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Modeling of organic Rankine cycle for suitable working fluid in HYSYS for power generation in Pakistan

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In this study organic Rankine cycle was modeled using Aspen HYSYS 8.8 to find suitable working fluids in 9 different locations which enlightened the scope of organic Rankine cycle in Pakistan. Different working fluids, namely R141b, R21, R142b and R245fa under different solar radiation-based temperature conditions at boiler inlet are reported in this study. R21 was found as the most promising working fluid due to its relatively better work output from a 0.59 MW turbine exploiting low quality heat, as compared to above mentioned working fluids investigated in this study.

Keywords: Organic Rankine cycle (ORC); Waste heat; Solar-thermal energy; Aspen HYSYS 8.8.

INTRODUCTION

Pakistan relies on different sources for power generation to meet its electricity demand. These sources are mainly comprised of natural gas, hydel, coal, nuclear, LPG and fuel oil [1-4]~~.~~ There is a continuous increase in demand of electricity in the country. However, the conventional sources for power production are limited and affect the environment by producing large amount of greenhouse gases as byproducts [5]~~.—~~Organic Rankine cycle (ORC) has a wide scope in Pakistan due to its potential utilization with waste heat recovery and solar energy. The ORC technology operates below 200°C and is innocuous to the environment. In Pakistan industrial waste heat and solar energy are the main energy resources for organic Rankine cycle. Almost 200 plants of ORC are working in different regions of the world [6]. Energy demand increases with increase in population growth. ORC modeling and its technology development may eliminate and secure energy future of Pakistan and would help in mitigating the current energy crisis of the country.

In contrast to steam Rankine cycle, organic Rankine cycle deploys organic fluid instead of water and consists of the same four processes named: compression (pump used for compression), vaporization (boiler for vaporization), expansion (turbine used for expansion work) and condensation (condenser for condensation) [6, 7]

Waste heat recovery from combined cooling, heating and power (CCHP) systems offers a way of utilizing the energy of fuel efficiently, economically and reliably. In addition to this, the overall efficiency of the plants also improves along with less degradation to the environment [7-10].

Velez et al. studied different working fluids for Rankine cycle operating at low temperature. Working fluids like water, some hydrocarbons and coolants were studied by modifying the inlet conditions (pressure and temperature) of the turbine. The influence of pressure ratio and inlet temperature of the turbine were also studied [11]. Ekwonu et al. investigated modeling of gas engines waste heat integrated with Rankine cycle and organic Rankine cycle in Aspen HYSYS 7.3 for potential waste heat recovery and consumption. The influence of exhaust gas temperature at different operating conditions on the efficiency and power of the system was investigated and compared [12]. Some researchers discussed the combination of ORC with waste heat and solar energy for power generation. However, these studies were conducted in different domestic weather conditions [13,14].

In this study, organic Rankine cycle was modeled to identify a working fluid appropriate for different climates in Pakistan for power generation from solar and waste heat energy. In this way an inexpensive alternate source for power generation could be employed.

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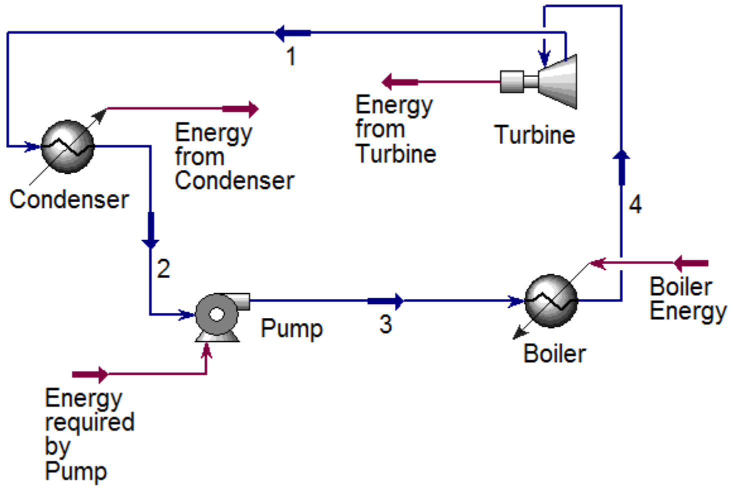

Fig. 1. Rankine cycle

WORKING OF ORGANIC RANKINE CYCLE (ORC)

The working fluid in liquid state is pumped into the boiler where it is heated at constant pressure by an external heat source like solar-thermal energy and/or waste heat, etc. This heat energy changes its phase into superheated vapors. Superheated vapors turn the turbine, expand and generate power. The expansion causes cooling at the outlet of turbine. The vapors are later condensed by removing latent heat at constant pressure to become a saturated liquid. This saturated liquid is introduced to the pump inlet all the time and the cycle goes on. Boiler and condenser are assumed to be isobaric whereas pump and turbine are assumed to be isentropic in nature. The process flow diagram of modeled organic Rankine cycle is shown in Figure 1.

SOLAR ENERGY AND ORC

Sun is the only sustainable energy resource and radiates in a unit second more energy than consumed by the earth inhabitants [14]. Depletion trends of fossil fuels have made it inevitable focusing renewable and sustainable energy resource development. Earth receives 174 PW from solar radiation at the upper atmosphere, 30% of this energy is reflected back whereas the rest of it is utilized by different sources such as water evaporation, etc. Total energy absorbed by the earth is 3850000 EJ per year [15]. If only 0.22% of earth area is covered with solar collectors having just 8 % efficiency, then this would be enough in meeting the present global energy requirements [16]. Pakistan is situated in the sunny belt and has long sunny days throughout the year. This exposure varies to some extent from place to place due to the geographical location of Pakistan. The minimum intensity of solar energy in Pakistan is 4.45KWh/m^2 and the highest one is of 6.65KWh/m^2 per day with a reported maximum of 7 KWh/m^2 per day. The annual mean value of solar radiation in Pakistan is 5.5 KWh/m^2 per day during the course of its sunshine hours[14, 17, 3].

