IMPLEMENTAION OF A SMALL SCALE ORGANIC RANKINCE CYCLE TEST BED SYSTEM USING STEAM AS HEAT SOURCE

Muhammad Usman[‡†], Muhammad Imran[‡†], Dong Hyun Lee[†] and Byung-Sik Park[*‡†]

‡Korea University of Science and Technology, 217 Gajeong-ro, Yuseong-gu, Daejeon 305-350, South Korea
usman@ust.ac.kr / usman7@live.com
Web page: http://www.ust.ac.kr/

[†]Korea Institute of Energy Research,
152 Gajeong-ro, Yuseong-gu, 305-343, Daejeon, South Korea
[*]Corresponding Authur e-mail: bspark@kier.re.kr
Web page: http://www.kier.re.kr

ABSTRACT

Organic Rankine cycle based power systems are well known for waste heat recovery application due to their adaptability to follow heat source variations. Industrial exhaust steam has an appreciable potential for the installation of waste heat recovery units. Korea Institute of Energy Research has developed waste heat recovery units which can generate power in the range of hundreds of kilowatts. In order to, rigorously test new cycle configurations and control strategies with least cost for heat source, a small-scale organic Rankine cycle test bed was implemented which a has steam condensing heat exchanger for using steam as a heat source in similar configurations as of larger units. The test bed was equipped with data logging and standalone control system and was configured for the electrical output around 1kW using R245fa as a working fluid. The system is composed of plate type heat exchangers, scroll type expansion machine, screw type working fluid pump and control valves with actuators. This work will present the difficulties, solutions and operational results in terms of design, equipment selection, fabrication and operational experience of system for small-scale power generation with efficiency over 5.2 % for a temperature difference of 120°C. Complexities involved in superheat control of working fluid for the system powered by steam will also be discussed.

INTRODUCTION

Organic Rankine cycle system (ORC) is the accepted viable technology for low-temperature heat conversion to electricity (Lecompte et al. 2015). Statistical analysis suggests that low-grade waste heat accounts for more than 50% of the total heat generated in the industry (Hung et al. 1997). Utilization of this waste heat energy to harness electrical power output will be a necessity of future to stay within energy budget allocations, to compete with the growing economies of the world. Low-grade waste heat power generation has been experimentally tested in many studies, where (Zhang et al. 2014), (Wenzhi et al. 2013), (Peris et al. 2015) & (Minea 2014) are the few works to mention in low-grade waste heat recovery works. Most of the published works presented their heat source as hot water or exhaust gas.

Korea Institute of Energy Research has implemented 100kW class ORC systems for low-grade industrial waste heat. The implementation of a very small-scale ORC system was to be tested for performance, controllability, and net power output using low-temperature exhaust steam (<135°C), as a heat source. As this system will be operated for 1kW power output with condensing steam as a heat source, already published literature rarely contain information for such configuration of a small power system with such heat source. The implemented test bed system will be used to test thermodynamic parameters and control strategies by using negligible operational costs as compared to the already installed 100kW scale system. It is suggested that for a small-scale power generation system (under 5kW) scroll machine is the best choice (Quoilin et al. 2012). Following the previous findings, a scroll machine is used in this work. The working fluid is an important factor of choice for ORC power system design, R245fa is known for its safety levels and environmental impacts for waste heat application (Wang et al. 2011). R245fa is also the best choice based on the criteria of net power and suitable working pressure (He et al. 2012). Thus, R245fa is selected as the suitable working fluid for the proposed system.

This work describes the design, fabrication and technical difficulties involved in the implementation of ORC system of such small power out using available components from the market. The test results are presented with performance evaluation for different degrees of superheating of the working fluid at expander inlet.

