THE CONCEPTUAL DEVELOPMENT OF AN EXPERT PROCESS DESIGN TOOL FOR ABOVE GROUND POWER GENERATION TECHNOLOGIES

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ABSTRACT

Low enthalpy resources such as geothermal or waste heat can be used to generate electricity using the Organic Rankine Cycle process. The magnitude of power generated depends on resource characteristics and usually requires a process design in place which takes process thermodynamics into consideration. Preliminary results can be achieved with the application of engineering knowledge in areas such thermodynamics, materials, turbines and controls but this is not conveniently available to the industrial end user.

Preliminary resource analysis for power output and process design can be made possible in a framework of organised process data and design algorithms. This is the basis of a design tool which possesses expertise in process selection and decision-making capability for the user. Such a tool can provide valuable guidance in technical considerations as well as investment strategies when designing a new process. The presentation reflects on the mechanisms for development of a conceptual design tool as well as options for its future.

1. AGGAT RESEARCH PROGRAMME

1.1 Low Enthalpy Power Generation

Above Ground Geothermal and Allied Technologies (AGGAT) is an industry led research and development initiative being championed by the Heavy Engineering Research Association (HERA) of NZ. The primary objective of this programme is to enhance the manufacturing capability of Organic Rankine Cycle (ORC) products in NZ via Heavy Engineering companies thereby contributing to the international low enthalpy product offerings and increase NZ presence internationally. This is a four-year NZ government funded programme which will be completed in 2016.

This programme is being run in collaboration with a number of partners including NZ Universities, local Heavy Engineering companies and heat resource providers as End-Users of ORC technology. Geothermal power now represents 16% of all power supply in New Zealand. ORC is a power generation method utilizing medium and low thermal grade heat source which makes it particular viable to recovery geothermal energy. (Baral, 2015; Wei 2008)

1.2 Industry Need

HERA represents and advocates for the NZ Heavy Engineering industry which is represented by its strong membership of 600+ companies. In 2010, a survey was conducted by HERA across its membership to identify the strategic direction going forward for industry growth and sustainability. A clear mandate was presented by HERA members to intensify efforts in clean energy development and to identify clean technology options for Heavy Engineering.

From international market surveys and gap analysis studies, low enthalpy geothermal and waste heat technology was found to be an emerging field presenting growth opportunities as well as an area which NZ holds considerable capability in owing to its strong history of geothermal developments. HERA holds and regularly updates a capability register (Inskip, 2014) of its members involved in the geothermal industry which demonstrates such capabilities.

Organic Rankine Cycle technology is a well-known process technology applied to low enthalpy power generation. Due to limited suppliers of this technology in the market and its premium-priced availability, it is an international market challenge that NZ companies are ideally placed to contribute to.

The AGGAT programme was conceived with the intention of providing a platform of research and development to aid in this contribution. This would be achieved by developing tools, facilities and capabilities to support engineering companies in this process. A number of objectives have been set up to span the breadth of the AGGAT programme and one of them is the development of a process design tool. The need for this was identified based on industry preference for user friendly and readily available tools to fast-track engineering exercises such as resource assessments, fluid selection etc.

1.3 Process Design Tool

The basis for this tool is the process configuration of an Organic Rankine Cycle. However to accommodate alternative scenarios such as process philosophies, configurations, heat source, fluid, material, equipment size, scale of operation, the tool needs a well-programmed infrastructure for technical information management and analysis. If the tool can provide guidance during selection from an enriched database of technical information and give advice on technical decision-making, it would be valued as a tool expertise. The design tool will provide an expert opinion and hence is the basis for being referred to as an 'Expert Design Tool (EDT)'.

The tool's primary role is to facilitate the engineer to carry out preliminary design and performance evaluation of ORC exploiting a wide range of geothermal and waste heat sources. An online engineering EDT will provide the engineer/designer with timely access to relevant data and information during the early, conceptual stages of design (Varma, 1996).