INVESTIGATED LOCATIONS OF PAKISTAN

The highest temperature recorded in Pakistan was 53.5°C on May 26th, 2010. It was the highest temperature measured in Asia [17]. The daily mean temperatures of 9 different locations of Pakistan that were investigated in the current study are shown in Table 1 [18].

MODELING OF ORGANIC RANKINE CYCLE USING ASPEN HYSYS 8.8

Organic Rankine cycle simulations were carried out using Aspen HYSYS 8.8 process simulator. HYSYS is useful for thermodynamic analysis at steady state conditions.

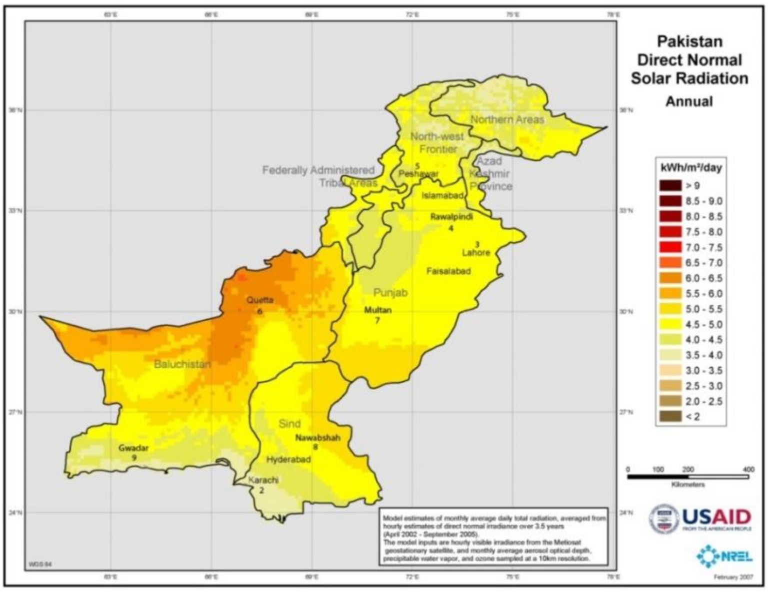

Fig. 2. Solar energy potential in Pakistan and the identified locations [14]

Table 1. Daily mean temperature of locations investigated [18]

Cities of Pakistan (9locations)	Daily Mean Temperature (°C)												
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
Islamabad (1)	10.1	12.1	16.9	22.6	27.5	31.2	29.7	28.5	27	22.4	16.5	11.6	21.34
Karachi (2)	18.1	20.2	24.5	28.3	30.5	31.4	30.3	28.9	28.9	27.9	23.9	19.5	26.03
Lahore (3)	12.8	15.4	20.5	26.8	31.2	33.9	31.5	30.7	29.7	25.6	19.5	14.2	24.32
Rawalpindi (4)	10.35	12.3	16.9	22.8	27.85	34.3	30	28.5	27.1	22.45	16.5	12	21.75
Peshawar (5)	11.2	12.9	17.4	23.2	28.6	33.1	32.2	30.7	28.9	23.7	17.6	12.5	22.67
Quetta (6)	3.7	6	11.1	16.6	21	25.6	27.9	26.4	21.1	14.6	9.2	5.1	15.69
Multan (7)	13	15.5	21.5	28	32	35.5	34	33	31	26.5	20	14.5	25.38
Nawabshah (8)	15.2	18.2	23.95	29.65	34	35.6	33.9	32.45	31	27.9	22.1	16.8	26.72
Gwadar (9)	18.95	20.1	23.2	26.8	29.55	30.5	29.7	28.65	28	26.85	23.5	20.1	25.48

It has the advantage of including fluid properties and ready to use optimization tools. Peng Robinson equation of state was used as the thermodynamic model.

The evaporator's heat duty was evaluated as a function of evaporator inlet temperature and pressure conditions. The process was assumed at steady state conditions, no drop in pressure or heat loss in the condenser, the evaporator or the pipes and constant isentropic efficiencies of 75% were considered for the turbine and pump.

The organic Rankine cycle process flow diagram in simulation is the same as shown in Figure 1. The inlet and outlet pressures of pump are 4.7 bar (0.47MPa) and 17.5 bar (1.75MPa), respectively. The flow rate is 25.51 kg/s. The refrigerants R142b, R21, R141b and R245fa were used in the simulations. R142b evaporates at 91°C, R21 evaporates at 114°C, R141b evaporates at 148°C and R245fa evaporates at 115°C. The inlet temperatures used weres the temperatures of all the investigated locations as listed in Table 1.