Materials & Method

The system's operational success is dependent upon its design and implementation. For small scale systems, it is customary to design the thermodynamic cycle for optimum performance at given source and sink conditions to obtain required power output and then finding the equipment (expansion machine, pump, heat exchangers, etc.) from the market, which can operate at required conditions of the power cycle. Contrarily, for bigger systems, it is common to design the components to strictly fulfil the performance requirements. For smaller systems, it is not viable to design and manufacture every single component as per requirements. In that case, components which match closely are selected and can be operated at slightly off design, compromising on performance. Component sizing & selection is difficult when the unusually small power requirement and cycle configurations are imposed. The mismatched components cause a lower overall performance of the system.

The system was designed to be operated by steam in the pressure range of 0~2 bar gauge pressure and the sink temperature at 12°C was available. Numerous working fluids have been under investigation for the usage in organic Rankine cycle based system for low-grade waste heat recovery. R245fa was selected for its closest match of required thermodynamic properties for available heat source and sink conditions and favorable environmental impact. The design procedure was initiated by fixing the pinch point temperature difference in heat exchangers (evaporator and condenser). Having fixed the pinching temperatures allowed to fix evaporation and condensing temperature of the organic Rankine cycle. The pressure ratio was calculated from evaporation and condensing pressures. Although when optimizing the performance of the waste heat ORC system, an optimum evaporating temperature exists that maximizes the output power (or overall efficiency) (Quoilin et al. 2011) but for prototypes and small systems it is more feasible to follow the equipment specifications. In current case, the expander inlet pressure for required output was selected as evaporation pressure. Isentropic enthalpy change was calculated at the calculated pressure ratio. Isentropic efficiency of the scroll type expansion machine was estimated from published literature (Song et al. 2014). The mass flow rate for the proposed system can be calculated from Equation (1).

$$\dot{W}_{shaft} = \dot{m}.(h_1 - h_{2s})\eta_{isen} \quad (1)$$

Power output for net electric power includes the mechanical losses in expander, coupling and generator. Also the generator efficiency reduces the generator output. In order to obtain 1kW electric output, W_{shaft} is estimated to be higher than 1kW. After performing the design calculations for the system, the scheme was modelled in cycle tempo software (Cycle Tempo) for verification and ease of study for various operational parameters. Major thermodynamic parameters at design point are presented in Table 1.

Table 1: Thermodynamic parameters at design point from design calculation and verified by cycle-tempo software simulation

Parameters	**Value**
Evaporator pressure	12.5bar
Condenser pressure	1.1bar
Expander Isentropic efficiency	50%
Working fluid mass flow rate	0.051kg/s
Heat source temperature (saturated steam)	120ºC
Sink Temperature	16ºC
Sink mass flow rate	0.73kg/s
Expander inlet temperature	101.5ºC
Condenser subcooling	3ºC

Table 2: Details of Equipment selected for implementation of test bed

Sr. no	**Equipment**	**Details**
1	Expander	Scroll Type expander (Airsquared Inc.), 12cc/rev, 1kW Nominal output, Magnetic coupling linked to 60Hz Generator 110V AC generator
2	Evaporator & Condenser	Braze plate heat exchangers (Janghan Engineers, Inc.) 60 & 50 plates, area of 6.5 & 5.38 square meter for evaporator & condenser, respectively
4	Feed Pump	Screw type pump (Tuthill Pump Company). Displacement of 2.6ml/rev Magnetic coupling linked to 0.75kW 3 phase 380V motor Condenser
5	Load Bank	Electric Bulbs of various power ratings were connected to the generator using single push single throw (SPST) type relays. Bulbs for 110V, were used in different power rating combination. 200W, 100W, 60W, 30W watt bulbs are used to obtain various step of resistive load connected to the generator
6	Heat Sink	Cooling tower already installed in facility
7	Heat Source	LNG based boiler with steam generation capacity of 500 kg/hr maximum
8	Flow rate meters	Working fluid with Coriolis type flow meter, sink flow rate measurement with electromagnetic flow rate meter, sink flow rate measurement with vortex type flow meter
9	Valves	Butterfly valves and globe valve for steam flow control (actuator controlled)
10	Temperature Measurement	T -type thermocouples for temperature measurement & RTD (PT100) for evaporator and expander inlet/exit
11	Pressure Transduces	Pressure Transducers with range of 0~16bar
12	Data Acquisition & Control	NI - cRIO 9074 with 8 slot integrated controller, NI I/O C-series model and Labview software

