An Overview of GRANEX Technology for Geothermal Power Generation and Waste Heat Recovery

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This paper reports on the recent advancement of the GRANEX technology platform developed by our group for power generation from low-grade heat sources. The technology is particularly suited to applications involving geothermal power generation and waste heat recovery. By combining the concepts of heat regeneration and supercritical Rankine cycle into a unified process, GRANEX improves the thermal efficiency of the cycle and increases the net electrical output which can be recovered from a given low-grade heat source. The regeneration of the thermal energy in GRANEX is achieved through a novel heat regenerator invented and patented by our group in partnership with Granite Power Limited (GPL). Development of GRANEX dates back to early 2006 when a Research and Development Agreement was established between the University of Newcastle and GPL. In conjunction with a program of fundamental studies an applied program of work was undertaken for proof of concept and prototype development with the assistance of a REDI grant from AusIndustry (2007-2009). By 2008, a 1 kW prototype had been built and experimental trials of the system had been completed, demonstrating considerable advantages over conventional systems in terms of both thermal efficiency and power generation (about 40% improvement). This was followed by the design of a 100 kW pilot-plant in early 2009. The pilot-plant is currently under construction and is due to be commissioned by late November 2009.

Keywords: Geothermal power, waste heat recovery, GRANEX

Introduction

The growing world-wide concern about energy conservation and the global impact of greenhouse gases have prompted a series of new research and development activities focusing on renewable energy sources, particularly solar, wind, biomass, and geothermal energy. By and large the geothermal energy is an untapped energy resource despite its potential and clear environmental advantages (e.g. minimal CO_2 emissions) over other sources of energy, such as fossil fuels and nuclear energy. According to an estimate by the IEA (International Energy Agency), currently only 0.3% of the world's electricity is generated from geothermal sources (Priddle; 2002). However, geothermal power production is expected to steadily increase at a rate of 4.3% per year reaching a share of 0.6% of the global electricity production by the year 2030 (Priddle; 2002, Barbier; 2002, Bertani; 2005). Although the predicted growth in the geothermal power production sector should be considered as a positive sign of the worldwide move towards more renewable and environmentally friendly energy sources, the growth clearly falls short of expectations. The contribution of the geothermal energy to the world's electricity production by 2030 can be potentially one order of magnitude higher than the IEA's estimate, should the technical problems associated with the use of geothermal energy are resolved (Barbier; 2002, Bertani; 2005). Within this context, the study of geothermal power cycles is regarded as one of the key areas for major technological improvements since many of the problems associated with the geothermal power technology are underpinned by inefficient and often unsuitable heat exchange processes within power cycles. That is partly due to the fact that most power cycles currently employed in geothermal applications (with the exception of Kalina power cycle) were originally designed for large-scale power production from fossil fuels where higher temperature sources are available for heat exchange.

In recognition of these shortcomings, the Granite Power Limited (GPL) and the University of Newcastle initiated a joint R&D program in 2006 with the goal of establishing alternative and potentially more efficient ways of generating power from geothermal and other low-grade heat sources, such as industrial waste heat. Reduction of industrial waste heat will undoubtedly lessen the demand for energy that would otherwise be met, either directly or indirectly, by primary energy resources such as fossil fuels. Industrial sectors such as power generation, aluminium, iron, and steel manufacturing, petroleum refining, cement production, chemical processing, and pulp and paper manufacturing account for approximately 65% of all industrial waste heat.

Theoretical Considerations

The fraction of heat that can be converted to mechanical work and/or electrical power is limited by laws of thermodynamics (Cengel and Boles; 2002). This fraction is commonly expressed in terms of the so called "grade (or quality)" of the waste heat although from a thermodynamic point of view the correct terminology is "exergy" (the useful work potential of a system at a given state). Source temperature rather than "quantity" is the primary consideration in determining the grade of a waste heat source. For instance no power can be generated from ambient air even though it contains huge quantities of thermal energy. Generally, waste heat streams with source temperatures within the range of 600^oC-1700^oC are considered high-grade while those within the temperature ranges of 250^oC-600^oC and 50^oC-250^oC are deemed medium-grade and low-grade, respectively. Geothermal sources have typically temperatures between 150-250^oC and, hence, can be categorised as low-grade.