The total cycle energy efficiency was determined using the following equations:

$$\eta = \frac{\dot{\mathrm{W}}\,\mathrm{turbine} - \dot{\mathrm{W}}\,\mathrm{pump}}{\dot{\mathrm{Q}}\,\mathrm{evaporator}} \quad (1)$$

where,

$$\dot{\mathrm{W}}\,\mathrm{turbine} = \dot{m} \times (h_1 - h_2) \quad (2)$$

$$\dot{\mathrm{W}}\,\mathrm{pump} = \dot{m} \times (h_3 - h_4) \quad (3)$$

$$\dot{\mathrm{Q}}\,\mathrm{evaporator} = \dot{m} \times (h_4 - h_1) \quad (4)$$

Pump, turbine, heater (boiler) and cooler (condenser) were the unit operations used in ORC simulations. HYSYS uses the following assumptions and equations in calculating unknown variables of the mentioned unit operations:

- *For pump:*

The pump unknown variables were calculated using equations (5-7):

$$\dot{W}_{pump.i} = \text{power required ideal} = \frac{(P_{out} - P_{in}) \times \dot{m}}{\rho_{Liquid}} \quad (5)$$

Equation (5) shows the ideal power required by the pump to increase the pressure of the liquid. The actual power required by the pump can be estimated by using the following co-relation:

$$\text{Efficiency } (\%) = \eta_{Pump} = \frac{\dot{W}_{Pump.i}}{\dot{W}_{Pump}} \times 100\% \quad (6)$$

When the pump efficiency is less than 100%, it means that the excessive amount of energy goes into raising the temperature of the outlet stream.

Combining equations (5) and (6) gives the correlation equation (7) for the estimation of the actual power required for the pump:

$$\dot{W}_{Pump} = (P_{out} - P_{in}) \times \dot{m} \times 100\% \Big/ (\rho_{Liquid} \times \eta_{Pump}) \quad (7)$$

- *For turbine*:

Efficiency of turbine is the ratio of actual power ($\dot{W}_{Turbine}$) obtained from the turbine in the expansion process to the power obtained for isentropic expansion ($W_{Turbine.i}$),). It can be given by the following relation equation (8):

$$\text{Efficiency } (\%) = \eta_{Turbine} = \frac{\dot{W}_{Turbine}}{\dot{W}_{Turbine.i}} \times 100\% \quad (8)$$

- *Evaporator and condenser*:

For the calculation of the performance to cycle it is only necessary to determine the amount of heat required for the process to run the turbine, our objective was not to study the conditions of the utility itself, the condenser and evaporator available in software wes used.

RESULTS AND DISCUSSIONS

It was found that the energy obtained from the turbine using different working fluids remains the same (Table 2). Following table shows the energy obtained from the turbine at work.

Table 2. Energy from turbine (MW)

Energy from Turbine(MW)	R245fa	R142b	R21	R141b
	0.43	0.56	0.59	0.57

The results obtained were plotted as the relationships of inlet temperature and the boiler duty for different working fluids. These graphs are shown in figures 3 to 20.

The boiler duty decreases with increase in inlet feed temperature to the boiler. As a result, less amount of heat is required to evaporate the working fluid. The graphs were plotted for monthly temperatures and the boiler duty for different locations of Pakistan. It was found that at given conditions working fluids as investigated follow the order: R141b >R245a>R21>R142 heat to produce vapors. Working fluid R245fa required less amount of heat to produce vapors. The working fluid R21 required a larger amount of heat than the working fluid R142, but a smaller amount of heat than R141b.

FOR ISLAMABAD (LOCATION 1)

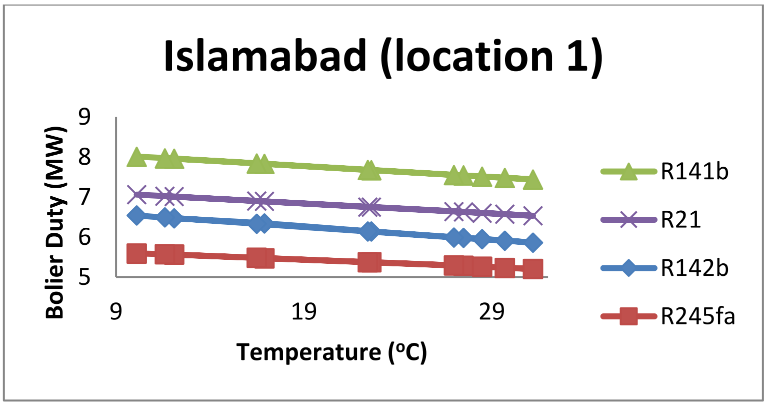

Fig. 3. For Islamabad (location 1): Temperature (°C) *vs* boiler duty (MW)