Table 2 presents the detail of selected equipment for test bed construction. Very few off the shelf expansion machines are available in the market, which can be used directly without alteration, but in this work a scroll machine designed for ORC application was available. Pump selection is another tough choice because of low flow rate, and large pressure head, no suitable centrifugal machine was found. A screw pump was able to cater our requirement with confidence as far pressure and flow rate requirements were required, but resulted in poor efficiency (<30%). Load bank was made by connecting electric bulbs of various power ratings to generator circuit and connections were controlled by relay operation.

Figure 1 presents the piping and instrumentation diagram for the test rig which was constructed according to the CAD diagram of system presented in Figure 2. Figure 3 presents the test rig in final fabricated form and under organic Rankine cycle system operation for power output.

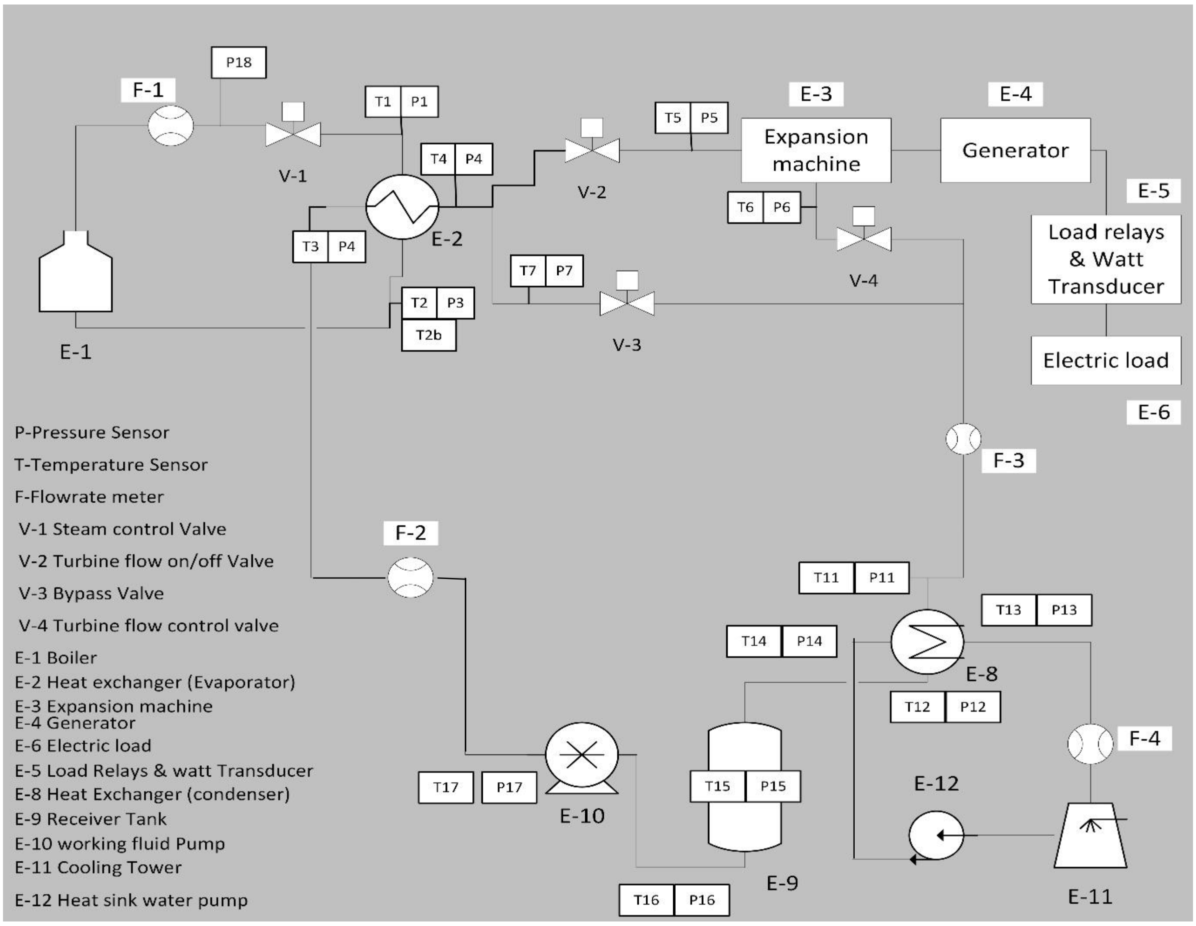

Figure 1: P&ID Scheme for proposed system

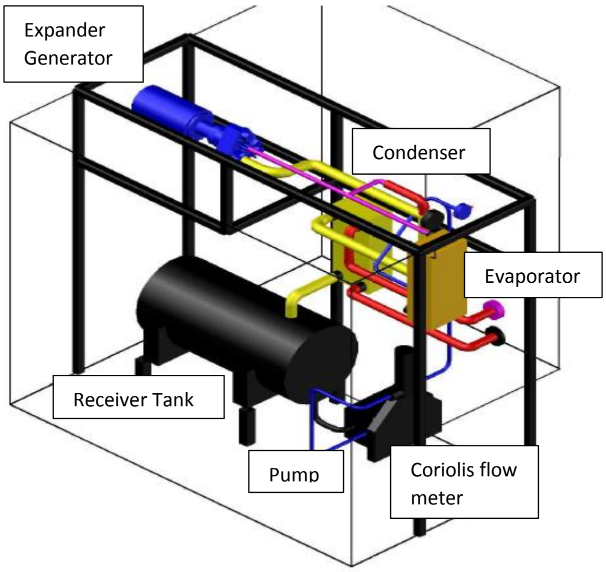

Figure 2: Isometric view of implemented system

Figure 3: System under operation

Results & Discussion

Figure 4 presents organic Rankine cycle test bed operational parameters for 20 minutes of its operating time. The system was operated in a way that the expander speed was kept below 3600RPM to follow safety recommendations from the manufacturer. Electric bulbs were connected to the load circuit one after another until a total of load of 1060W was imposed to the electric generator. After increasing the electric load, the pump speed controlled by variable frequency drive was increased to increase the mass flow rate and increase the evaporator pressure which increase the expander speed. After attaining the expander speed around 3600RPM, next electric bulb was connected which would reduce the expander speed as the torque on generator increased and for the same power output the rotational speed was decreased. Increasing the mass flow rate further, increased the evaporator pressure which allowed higher power output from the expander. The Figure shows that the evaporator pressure follows the pump speed (Mass flow rate). Generator power output increased to a maximum value of 1020W, when evaporator pressure is around the maximum operating design point of 11.5 barg. Expander speed was 3400 RPM while the generator was connected to a circuit of 8 bulbs (200W x 4, 100W x 2, 30W x 2) rated at 110V which summed up to yield 1060W resistive load.