During the preliminary design task several alternative designs should be considered with respect to their feasibility and one alternative is selected for further consideration, based on the satisfaction of a few key constraints. (Maher, 1984)

EDT is an interactive tool that incorporates the knowledge and judgment of experts in appropriate domains. The development of EDT involves the cooperative effort between one or more experts with domain-dependent knowledge. This project will involve liaising with other researchers in the AGGAT programme to collect information for algorithms involving equipment selection and performance such as heat exchangers, turbines, materials and fluids.

In the framework of a systematic investigation approach, various possible modifications to the simple ORC layout need to be analysed and compared, in order to improve the ORC performance. Thermodynamic cycle arrangements such as recuperation, superheated cycle, supercritical conditions, regenerative cycle and their combinations should be taken into consideration. In order to quantify, discuss and compare performances of various ORC configurations by means of simple, aggregated and easy to obtain indexes, the seek for meaningful performance indicators is essential to offer comprehensive information on energetic and size/economic of ORC systems.

The ORC performance is calculated in terms of six different thermodynamic indices namely: cycle efficiency, specific work, recovery efficiency, turbine volumetric expansion ratio, ORC fluid-to-hot source mass flow ratio and heat exchangers size parameter (Branchini Lisa et al. 2013). An in-house numerical tool should be developed to compute the values of the identified ORC performance indices, which includes thermodynamic calculations for each layout component, based on a lumped model approach. In order to accurately model an ORC system, the main aspects which have to be addressed thoroughly include: estimating the working fluid thermodynamic and transport properties; determining the heat transfer rate in the evaporator and the condenser; modelling the expansion machine.

Other design considerations such as two-phase flow conditions, pressure drops, part-load conditions and geometric properties of the components also should be taken into account in order to maximize reliability of the simulation model. The developed general routine can be utilized not only to investigate the effect of various design input data (mainly the evaporation pressure and the maximum cycle temperature) on key performance indexes but also to research other conversion technologies such as Stirling Cycle, Kalina Cycle etc. and provide recommendations for optimum design of ORC systems. The comparison and investigation is based on a series of reasonable assumptions, boundaries and constraints which are derived from literature data and experimental results obtained from other areas of the research programme.

2 DESIGN TOOL STATUS QUO

The context of building this design tool is distinct from the context of commercial software packages available for process design and analysis as it caters specifically to the needs of the AGGAT programme on an online platform. The EDT will attempt to integrate real data derived from experimental rigs and understanding based on this data to inform the design tool decision-making process.

Previous attempts to provide similar tools online have been made with reasonable success (Turboden, 2015; GDA, 2014) and provide a good starting point. Turboden (2015) has an online power calculator on its website which allows selection among pre-determined heat sources and then requests for process operating conditions and ranges. It is a simple tool for calculating preliminary estimates.

Geothermal Development Associates (GDA, 2014)) have developed an online process modelling tool which also requests for input data. The model of interest is the binary geothermal power plant and is limited to geothermal brine as such. However it limits the range of values for heat source temperature and in particular flow rate to high numbers (>2000l/m) which suggests the preference of working on large scale plants only. A reasonable variety of working fluid options have been offered to allow some degree of comparative modelling. An option has been provided to request for a specific model is required.

Thermocycle is a similar tool in this category developed by University of Liege, Belgium (Quolin, 2014). It contains a library and a downloadable post-processing tool developed in Python, Thermocycle Viewer.

The above mentioned examples offer separate aspects of EDT in their application and these all need to be amalgamated into one tool offering these capabilities and more. This paper outlines the efforts and results from EDT developed so far.