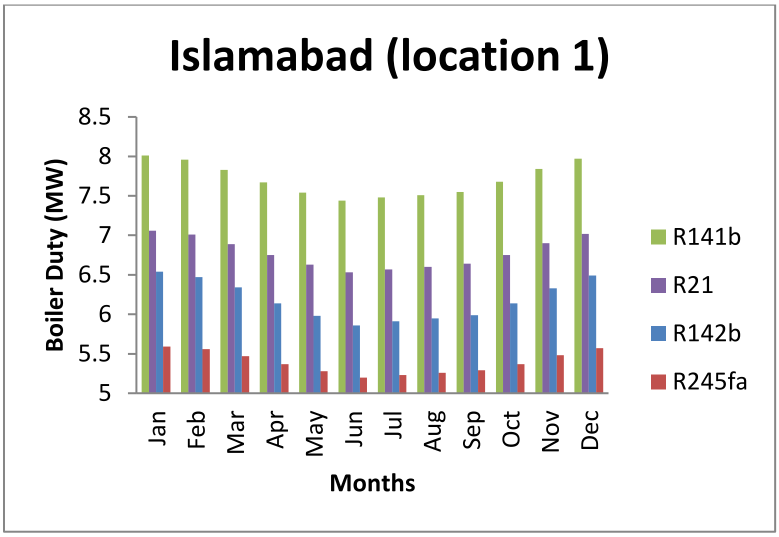

Fig. 4. For Islamabad (location 1): Boiler duty (MW) *vs* months

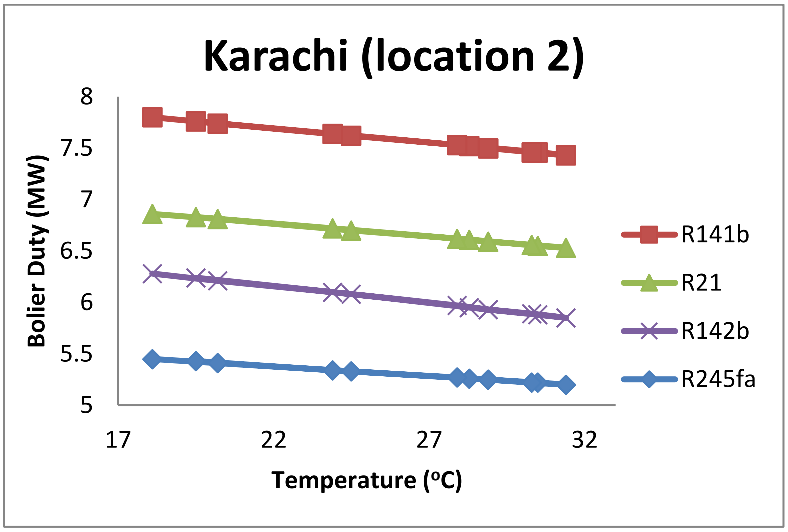

Fig. 5. For Karachi (location 2): Temperature (°C) *vs* boiler duty (MW)

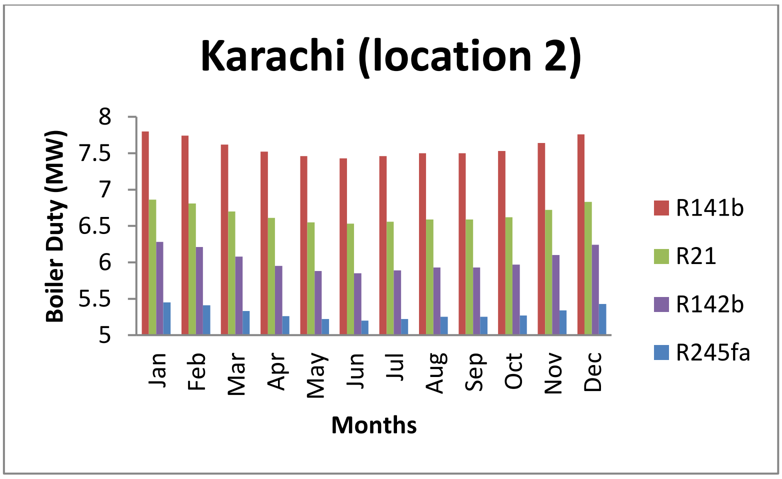

Fig. 6. For Karachi (location 2): Boiler duty (MW) *vs* months

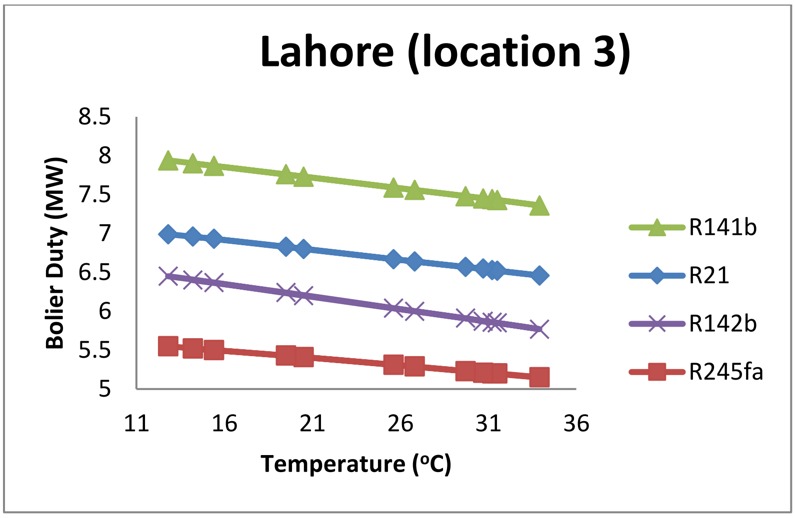

Fig. 7. For Lahore (location 3): Temperature (°C) *vs* boiler duty (MW)

