ORC) is a system that uses an organic fluid for it to produce mechanical work or electricity. The process of ORC is composed of a series of four thermodynamic processes applied on the fluid – compression, vaporization, expansion, and condensation.

1) Scroll expander

The Sanden TRS lines of compressors are mainly used for refrigeration of automobiles instead of split-type air-conditioning units. It is totally desirable for the researchers to use because it has a built-in mechanical shaft seal. The Sanden TRS model proved to be arguably one of the easier refrigerant scroll compressors to convert into a scroll expander because compared to the previous model, its enclosure is not hermetically sealed. This completely eliminated the need for fabrication of a custom enclosure and shaft coupling. Only two significant modifications were needed in order to convert the said scroll compressor to a scroll expander; interchanging of inlet and outlet ports; and removal of the check valve found inside the high pressure chamber of the assembly.

2) Diaphragm pump

A Wispump WSC21000L, a duplex-type diaphragm and oil-less pump was selected [5]. As noted in the previous researches of Sylvain Quoilin and Sebastian Declaye, a duplex diaphragm pump proved to be the more effective type of pump for their studies on ORC for waste heat recovery [6]. The piston inside the diaphragm pump does not make direct contact with the working fluid, thus making it more appropriate for high pressure and temperature applications

3) Heat exchanger - evaporator

A second-hand Fedders split-type air-conditioning unit was used. To simulate the latent heat produced by the geothermal Rankine cycle, it is submerged in hot water and enclosed in a stainless steel tub to contain the stored heat around the evaporator, enabling it to act as the hot reservoir of the system.

4) Heat exchanger – condenser

The second radiator used as the condenser was also stripped off the same Fedders air-conditioning unit. It is placed after the expander to further reduce the pressure of the working fluid and discharge heat energy from the fluid. It is simply exposed to the surrounding air without any housing. The researchers opted to maintain the condenser as passive cooling because to lessen the temperature of the cold reservoir, TC, below the ambient temperature will require a separate system, such as a refrigerator, to be supplied with additional work input [7].

5) Working fluid

All major components used in the ORC system were primarily compatible with refrigerant R-134a, such as the converted scroll compressor and set of radiators. It was also deemed appropriate for the purposes of this study due to its non-toxic, non-flammable, and non-corrosive properties. As a safety consideration incorporated later in the study, the working fluid cannot be allowed to reach its maximum allowable working temperature and pressure, listed as its critical point.

6) Heat source

Two generic household water heaters, with an electrical rating of 240VAC, 10A, & 1000W, were connected in parallel to serve as the heating element for the aforementioned hot reservoir. The researchers opted to use this type of heater for the following reasons: 1) It is directly in contact with the heat storage medium; 2) It is cheap and easily available from hardware stores; 3) It is small in size; and 4) Since it is an electrical appliance, it can be controlled by automation using a relay circuit and microcontroller.

7) Piping system

Copper tubes and couplings were used to complete the closed loop of the ORC system. Copper was arguably deemed to be the most desirable type of material to use for refrigeration applications because of its high thermal conductivity to help yield a more accurate temperature reading for the sensors, placed in direct contact with the tube walls [8].

8) Microcontroller

The microcontroller in charge of the control system was a Gizduino+ w/ ATMega 644+ [9], compatible with the Arduino IDE platform. This particular type of board was selected for its analog voltage processing and digital signal switching features. Arduino was the preferable platform for the researchers to work with due to the easier availability of references, libraries, and basic source codes that aided in the development of the software for the study. It is used primarily to process the data returned by temperature sensors as well as to monitor the logic states of the heater and the refrigerant pump.

9) Temperature sensors

For digital monitoring of the cycle temperature at various points of the machine, five LM35 Precision Centigrade Temperature sensors housed in a TO-220 package were used due to their low cost, direct calibration in degrees Celsius, and its wider temperature signal range of 2 – 150 °C compared to other conventional temperature sensors. It outputs a rated signal of 10mV / °C reading at ± 0.5 °C accuracy [10].