The principles of power generation from low to high-grade heat sources are not different and the constraints that apply to any power generation process equally apply to all. Three processes must be accomplished within the temperature range defined by the source (T_{so}) and sink (T_{si}) temperatures. These are: (i) heat addition from the source to power plant driven by the temperature differential $\Delta T_{so} = (T_{so} - T_H)$ where T_H is the absolute temperature at which energy is introduced into the plant, (ii) power generation by an expander (i.e. turbine) driven by the temperature differential $\Delta T = (T_H - T_L)$ where T_L is the absolute temperature at which heat is rejected to the sink, and (iii) heat rejection from the power plant to the sink driven by $\Delta T_{si} = (T_L - T_{si})$. Among temperature differentials ΔT is of significant importance since many key features of the plant depend on ΔT. For example, the required energy input per unit power (Q/W) and plant size per unit power (A/W) can be expressed in terms of ΔT using the following equations:

$$(Q/W) = (T_H / \Delta T) \quad (1)$$

$$(A/W) = (T_H / \Delta T^2) \quad (2)$$

For low-grade heat sources ΔT is inherently small, hence, for a given power a low-grade heat source is required to provide more energy than a high-grade source (Eq 1). The plant size corresponding to the low-grade heat source will be also much larger than that of the high-grade one (Eq 2).

The other major difficulty with low-grade heat sources is that, if not minimised, ΔT_{so} and ΔT_{si} will take significant fractions of the possible temperature drop (i.e. T_{so}-T_{si}) reducing ΔT and, thereby, the net power output and thermal efficiency of the plant. While the Carnot efficiency (η_C in Eq 3) defines the upper limit of thermal efficiency the actual efficiency is given by Eq (4):

$$\eta_C = (W_{Max}/Q) = (T_{so} - T_{si}) / T_{so} \quad (3)$$

$$\eta = (W/Q) = (T_H - T_L) / T_H = \Delta T / T_H \quad (4)$$

If ΔT_{so} and ΔT_{si} are minimised (T_I - T_R) will approach (T_{so}-T_{si}) and, hence, η and W move towards η_C and W_{Max}, respectively (see Eqs 3 and 4). Minimisations of ΔT_{so} and ΔT_{si} are particularly important for real-world finite capacity sources (and sinks) where T_{so} and T_{si} do not necessarily remain constant during the heat addition and/or rejection processes. Among conventional power cycles the Organic Rankine cycle (ORC) possess the largest source and sink temperature differentials (ΔT_{so} and ΔT_{si}) and, thus, suffers the most from problems associated with small ΔT. This is clearly illustrated in Figure 1 where the temperature entropy (*T-S*) plots of the ORC, Kalina cycle and Supercritical Rankine cycle (SRC) are shown by the thick solid lines while dashed lines represent the phase diagram of the working fluid. As can be seen, there are significant temperature differences between the source and the working fluid in an ORC during the heat addition process because the phase change of the working fluid takes place at constant temperature under the saturation dome.

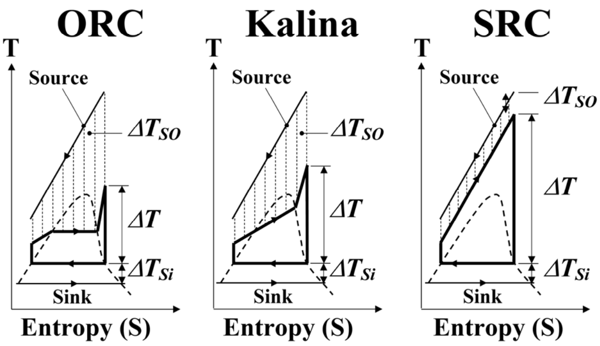

Figure 1: T-S plots of ORC, Kalina, and SRC.

Kalina cycle reduces the temperature mismatch between the source and the working fluid using a zeotropic mixture of ammonia and water with variable temperature phase change (Figure 1). While this approach increases ΔT, η and W, it requires a complex array of absorption and distillation hardware. The added complexity together with the high sensitivity of Kalina cycle to pressure and composition of the ammonia-water mixture, limits its application over a wide range of source temperatures and significantly adds to the capital and operating costs (DiPippo; 2005).

SRC also avoids the constant temperature phase change except that the heat addition and/or rejection processes are carried out under supercritical conditions using a single-component working fluid rather than a zeotropic mixture like that employed in the Kalina cycle (Figure 1). This approach not only results in a simple plant layout but a small ΔT_{so} and, hence, higher ΔT, η and W.