3. EDT INFRASTRUCTURE AND ALGORITHMS

3.1 Infrastructure development

The objective here is to develop a web application using an appropriate programming language that can run the numerical calculation of ORC and provide technical advice on equipment selection and design. A conceptual structure of this online EDT is illustrated in Fig.1.EDT functionality is sub-divided into the following three stages:

- Input data and present result: In this first stage, a selected browser is used to display the web user interface. This part is the user-end of the EDT process which asks for input and displays results. A conceptual Graphical User Interface (GUI) is displayed in Fig. 6.
- Build web application: In this intermediate stage, the web based framework for data storage and management is prepared for online use. This is being created using the Web2Py environment.
- Run Simulation: This part contains the programmes that execute the process models. The programmes rely on calling the necessary information modules such as materials database etc. based on user input data. It includes the mathematical models and all the technical information such as classification of fluids and materials and equipment including thermodynamic properties. All this is being done using the open-source Python programming language.

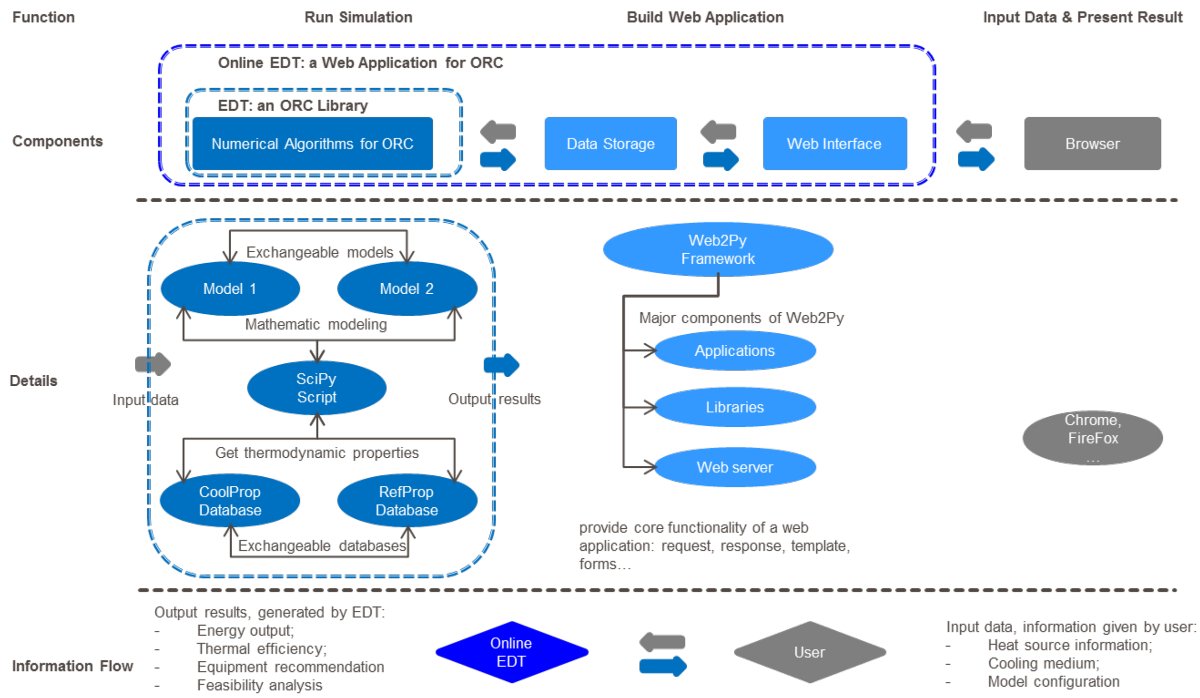

Figure 1 - Conceptual structure of online EDT

The tool used for online deployment is web2py which is a Python based web framework. Web2py is composed of the following components to realize the key functions of an online EDT (Pierro, 2015):

- Web server;
- Libraries: provide core functionality (request, response, forms, templates);
- Applications: to create, design, and manage applications for logic functions

3.2 Algorithm Development

3.2.1 Numerical Solver and Database

The software used to establish a numerical simulator for ORC is Python scripted and existing thermodynamic properties database.