10) Relay switch

Two electrically actuated relays were used to control the AC devices in the machine, namely the heater and the refrigerant pump. The specific relays used were an OMRON LY4-D with a capacity of 240VAC & 10A for the heater, and an OMRON MY4-D rated at 240VAC & 5A for the pump. Both relay switches activate with a 12V signal passing through their coils.

11) Power Supply

To provide the required 12V for the relay coils and microcontroller, a Cannon AM-858S external power supply rated at 4.5-12V & 1000 mA maximum current, was used. The maximum rated current draw of the supply is also considered as a work input for determining power efficiency.

3. RESULTS AND DISCUSSION

Several experiments were done but the main experiment focused on estimating the overall efficiency of the machine by checking the power output of the expander. This was done by calculating the torque and revolutions per minute of the expander pulley. To measure the torque generated by the output power shaft of the scroll expander, the researchers used a Prony brake system.

The actual kg-force reading at which the expander pulley completely stopped rotation was estimated to the nearest interval shown on the scale. Similar to the pressure readings, the stopping force remained consistent between the three trials, and as such, was assumed to be constant. Using the torque parameters measured, the resistant torque is computed using Equation 1. The parameters obtained are listed in Table 1.

$$Torque = Force \ x \ distance \ x \ \sin\theta \qquad (1)$$

Table 1. Resulting torque parameters measured

Resistant force, *F*	25g
Lever arm distance, *d*	0.056 mm
Lever arm angle, *θ*	90°
Torque	**0.001251 N-m**

The next parameter required to get the power output of the expander was its revolutions per minute (RPM) during operation. The RPM was measured with the use of a tachometer. For this purpose, the rotating face of the expander was covered in black tape to allow the tachometer to detect a single revolution. The tachometer was then secured and levelled to the expander face as opposed to being manually handheld during measurement in order to avoid human motion interfering with the accuracy of the readings.

Three sets of data recording were conducted over a 30-minute operation of the machine per sample. The tachometer reading was sampled around 2-3 times every minute. The resulting average and maximum RPM readings are listed in Table 2, along with their corresponding trend lines at Figure 1.

Table 2. Resulting average and max expander RPM

	Trial 1	Trial 2	Trial 3
Maximum speed (RPM)	606.5	1157	501.5
Average speed (RPM)	396.52	824.62	406.68

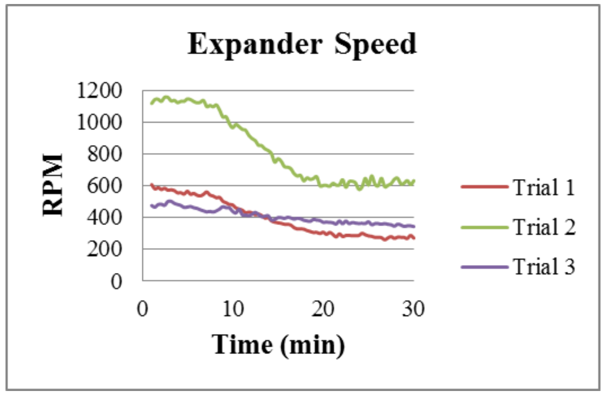

Fig. 1. RPM trend of scroll expander

To compute the power efficiency of the system, the researchers first calculated the sum of all power inputs to the system. Based on the energy balance diagram, there are 3 prominent parts in the system which require energy input to run.

1) Heater (as heat energy)
2) Pump (as electrical work)
3) Control System (as electrical work)

For the heater, the researchers computed the power needed by the using the heat transfer formula in Equation 4.5:

$$Q = mc\Delta T \qquad (2)$$

Where:
m=mass of water (g)
c=specific heat of water (J/(g*°C))
ΔT=change in temperature (°C)

The researchers measured the mass of the water in tank by calculating its volume and multiplying it by the density of water. This estimated method was preferred since the evaporator and its piping system was welded within the tank and removing it would require additional resources to dismantle and put back together again.