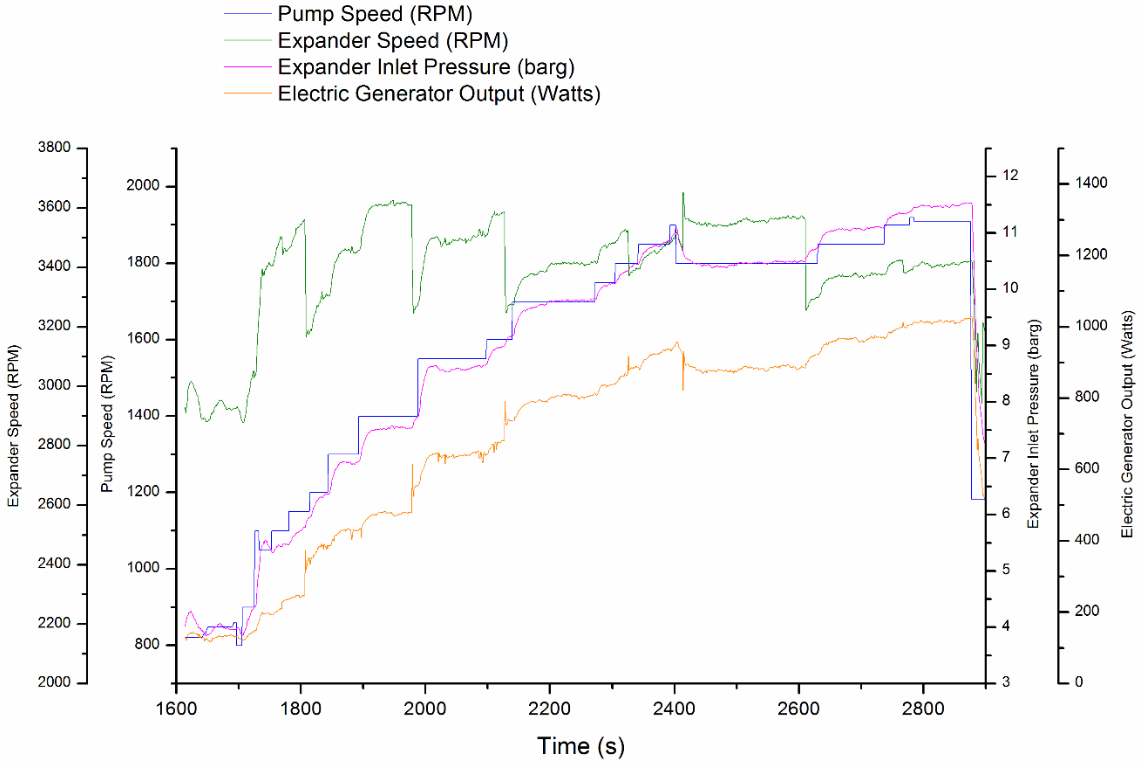

Figure 4: Organic Rankine cycle system operational parameters for different power output range

The sharp spikes in generator power output data occurred at the same time when expander speed was reduced at constant pump speed, increasing the imposed torque reduced the expander speed for the same power output. This was due to the connection of the relay with bulb. When the applied load increased as a step change the expander speed was reduced, to get back to recommended expander speed, pump speed was carefully adjusted to carry higher loads.