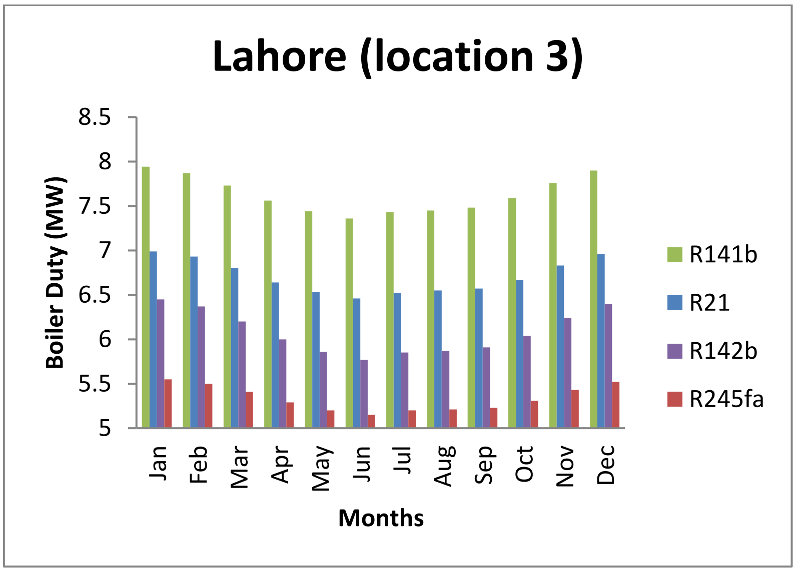

Fig. 8. For Lahore (location 3): Boiler duty (MW) *vs* months

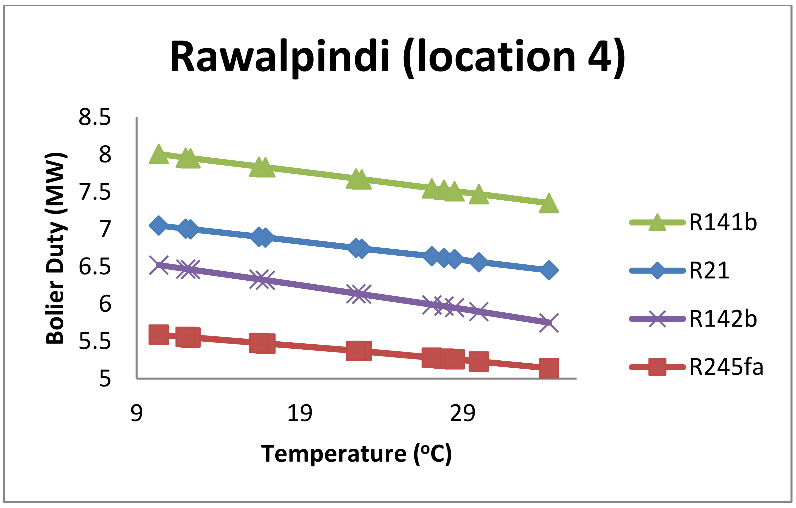

Fig. 9. For Rawalpindi (location 4): Temperature (°C) *vs* boiler duty (MW)

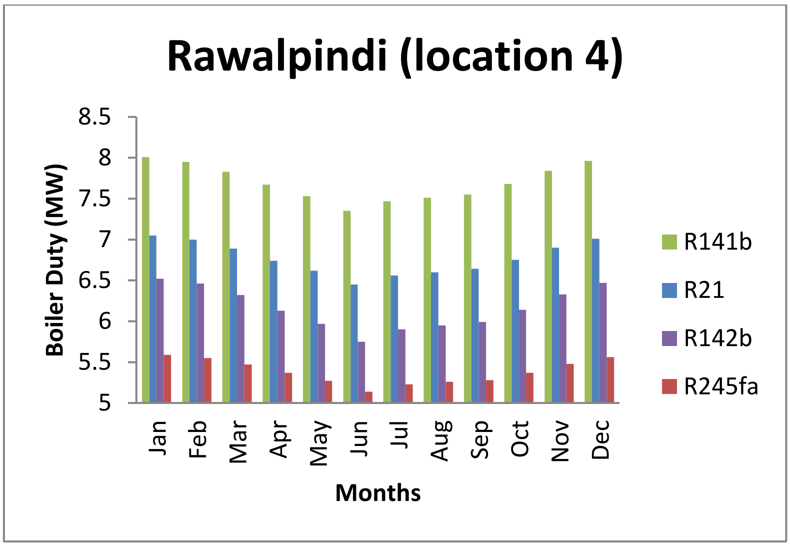

Fig. 10. For Rawalpindi (location 4): Boiler duty (MW) *vs* months

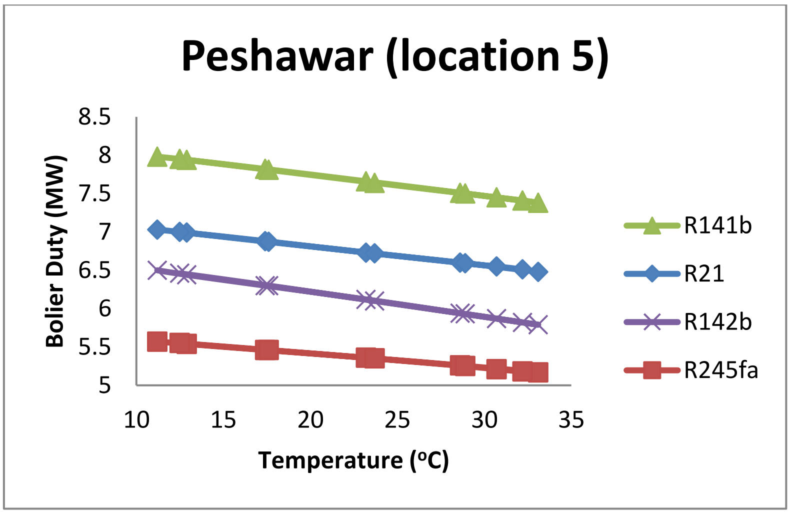

Fig. 11. For Peshawar (location 5) Temperature (°C) *vs* boiler duty (MW)