The evaporator heat input measurements are based on the different temperature drops at the heater for the three trials. For the measurement of the feed pump's electrical consumption, it is computed using the formula listed in Equation 3.

$$Power = Voltage \times Current \quad (3)$$

The pump voltage is rated at 220VAC. The current draw is measured at 3.6A with the use of a clamp meter.

For the last of the power inputs, the control system power consumption was based from its power supply's maximum current draw of 1000mA multiplied by 12V. The total power inputs of the ORC system are listed in Table 3.

Table 3. Total power input of the ORC system

	Trial 1	Trial 2	Trial 3
Change in hot reservoir temperature, ΔT_H	2.44 °C	2.93 °C	1.95 °C
Evaporator, Q_{heater}	562.11 W	674.99 W	449.23 W
Feed pump, W_{pump}	792 W		
Control system, $W_{control}$	12 W		
Total	**1366.11 W**	**1478.99 W**	**1253.23 W**

The power output generated by the system is then calculated by using the formula in Equation 4.

$$W\_expander = (Torque * RPM)/9.5488 \quad (4)$$

The work generated by the expander is compared to the power input, using the formula in Equation 5, to compute for the overall power efficiency achieved by the system during operation. The maximum and average power efficiencies attained during the three trials are listed in Table 4.

$$\eta_{overall} = \frac{Work\ Output}{Power\ Input} \quad (5)$$

Table 4. Power efficiency of the ORC system

Maximum			
	Trial 1	**Trial 2**	**Trial 3**
RPM	606.5	1157	501.5
Work Output (W)	79.5	151.65	65.73
Power Efficiency	5.82%	10.25%	5.25%
Average			
	Trial 1	**Trial 2**	**Trial 3**
RPM	396.52	824.62	406.68
Work Output (W)	51.97	108.09	53.31
Power Efficiency	3.80%	7.31%	4.25%

Trial 2 resulted in the highest power cycle efficiencies of the ORC system with 10.25% maximum and 7.31% average respectively, and as such, it was the only trial that successfully reached the intended objective of 5% overall efficiency of the system. The relatively high difference with respect to the other trials was presumably an effect of the expander not being run earlier in the day prior to the sampling period of Trial 2. On the other hand, although the other trials were also able to reach the target efficiency plateau during the start of operation, their efficiencies fell short with respect to time, thus, achieving average efficiencies of only less than 5%. This was because the other trials were conducted after the machine had already been running beforehand. Trial 1 was conducted after a series of unrecorded initial test runs, while Trial 3 was conducted directly after Trial 2. The results indicated that successive trials resulted in a steady decrease of the ORC system's power efficiency over continuous operation due to the accumulated build-up of condensed water in the expander.

4. CONCLUSIONS

The development of a small-scale ORC system producing energy with a converted scroll expander was successfully done but the desired working conditions were not fully attained, namely due to the partial incapability of the pump to work with the high pressures of R-134a fluid and the presence of condensed water inside the expander during prolonged operation.

Despite the operating issues, the researchers were still able to achieve the intended overall power efficiency of 5% from the scroll expander. The conversion of a scroll compressor to a scroll expander was also deemed effective due to its consistency in expanding the fluid and by virtue of having achieved an acceptable isentropic efficiency of around 50%. For characterizing the effectiveness of the heat exchangers, however, the results did not end up to be ideal because the power generated by the scroll compressor was also largely affected by the pump compressing the fluid rather than solely the heat transfers and expansion of the working fluid in the closed loop.

Different types of scroll compressors have different methods of conversion along with varying structural configurations which dictate the compatibility and capability of a scroll expander to work in an ORC model. The conversion of the scroll compressor can be very rigorous if the selection of the compressor is not prepared for beforehand. Researchers found the conversion of the first scroll expander prototype from a refrigerant split-type scroll compressor troublesome due to structural issues such as enclosure leakage and power transmission incompatibilities.

The main reason for the low cycle efficiency and low thermal exchange boils down on the selection of pump and the heat exchanger. The pump was unable to circulate the chosen refrigerant properly because of the limitation of its rated working pressure and the heat exchanger may have presumably demanded more work requirement from the pump due to its damaged fins and corrugated configuration.

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