SciPy (SciPy, 2015) is an open-source ecosystem of software for numerical and scientific computing in Python environment. It is an alternative to MATLAB to carry out numerical analysis. To obtain relevant fluid properties CoolProp (Bell, 2015) is used, which is also an open-source thermodynamic properties database able to support Python environment.

The mathematical models and database used in this ORC simulator are exchangeable. This means that different user requirements can be satisfied by the combination of specific model and database arrangements. For example, in this project, a full open-source stack is achieved by the use of CoolProp and Scipy. Alternatively a modified model coupled with an alternative database could be used to improve the performance.

3.2.2 Algorithms

The algorithms of this EDT are shown in Fig.2, which is an elaboration of the Numerical Algorithms for ORC as illustrated in Fig.1. The core algorithms in this EDT are modelling, optimization decision matrix for unit components in the process and financial model.

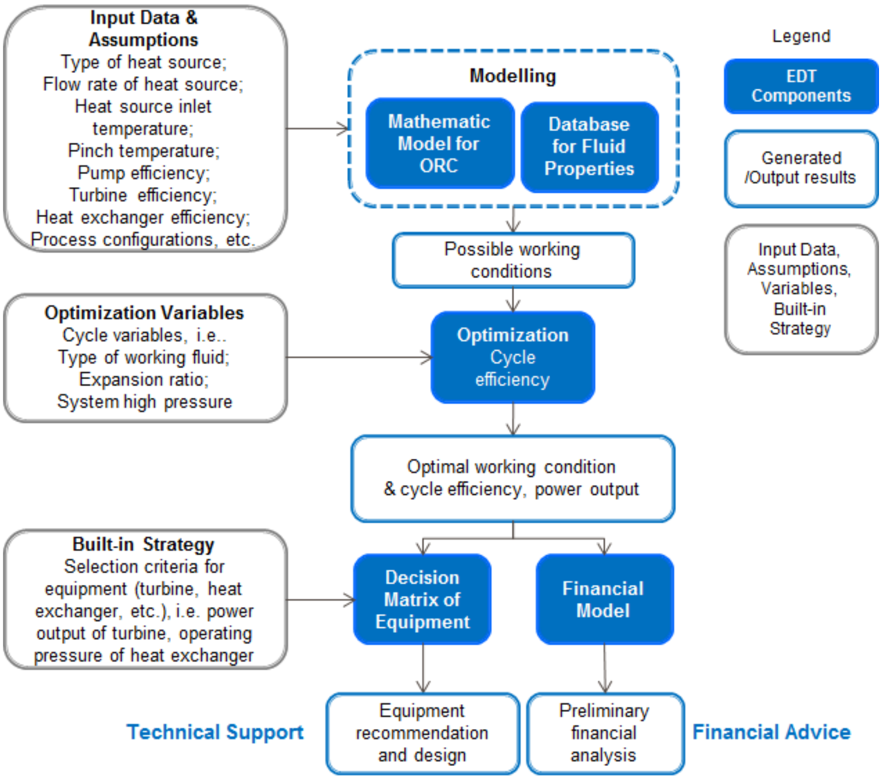

Figure 2 – Algorithms of the EDT shown in sequence of operation

A set of working condition data was defined and optimized to maximise cycle efficiency gains. The optimization variables included the type of working fluid, expansion ratio, and system high pressure among other variables. A recuperative ORC model was adopted for this analysis. The process included an evaporator, a turbine, a recuperator, a condenser and a pump. Assumptions of operating parameters, data input and variables for calculation of fluid properties are shown in Table 1 and Table 2. These properties have been defined according to its position in the cycle represented as a 'stream' which is indicated with index numbers according to Fig. 3.