However, the constant pressure lines in the supercritical region are generally too close and as such the conventional SRC has a relatively low net power per unit of enthalpy change. Thus the turbine outlet stream in a conventional SRC may contain large amount of thermal energy which is typically wasted during the heat rejection process leading to thermal efficiency losses. Moreover, relatively high operating pressures may be required to achieve a desired power output under supercritical conditions. As shown in the next section, GRANEX effectively resolves the above shortcomings of the conventional SRC in a relatively simple manner.

GRANEX Technology

Figure 2 shows the schematic representation of a GRANEX based power plant. The system is essentially a conventional SRC fitted with a heat regenerator. The inclusion of the regenerator resolves the issue of low net power per unit of enthalpy change by utilising the unused thermal energy of the turbine outlet stream in the heat-up of the cold working fluid exiting the pump. This version of SRC which is also referred to as "Regenerative Supercritical (RGSC) Rankine cycle" has higher thermal efficiencies than the conventional SRC. The issue of potentially high operating pressures is also overcome by selecting suitable working fluids with sufficiently low critical pressures. In addition, the patented design of the regenerator in GRANEX avoids the so-called maximum enthalpy points for which the driving force for heat transfer is zero. This ensures a much smoother heat exchange during supercritical operation.

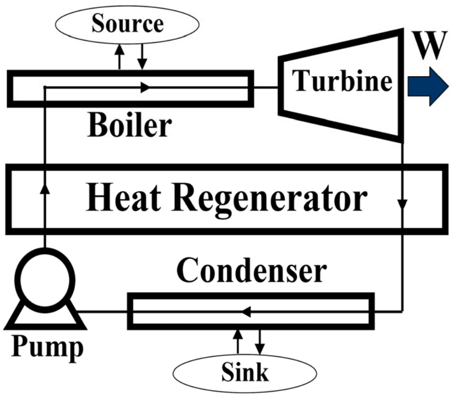

Figure 2: Schematic of GRANEX system.

Power Cycle Analysis

The performance of the GRANEX cycle was theoretically assessed by a numerical model developed using the process simulation software HYSYS. For a large selection of working fluids first- and second-law thermodynamic analyses of the cycle were carried out to determine the values of W (net power), η (thermal efficiency), and η_{II} (exergy efficiency) under a range of operating conditions in terms of heat source/sink temperature (that is 150°C < T_{so} < 250°C and 15°C < T_{si} < 35°C). This was to establish the so-called envelop of operation for each fluid and rank them on the basis of thermal and exergetic efficiencies. The interplay between the sink temperature and condensation properties of the working fluid will be carefully examined to assess the impact of ambient conditions on the overall cycle performance. A series of calculations will be also performed to investigate the impact of molecular weight and density on key turbine (i.e. expander) characteristics such as number of stages, exit area, sonic velocity, and leave loss.

As part of these studies, the performance of GRANEX was compared with several existing geothermal power plants (Table 1). In each case the calculations associated with GRANEX were carried out using a working fluid referred to as "Fluid-6" under source and sink temperatures identical to that of the actual plant. The results have been summarised in Figures 3 to 5.

Table 1: List of case studies

Case	Case Description	Ref
1	Kalina	DiPippo; 2005
2	Otake	DiPippo; 2005
3	Nigorikawa	DiPippo; 2005
4	Heber (SIGC)	DiPippo; 2005
5	Brady (Double Flash)	Kanoglu & Cengel, 1999
6	Single Flash-1 (Nevada, US)	Kanoglu & Cengel, 1999
7	Single Flash-2 (Nevada, US)	Kanoglu & Cengel, 1999
8	Double Flash (Nevada, US)	Kanoglu & Cengel, 1999
9	Binary (Nevada, US)	Kanoglu & Cengel, 1999
10	Combined (Nevada, US)	Kanoglu & Cengel, 1999
11	Pseudo-SC (Nevada, US)	Gu & Sato; 2002

Figures 3 and 4 illustrate the plots of thermal conversion and exergetic efficiencies as a function of the temperature difference between the geothermal fluids at the production and reject wells, ΔT_{geo}. Plots have been drawn using the data shown in Table 1 for both conventional and RGSC (GRANEX) Rankine cycles.

As can be seen, the performance of the RGSC cycle is far superior to that of conventional cycles. For the range of investigated source temperatures, the thermal efficiency varies between 10-18% with an average of 16.5% for RGSC cycle whereas for conventional cycles, including Kalina, the thermal efficiency does not change and plateaus around a nominal value between 11 to 12%.