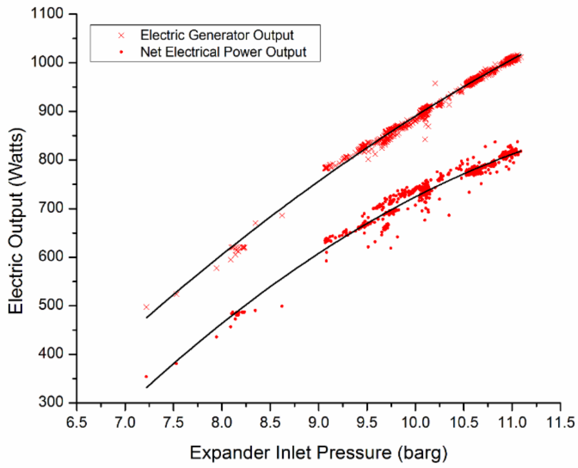

Figure 5: Electric Generator Output and Net Output vs Expander Inlet Pressure

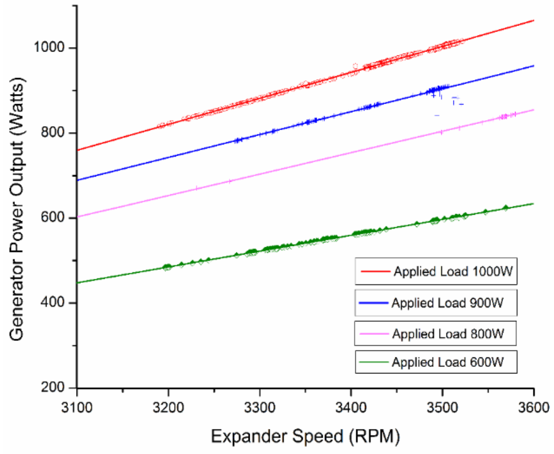

Figure 6: Electric Generator Power Output power vs Expander Speed

Figure 5 presents the electric output of generator with respect to the evaporator pressure while condenser conditions were held constant at 0.3barg. The figure also presents the net electric power output from the system. The pump electric power consumption was measured and used for evaluation. Both data plots are fitted with a 2nd order polynomial for analysis. Figure 6 presents generator output at various electric loading conditions. An applied load of 1000W refers to the connected electric bulbs with a combined power rating of 1000W to the electric generator circuit.

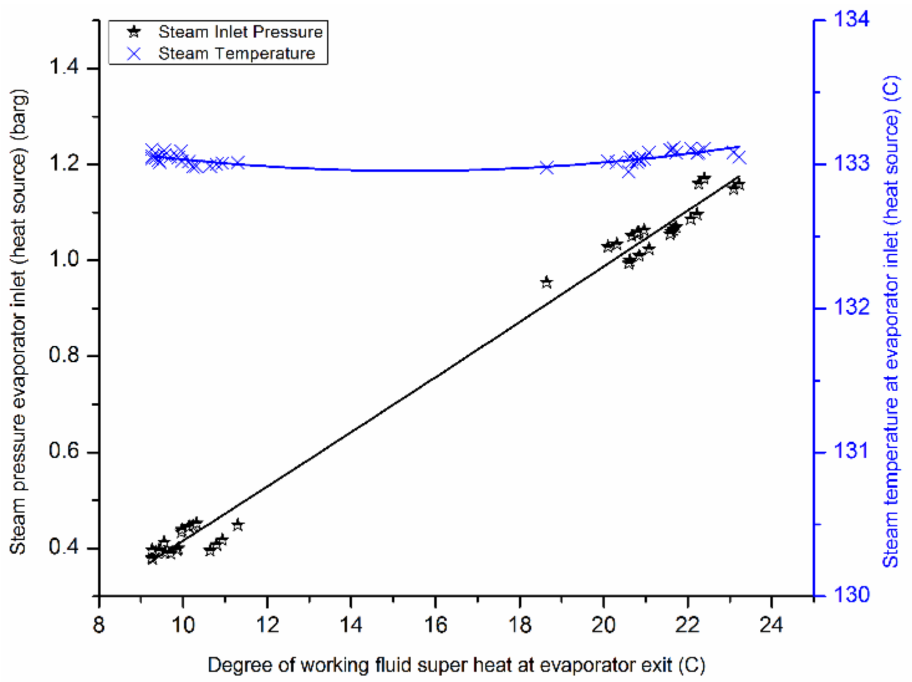

Figure 7: Variation of degree of super heat of working fluid at evaporator exit with respect to steam (heat source) pressure at heat source inlet side.