Table 1 – Fluid properties defined for different streams (shown in Fig.3) in the cycle

Stream number	Description	P	T	H	S
1	Pump inlet	P1, Variable	@P1, Saturated liquid	*Db	Db
2	Pump outlet	P2, Variable	Db	**Cal	=S1
3	Preheated fluid	=P2	Db	Cal	Db
4	Turbine input	=P2	@P2, Saturated vapour	Db	Db
5	Turbine output	=P1	Db	Cal	=S4
6	Condenser inlet	=P1	Db	Cal	Db
7	Heat source inlet	Input, 1atm	Input	Db	Db
8	Heat source outlet	Input, 1atm	=(T3+10) K	Db	Db
9	Cooling water inlet	Input, 1atm	Input, 303.15 K	Db	Db
10	Cooling water outlet	Input, 1atm	Input, (T9+10) K	Db	Db

Where P is Pressure, T is Temperature, *Db is Database sourced property as obtained from CoolProp, **Cal is calculated property using the isentropic efficiency of turbine/ pump and the energy balance in heat exchanger.

Neglecting the pressure losses and internal irreversibility in the process, the component equations are as follows.

$$W_{Pump} = m_{wf}(h_2 - h_1) \qquad (1)$$

$$W_{Turbine} = m_{wf}(h_4 - h_5) \qquad (2)$$

Where h are the specific enthalpies of different streams of the process. And m_{wf} is the mass flow rate of the working fluid. The units of W, h and m_{wf} are kW, kJ/kg, and kg/s respectively.

$$W_{net} = W_{Turbine} - W_{Pump} \quad (3)$$

$$Q_{in} = m_{wf}(h_4 - h_3) \quad (4)$$

The isentropic efficiencies are calculated by (5) and (6).

$$\eta_{Pump} = \frac{\Delta h_{isentropic}}{\Delta h_{real}} \quad (5)$$

$$\eta_{Turbine} = \frac{\Delta h_{real}}{\Delta h_{isentropic}} \quad (6)$$

The cycle efficiency is given by the ratio of the net mechanical work output and the heat input.

$$\eta_{cycle} = \frac{W_{net}}{Q_{in}} \quad (7)$$

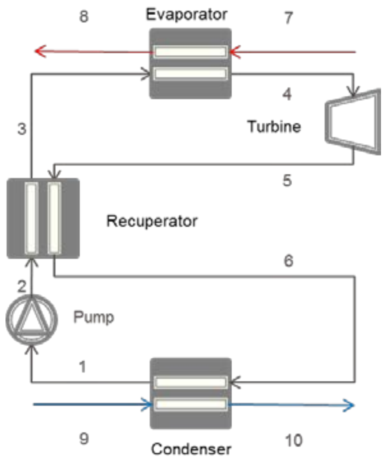

Figure 3 – Recuperative model process configuration

Table 2 – Assumptions, inputs and variables for the recuperative process model

Parameters	
Pinch temperatures	10K
Pump efficiency	85%
Turbine efficiency	85%
Heat exchanger efficiency	75%
Heat source inlet temperature	Input
Heat source mass flow rate	Input
Heat source type	Input
System low pressure	Variable
System high pressure	Variable
Type of working fluid	Variable

The state of all the parameters including fluid enthalpies h can be referred back to the streams shown in Fig. 3. Once all the parameters and states are determined, the process simulation can be performed. A model is built based on the information above. It could be modified by adding different component to alter the process configuration and also could be adjusted by adding more specific working condition information such as pressure loss and superheat temperature to get more practical data.

Following optimization exercises within the optimization algorithms, the optimized data is interfaced with equipment performance algorithms. These are to be prepared for all unit components in the ORC process and contain the logical decision making process for selecting the appropriate equipment for required results. These are being developed for heat exchangers, turbines, pumps, control logics and overall process configurations. A typical decision matrix algorithm for turbines is illustrated in Fig. 4 (Wong, 2015). As mentioned earlier, the different algorithms are provided through liaising with other AGGAT researchers and this one is provided by Heavy Engineering Education Research Foundation (HEERF) scholar Choon Wong as a research outcome. The turbine selection algorithm demonstrates selection process based on scale of operation, required pressure ratio, number of stages and efficiency as well as cost requirements. It also leads to the option of designing a customised turbine should the need arise.