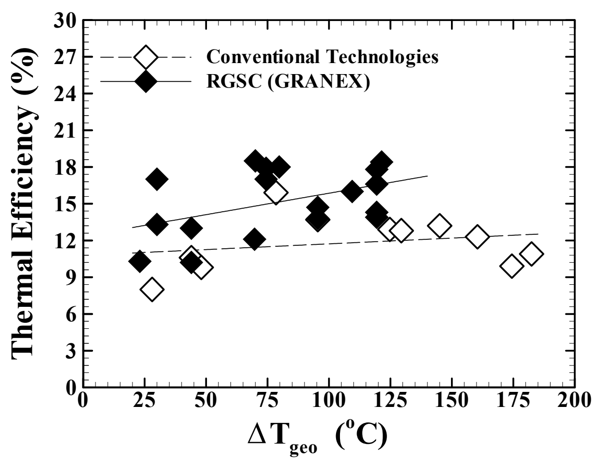

Figure 3: Comparisons of thermal efficiencies of the RGSC (GRANEX) and conventional cycles.

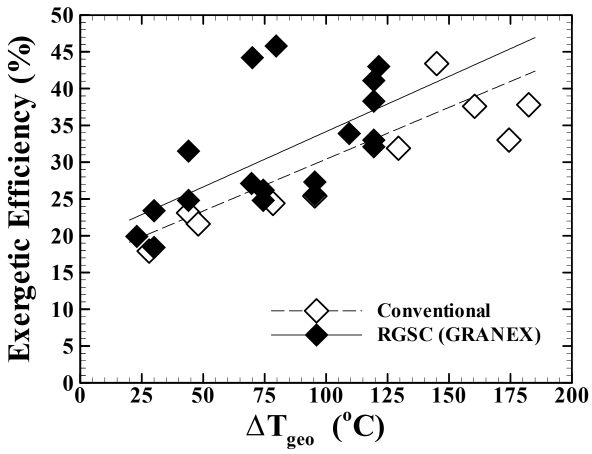

Figure 4: Comparisons of exergetic efficiencies of the RGSC (GRANEX) and conventional cycles.

The higher thermal efficiency of the RGSC cycle implies that more power can be generated from this cycle per unit of input energy than from a conventional cycle. This is quite evident from Figure 5 where the specific power (W_{spc}) has been plotted against ΔT_{geo}. The specific power is defined as:

$$W_{spc} = W_{net} / \dot{m}_{geo} \ . \tag{5}$$

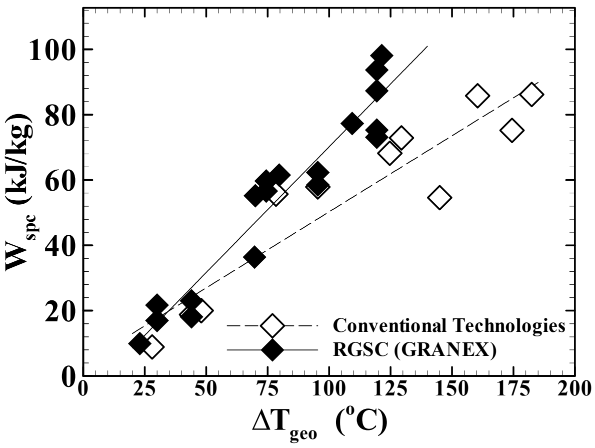

Figure 5: Plots of specific power versus ΔT_{geo}.

Experimental

Fifteen candidate working fluids were selected from power cycle analysis. The shortlist of selected fluids was shortened by eliminating fluids which in terms of W, η and η_{II} underperforming a reference ORC with iso-pentane as working fluid. The remaining fluids were experimentally studied over a range of source and sink temperatures (150°C<T_{so}<250°C and 15°C<T_{si}<35°C) in a 1 kW proof-of-concept (POC) plant.

The POC plant (Figure 6) is a unique facility in Australia which has been established using a $2,400,000 grant jointly funded by GPL and AusIndustry. The facility can be operated at pressures of up to 30 MPa and temperatures up to 300°C under GRANEX or ORC configuration. The prototype facility comprises a water chiller (i.e. heat sink), a condenser unit, a cycle pump with a maximum operating pressure of 28 MPa, a regenerator module consisting of 4 tube and tube heat exchangers fitted with our patented heat exchange technology, an electrical heater (i.e. heat source) with a 30 kW rated capacity, a boiler, and a turbine simulation unit fitted with a collection of valves and heat exchangers to reproduce the pressure and temperature drops of typical expanders. The facility is fully automatic (uses delta VB) and has been equipped with an array of sensors (T, P, and flow) and safety devices such as pressure relief valves, gas sensors, alarms, an air extraction system.