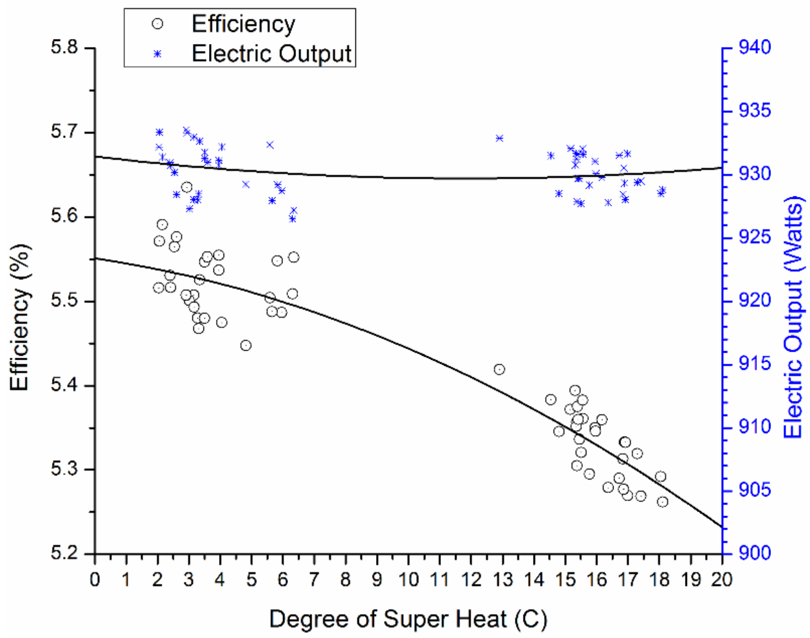

Figure 8: Effect of degree of super heat of working fluid at expander inlet vs electrical efficiency for same power output

An experiment to investigate the effects of superheat of the working fluid at expander inlet was performed. Extensive research and theoretical background suggested the lesser the degree of superheating, the better would be the performance for a system without recuperator using R245fa working fluid. In reality to maintain, superheat value of 0 would be ideal but is very challenging task to maintain a stable working fluid output with all vapor exit quality without any superheating. The ability to maintain the minimum superheating degree depends on various equipment and control characteristics. Evaporator type, size& geometry, plays an important role in this regard. In case of plate heat exchanger, the number of channels, aspect ratio, port design & thermal inertia influence the performance in such a way that to obtain a superheat of 0 is very difficult. The heat source type is also an important factor when considering the controllability of superheating of the working fluid at evaporator exit. In case of current system the heat source is steam, which is condensed in evaporator and subcooled to certain level.

Control of heat source was performed by using a globe valve which has been carefully sized and custom manufactured for the current conditions of steam pressure & flow rates. The actuator controlled valve allowed control of heat source for a steam requirement of less than 40 kg/hr. Figure 7 presents the controllability of working fluid superheat at evaporator exit. The globe valve which has an upstream steam pressure of 1.95 ~ 2barg was opened in such a way that the downstream pressure of globe valve was increased. As a result, condensing pressure in evaporator (heat source side/steam) was increased. Superheat at evaporator exit (Working fluid side) was observed as 10^{O}C when source pressure was 0.4barg, when steam pressure was increased to 1.1barg the super heat value was observed around 21^{O}C. While the source temperature was observed around 133^{O}C in both cases. Figure 8 presents superheating degree at expander inlet and cycle efficiency for same electrical power output. Figure 7 and Figure 8 present data from same experiment, but the Figure 8 presents superheat value at expander inlet while Figure 7 presents the superheat value for evaporator exit. The difference in super heat values is due to heat loss in piping network when the working fluid flows from evaporator to expander. The data in Figure 9 and 8 is used to plot 2^{nd} order polynomial fits for analysis. Electrical efficiency of system was obtained by equation (2).

$$\eta_{elec} = \frac{Electric\ Generator\ Power\ Output\ (kW)}{\dot{Q}_{evaporator.\ working\ fluid}\ (kW)} \tag{2}$$

Where

$$\dot{Q}_{e,wf}\ (kW) = \dot{m_{wf}}\ (h_{eo} - h_{ei}) \tag{3}$$

Figure 8 data results used to obtain 2nd order polynomial relation which suggest the drop in efficiency of system with increasing super heat value. The relation is presented as Equation (4)

$$\zeta = 5.55084 - 0.00542(\theta) - 0.0005245(\theta)^2 \tag{4}$$

Where

$$\zeta - electric\ efficiency\ (percentage)\ as\ a\ function\ of\ superheat$$

$$\theta -\ is\ degree\ of\ superheat\ (Celcius)\ at\ expander\ inlet$$

Equation 4 can be used to estimate the reduction in efficiency with respect to superheating degree for the same electrical power generated. In this case power output was held constant by maintaining a constant expander speed to hold power output around 930W and heat source carefully adjusted to obtain different superheat values. It was noted that for current system an increase in 1ºC of super heat will reduce 0.011% in electric efficiency if evaporator superheat is around 10ºC. As the relation is nonlinear curve it suggests reduction in electric efficiency of 0.025% with increase of 1ºC after super heat at heat exchanger exit is above 20ºC. The relation is only valid for current system and is a basis for the future research work to be carried out to establish relationship for efficiency and superheating degree for various systems of various power range.