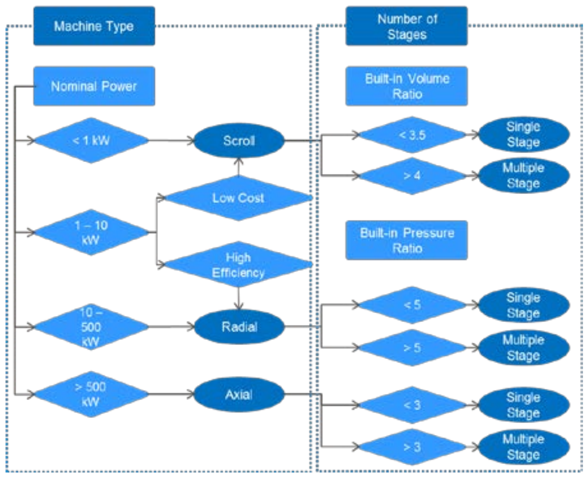

Figure 4 - Decision matrix algorithm for turbine selection (Courtesy Choon Wong – HEERF PhD Scholar)

In addition to the above technical analysis, a preliminary economic assessment is conducted with a financial model. The data of net power output generated by the EDT is used to predict the initial investment of ORC plant. And the profitability of the investment is then measured with the economic indicators including the net present value (NPV), and internal rate of return (IRR). The assumptions made to perform this financial analysis are listed in Table 3 (Jung, 2014). The installation costs range from $2,000 to $4,000 per kilowatt in 2009 (Roos, 2013). ORC manufactures provide commercially ready products which end-user can select from with specific capital cost of $2,000 to $3,000 per kilowatt (Arvay, 2011). Typically, the investment covers the cost of the following components associated with above ground engineering activities: recovery heat exchanger, ORC module, cooling tower, mechanical auxiliaries, civil works and project costs (David, 2011).

Table 3 – Assumptions used in financial model

Assumptions	Value
Specific cost per net power output	$3000/kW
Plant lifetime	20 years
Electricity price	$0.083/kW h
O&M cost	$0.013/kW h
Annual electricity price escalation	3.0%
Discount rate	10.0%

4. PRELIMINARY RESULTS

4.1 EDT Validation

The EDT was validated against an existing 250 kW ORC unit utilizing the heat from an underground hot spring in Chena, Alaska (Aneke, 2011). This power plant was designed based on the PureCycle 200® product which is designed to recover heat of waste gas. Several modifications were made to enable PureCycle to work with geothermal fluid. The most critical aspect was a single-stage centrifugal compressor which ran in reverse as a radial inflow turbine. The designed working fluid for the PureCycle was R245fa and it was changed to R134a because of the low temperature geothermal in Chena hot springs.

The detailed working parameters of the ORC are shown in Table 4 (Chena Power, L.L.C., 2007). The hot spring water temperature is 73.3 °C, at a flow rate of 33.3 kg/s and is used to heat the binary fluid in the evaporator section of Fig. 3. The binary fluid used for this process is a non-flammable refrigerant R134a boiling under high pressure at a temperature of 57 °C.

Table 5 shows the comparison of simulation results from the EDT and the existing unit data. It is observed that the difference on comparison between the two is at a maximum of around 5% with most of the values well below this difference.