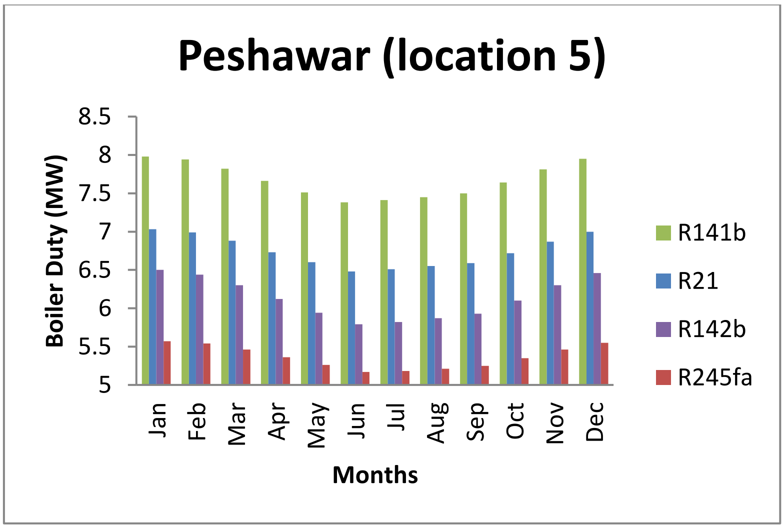

Fig. 12. For Peshawar (location 5): Boiler duty (MW) *vs* months

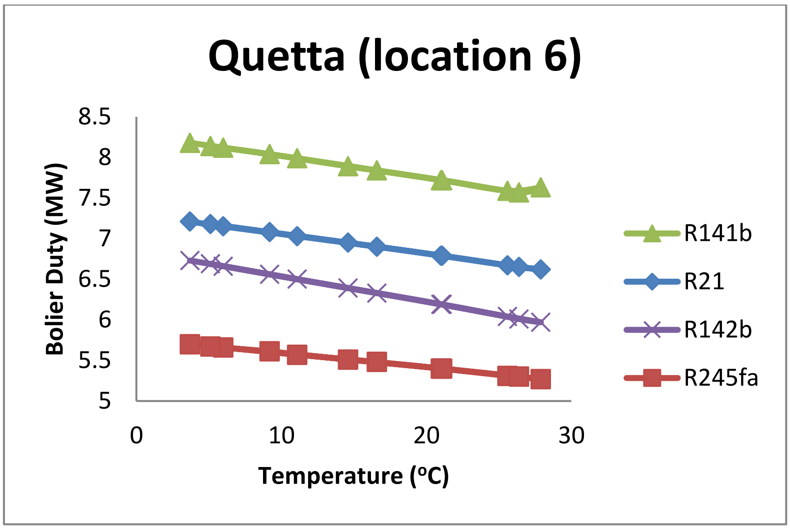

Fig. 13. For Quetta (location 6): Temperature (ºC) *vs* boiler duty (MW)

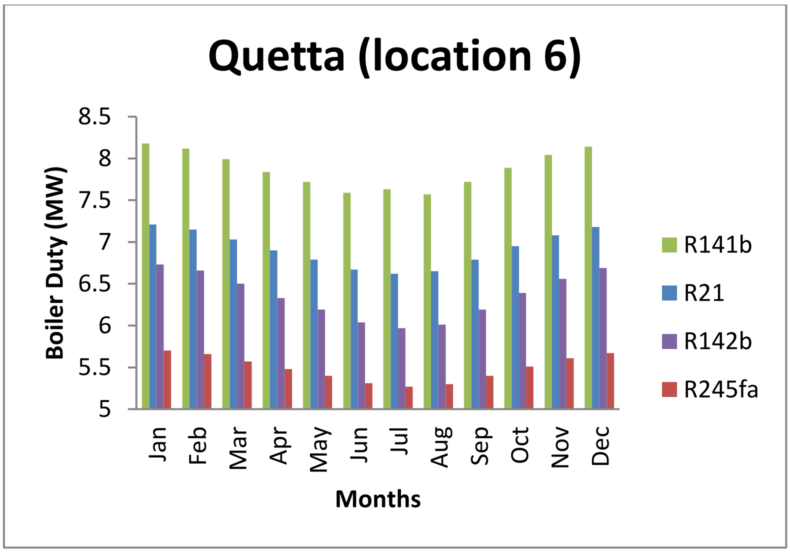

Fig. 14. For Quetta (location 6): Boiler duty (MW) *vs* months

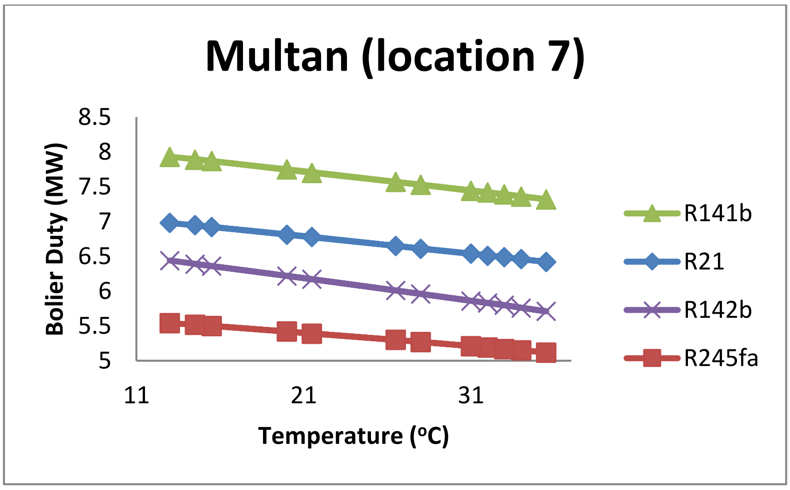

Fig. 15. For Multan (locationt 7): Temperature (ºC) *vs* boiler duty (MW)