Conclusion

In this work, design, equipment selection and fabrication of a small scale organic Rankine cycle test bed system, using steam as heat source was performed. The fabricated test rig was operated and following conclusion were made:

- 1kW scale organic Rankine cycle system can be designed and fabricated with major components available from market.
- Design requirement of components and availability causes mismatching in component selection, whereas losses (isentropic, frictional, electrical etc.) involved in components should be carefully analyzed to achieve required performance.
- A 1kW scale ORC system is capable of producing net electrical output if components are precisely selected
- The system was able to produce 1kW electric output with efficiency value of 5.2%.
- The best efficiency points are not at the highest output power.
- Using a steam condensing evaporator for small flow rates of steam and working fluid superheat control at constant pressure is difficult procedure.
- Efficiency depreciation with increasing superheat level can go as high as 0.02% per degree Celsius for this system.
- An attempt to establish a practical approach for relating efficiency depreciation with higher superheat is initiated. The future work will incorporate various types of systems at various power range will be studied for efficiency drop due to superheat to highlight how much research attention and work will be required for improvement of control systems and heat exchangers to obtain minimum super heat levels.

NOMENCLATURE

ORC	Organic Rankine Cycle
$\dot{W}_{shaft}$	Expander shaft power output
$\dot{m}_{wf}$	Working fluid mass flow rate (R245fa)
h_{eo}	Working fluid enthalpy at evaporator outlet
h_{ei}	Working fluid enthalpy at evaporator inlet
η_{isen}	Expander Isentropic efficiency
η_{elec}	Thermal to electric conversion efficiency
$\dot{Q}_{e,wf}$	Heat transfer to the working fluid

REFERENCES

Cycle Tempo. TU Delft (Delft University of Technology), http://www.asimptote.nl/

He, C. et al., 2012. The optimal evaporation temperature and working fluids for subcritical organic Rankine cycle. *Energy*, 38(1), pp.136–143.

Hung, T.C., Shai, T.Y. & Wang, S.K., 1997. A review of organic rankine cycles (ORCs) for the recovery of low-grade waste heat. *Energy*, 22(7), pp.661–667.

Lecompte, S. et al., 2015. Review of organic Rankine cycle (ORC) architectures for waste heat recovery. *Renewable and Sustainable Energy Reviews*, 47, pp.448–461.

Minea, V., 2014. Power generation with ORC machines using low-grade waste heat or renewable energy. *Applied Thermal Engineering*, 69(1-2), pp.143–154.

Peris, B. et al., 2015. Experimental characterization of an ORC (organic Rankine cycle) for power and CHP (combined heat and power) applications from low grade heat sources. *Energy*, 82, pp.269–276.

Quoilin, S. et al., 2011. Thermo-economic optimization of waste heat recovery Organic Rankine Cycles. *Applied Thermal Engineering*, 31(14-15), pp.2885–2893.

Song, P. et al., 2014. A review of scroll expanders for organic Rankine cycle systems. *Applied Thermal Engineering*, 75, pp.54–64.

Wang, E.H. et al., 2011. Study of working fluid selection of organic Rankine cycle (ORC) for engine waste heat recovery. *Energy*, 36(5), pp.3406–3418.

Wenzhi, G. et al., 2013. Performance evaluation and experiment system for waste heat recovery of diesel engine. *Energy*, 55, pp.226–235.

Zhang, Y.-Q. et al., 2014. Development and experimental study on organic Rankine cycle system with single-screw expander for waste heat recovery from exhaust of diesel engine. *Energy*, 77, pp.499–508.

ACKNOWLEDGEMENT

This work was conducted under the framework of Research and Development program of the Korea Institute of Energy Research and University of Science & Technology (b4-5524).