Table 4 – Specifications of the Chena Alaska ORC unit

Parameter	Unit	Value
Refrigerant	-	R134a
Heat source type	-	Hot spring water
Heat source temperature inlet	°C	73.30
Hot water mass flow rate	kg/s	33.30
Gross power	KW	250.00
Pump power	KW	40.00
Turbine inlet pressure	Bar	16.00
Turbine outlet pressure	Bar	4.39
Turbine mechanical efficiency	%	80.00
Cooling water inlet temperature	°C	4.44
Cooling water outlet temperature	°C	10.00

In addition to the predicted operating parameters, the EDT can also provide the correct recommendation of expander by virtue of the built-in turbine selection matrix illustrated in Fig. 4. The total capital investment, NPV and IRR calculated by the financial model was $636.15 kUSD, 691.68 kUSD and 22.10% respectively. The technical support and financial advice are the most significant aspects to enhance the reliability of the EDT.

The difference of simulation results from EDT and actual unit data could arise from the inaccuracy of fluid thermodynamic properties database. The assumptions made in the production of the EDT were also not the same as in the real modules.

Therefore, the comparison of simulation results justifiably demonstrates the EDT capability to deliver reliable results. Future modifications are going to be implemented into EDT which will include switching to a more accurate and comprehensive database.

Table 5 – Comparison of simulation data from EDT and existing unit data

Parameter	Unit	Chena plant data	Simulation result	Difference	Difference (%)
Heat source information					
Composition	-	Hot spring water	Water	-	-
ORC power plant description					
Gross power	kW	250.00	248.81	-1.19	-0.48
Net power	kW	210.00	212.05	2.05	0.98
ORC efficiency	%	8.20	8.03	-0.17	-2.08
Working Fluid					
Working fluid type	-	R134a	R134a	-	-
Mass flow rate	kg/s	12.20	12.04	-0.16	-1.33
Evaporator					
Evaporator heat transfer	kW	2580.00	2640.89	60.89	2.36
Condenser					
Condenser heat transfer	kW	2360.00	2280.25	-79.75	-3.38
Cooling water flow	kg/s	101.00	97.64	-3.36	-3.33
Expander design					
Expander type	-	Radial, Single stage	Radial, Single stage	-	-
Financial Analysis					

Parameter	Unit	Chena plant data	Simulation result	Difference	Difference (%)
Initial investment	kUSD	-	636.15	-	-
NPV	kUSD	-	691.68	-	-
IRR	%	-	22.10	-	-

4.2 Results and Discussion

The EDT is designed not only to facilitate the engineer to carry out preliminary evaluation of ORC but also to assist them to research into the performance of a wide range of working fluids under given operating conditions.

Different refrigerants can be tested by the EDT to assess their feasibility and performance. Theoretically, all the working fluids supported by the database can be calculated by the model. In this manner, a working fluid selection for Chena ORC plant is possible under the exact working conditions of the existing unit given in Table 4.

The tested refrigerants were: iso-pentane, n-butane, iso-hexane, iso-butene, iso-butane, ammonia, n-pentane, n-hexane, R11, R113, R114, R116, R12, R123, R1233zd(E), R1234yf, R1234ze(E), R1234ze(Z), R124, R125, R13, R134a, R14, R141b, R142b, R143a, R152A, R161, R21, R218, R22, R227EA, R23, R236EA, R236FA, R245fa, R32, R365MFC, R404A, R407C, R41, R410A, R507A, RC318.

The temperature of working fluid before and after evaporator (T3 and T4, as shown in Fig. 3), before and after condenser (T6 and T1, as shown in Fig. 3), and the vapour quality after the turbine were examined to select suitable substitutions of R134a used in Chena plant. The calculated temperature of working fluid should allow the heat transfer in evaporator and condenser. The calculated vapour quality after the turbine should not be less than 95% to avoid erosion of the turbine blade.

The result shows that R152A and R1234ze(E) are suitable for the operating conditions of Chena plant, while other refrigerants failed to meet the specific requirements to utilize the low temperature geothermal fluid to generate power.