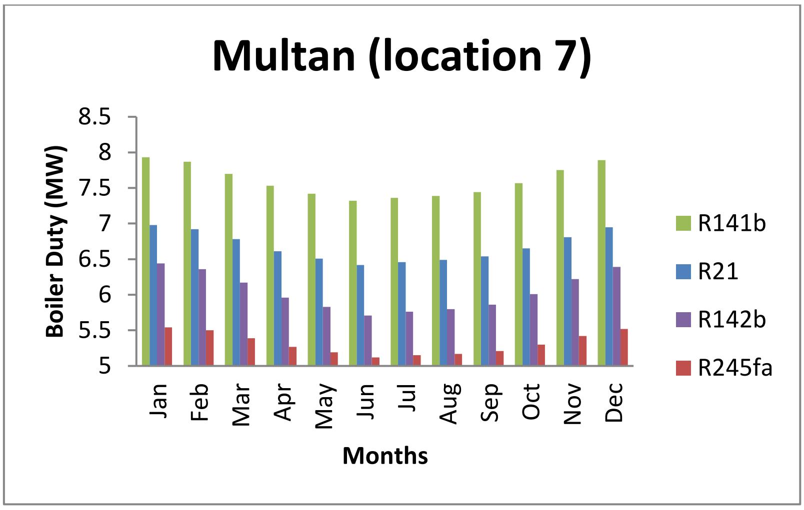

Fig. 16. For Multan (location 7): Boiler duty (MW) *vs* months

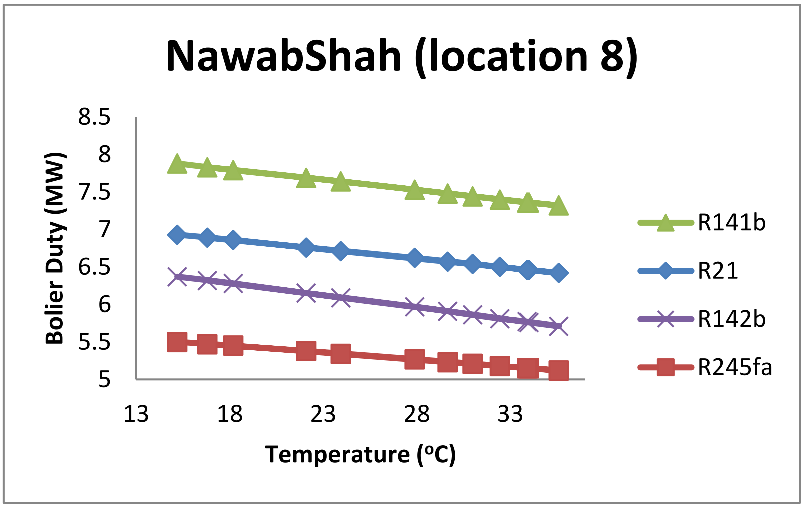

Fig. 17. For Nawabshah (location 8): Temperature (°C) *vs* boiler duty (MW)

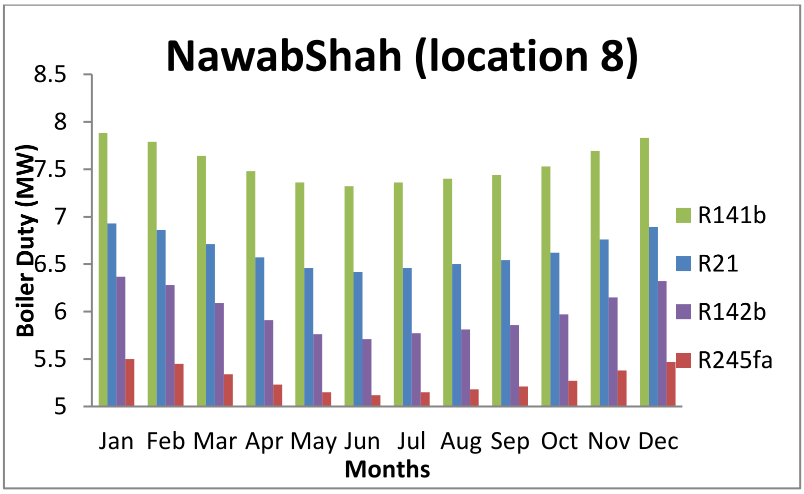

Fig. 18. For Nawabshah (location 8): Boiler duty (MW) *vs* months

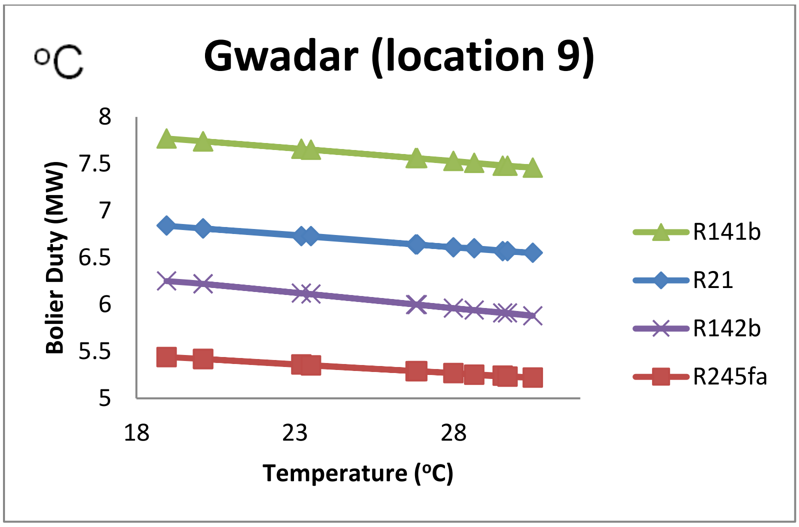

Fig. 19. For Gwadar (location 9): Temperature (°C) *vs* boiler duty (MW)