Measurements of pressure, temperature, and flow rate were taken in 20 different points around the plant at a frequency of 10 per minute using a sophisticated data acquisition system. For any given combination of operating conditions (working fluid, T, P, and flow rate), experiments were carried out over a 1.5 hours period and were repeated at least twice to ensure the statistical integrity of the results. The aim was to develop an experimental version of the operational envelop and compare it with that developed from theoretical predictions. About 650 individual experiments were completed over an eight months period to achieve the broad objectives of the project.

Figure 6: The picture of 1 kW POC plant.

Figures 7 and 8 show bar charts of experimental results obtained from the 1 kW plant for the net power and the thermal efficiency improvement. It can be seen from Figure 7 that for a given set of conditions GRANEX in conjunction with Fluids 1 to 6 can deliver higher net powers that those obtained from Kalina and ORC. Fluid 1, in particular reaches the prototype plant's rated output of 1 kW.

Figure 8 also clearly indicates that with respect to a reference ORC, improvements of up to 40% in thermal efficiency can be achieved when Fluids 1 to 6 are employed.

The efficiency improvement of GRANEX over Kalina cycle is approximately 20% owing to the fact that Kalina is a much more efficient process than ORC, although it has a complex hardware.

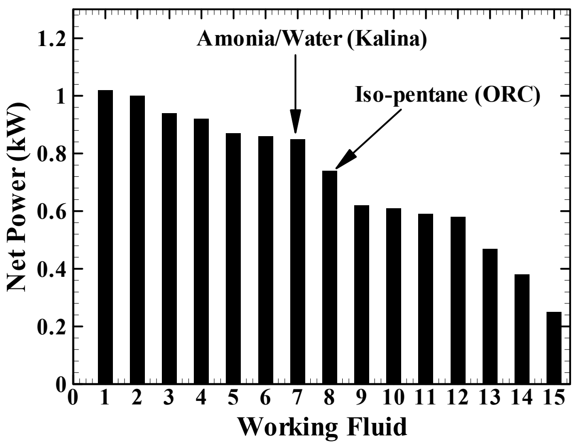

Figure 7: Measurements of net power from the 1 kW unit.

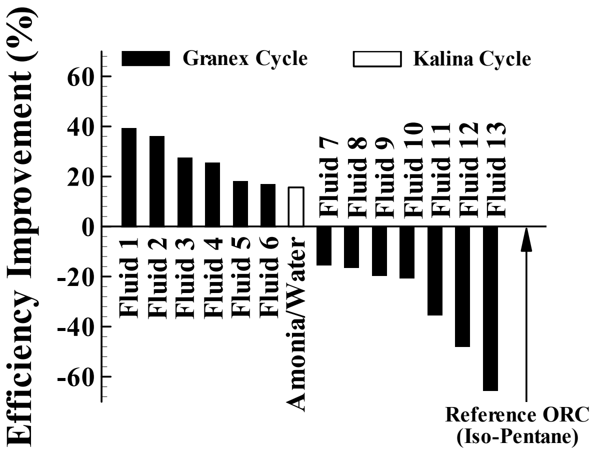

Figure 8: Efficiency improvement (%) with respect to a reference ORC.

Work in Progress

A set of experiments is being carried out using the 1 kW POC unit at temperature ranges between 80°C and 150°C. This lower temperature range is of more relevance to waste heat recovery applications. The preliminary findings indicate that GRANEX can maintain its advantage over conventional systems even at lower source temperatures if a suitable working fluid is employed.

Also, based on theoretical and experimental research conducted since 2006 on GRANEX for geothermal applications, the design of a 100 kW prototype has just been completed. The prototype which is currently under construction is due for commissioning by the end of Nov 2009. The prototype will be employed in a comprehensive series of pilot-scale experiments in early 2010 to develop the scale-up rules.

Conclusions

The present document summarises the result of a combined theoretical and experimental study on GRANEX technology. The study is part of a larger project aimed at developing a technology platform with thermal efficiency and economics superior to conventional system for power generation from low-grade heat sources. GRANEX combines the established concepts of supercritical power generation and heat regeneration into a unified platform. As shown in this document GRANEX, leads to significantly higher conversion efficiencies than those currently provided by conventional power cycles.

Owing to its simplicity, the RGSC cycle also offers a greater degree of flexibility and robustness, which in turn, will translate into much better economic characteristics when compared with conventional power cycles.

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