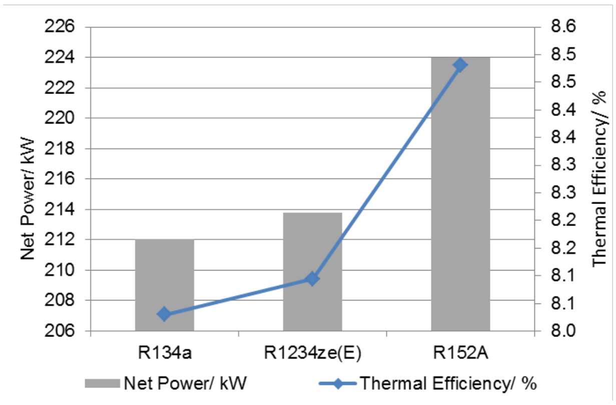

Figure 5 - ORC net power and thermal efficiency of suitable working fluids studied

Fig. 5 shows the net power output and thermal efficiency of R134a, R1234ze(E) and R152A. Refrigerant R152A generated the highest power followed by R1234ze(E) and R134a. From this calculation, both R152A and R1234ze(E) might be an appropriate substitution for R134a.

Table 6 – Refrigerant properties *(http://webbook.nist.gov)*

	Safety class	Atmospheric life	*ODP	**GWP
R134a	*A1*	*14*	*0*	*1430*
R152A	A2	1.4	0	124
R1234ze(E)	A2	NA	NA	NA

*ODP: Ozone depletion potential relative to R11
**GWP: Global Warming Potential relative to CO_2

Table 6 shows some selected properties of R134a, R1234ze(E) and R152A. The safety class of R134a is A1, which is better than the other two fluids.

The study of working fluid selection proves that R134a is a suitable option for the low temperature geothermal ORC application and R152A and R1234ze(E) show an attractive performance with safety concerns.

4.3 Preliminary EDT Graphical User Interface (GUI)

A conceptual Graphical User Interface (GUI) is displayed in Fig. 6. An online EDT would interact with the end user to read the input data and call the appropriate model to provide preliminary prediction of an ORC plant proposed by the user.

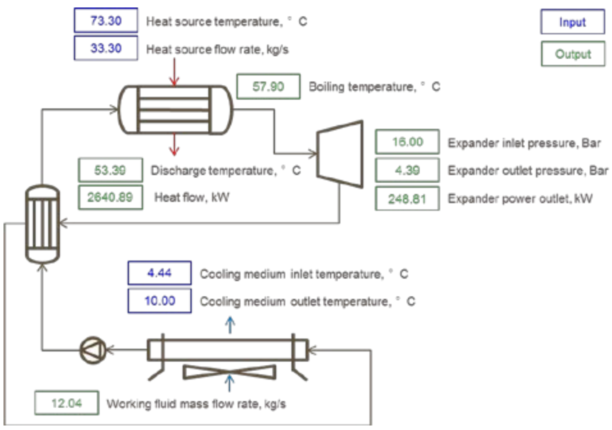

Figure 6 – Conceptual Design of the GUI of an Online EDT

The detailed operating parameters will be listed in a process diagram as shown in Fig. 6; the equipment design advice and financial analysis will be offered to the user through a webpage in the form of text.

The EDT platform has demonstrated with success the modelling of ORC and application for assessment exercises. This is a promising step towards ultimately achieving a reliable and valuable design and process modelling tool that will be of benefit to the engineering community within New Zealand.

5. CONCLUSIONS

The design tool will provide an expert opinion and hence is the basis for being referred to as an ‘Expert Design Tool (EDT)’. The tool’s primary role is to facilitate the engineer to carry out preliminary design and performance evaluation of ORC exploiting a wide range of geothermal and waste heat sources. The mathematical models and database used in this ORC simulator are exchangeable. This means that different user requirements can be satisfied by the combination of specific model and database arrangements.

The EDT was validated against the actual data obtained from Chena geothermal ORC power plant. The comparison demonstrated the EDT capability to deliver reliable results. Future modifications are going to be implemented into EDT which will include switching to a more accurate and comprehensive database.

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