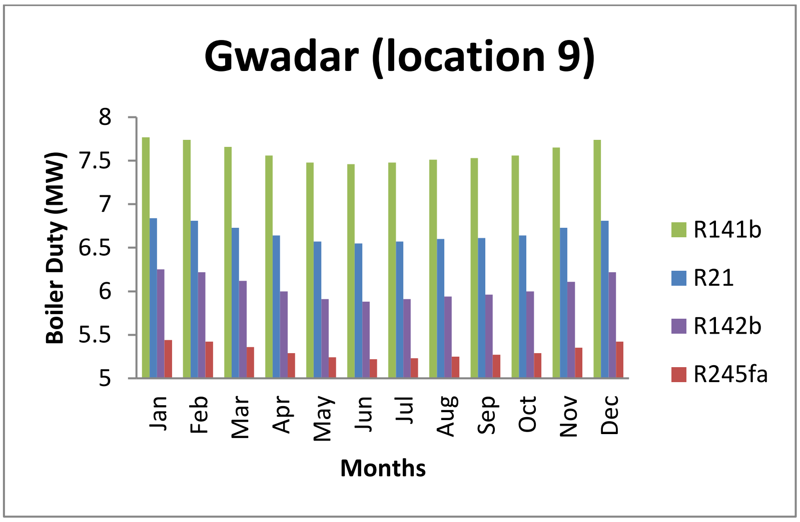

Fig. 20. For Gwadar (location 9): Boiler duty (MW) *vs* months

CONCLUSIONS

Based on simulations results, it can be concluded that:

- R21 was identified as propitious working fluid based upon the relatively better work output from the turbine which is 0.59 MW by exploiting low-quality heat.
- The organic working fluid R141b gives work output of 0.57 MW, but it requires more energy as compared to R21.
- The working fluid R142b gives work output of 0.56 MW by using low-quality heat as compared to R21 and R141b but it is not recommended because it is extremely flammable and dangerous for the ozone layer.

FUTURE WORK RECOMMENDATION

Selection of working fluid is very critical as it requires certain factors to be considered that include:

- Cost effectiveness and availability;
- Non-toxicity and non-flammability;
- Low global warming potential and zero ozone depletion factor;
- Low viscosity, thermal and chemical stability;
- Low freezing point.

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REFERENCES

1. G. Abdullah, A. Shair, W. S. Ali, *EJBM*, **7,** 442 (2015).
2. A.W. Bhutto, A. A. Bazmi, , G. Zahedi., *Renew. Sust. Energ. Rev.*, **15**, 3207 (2011).
3. M.A, Chaudhry, R. Raza, S.A. Hayat, *Renew. Sust. Energ. Rev.*,, **13**, 1657 (2009).
4. B. Fatima, F. Ali, History of Private Power in Pakistan. Sustainable Development Policy Institute, Islamabad, 2007.

5. M. Abid, M.S. Khurram, S. Rafiq, S.A. Memon, M. Ghauri, K. Shahzad, M. Jaffery, M.G. Doggar, N. Muhammad, JoET, **6**, 352 (2017).
6. K. Arun, S.K Shukla, *Proc. Technol.*, **23**, 454 (2016).
7. K. C. Kavvadias, A. P. Tosios, Z. B. Maroulis, *Energy Convers. Manage.*, **51**, 833 (2010).
8. S. M. Lai, C.W. Hui, Energy, **34**,1693(2009).
9. F.A. Al- Sulaiman, I. Dincer, F. Hamdullahpur, *Appl. Therm. Eng.*, **31**, 2829 (2010).
10. G. Angrisani, A. Rosato, C. Roselli, M. Sasso, S. Sibilio, *Appl. Therm. Eng.*, **38,** 78 (2012).
11. F. Velez, J.S. Jose, M. C. Martin, G. Antolin, F. Chejne, A. Quijano, *Fuel Process. Technol.*, **103**, 71 (2012).
12. M. C. Ekwonu, S. Perry, E. A. Oyedoh, *ACER*, **3**, 42(2014).
13. J. Freeman, K. Hellgardt, C.N. Markides, Appl. energ., **138**, 605 (2015).
14. S. Adnan, A.H. Khan, S. Haider , R. Mahmood, *J. Renew. Sustain. Energy*, **4**, 1 (2012).
15. GOP Pakistan Economic Survey, Islamabad. Economic Advisers Wing: Ministry of Finance, (2014).
16. GSRR - REN 21, Renewables, 2013. http://www.ren21.net/*Portals/0/Documents/Resources /GSR/2013 /GSR 2013_lowres.pdf.*
17. H. B. Khalil, S. J. H. Zaidi, *Renew. Sust. Energ. Rev.*, **31,**194 (2014).
18. GOP Pakistan Meteorological Department. 2013. http://www.pmd.gov.pk/

МОДЕЛИРАНЕ НА ОРГАНИЧЕН RANKINE ЦИКЪЛ ЗА ПОДХОДЯЩ РАБОТЕН ФЛУИД ЧРЕЗ HYSYS ЗА ПРОИЗВОДСТВО НА ЕНЕРГИЯ В ПАКИСТАН

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(Резюме)

В настоящата статия е моделиран органичен Rankine цикъл с използване на Aspen HYSYS 8.8 за намиране на подходящия работен флуид в 9 различни области, представителни за обхвата на органичния Rankine цикъл в Пакистан. Изследвани са различни работни флуиди, именно R141b, R21, R142b и R245fa, при различни температурни условия на входа на нагревателя, базирани на слънчевото греене. Установено е, че R21 е най-перспективният работен флуид, даващ относително по-добър ефект за 0.59 MW турбина с използване на нискокачествено гориво, в сравнение с другите изследвани флуиди.