CHAPTER 1

INTRODUCTION

1.1 Rationale

World net electricity generation increases continually, e.g. from 13.29 trillion kWh in 2001 to 18 trillion kWh in 2006, with a growth rate of 6.3 present per year (EIA, 2004, EIA, 2009) and it could be found that coal gives a biggest share around 40 % while natural gas and renewable energy occupy the market share at roughly 21 and 19 %, respectively (EIA, 2006). Fossil fuels such as coal and natural gas power plants have caused many environmental problems such as global warming and atmospheric pollution as shown in Table 1.1.

Table 1.1 Estimation of the pollutant emissions from electricity energy consumption (Jaruwongwittaya and Chen, 2010).

Years	Pollutant emissions (10^3 tons)				
	CO_2	CO	CH_4	SO_2	NO_x
2004	72,637	47	5	199	213
2005	75,956	52	5	213	224
2006	75,839	53	5	231	227
2007	82,087	59	6	359	258
2008	83,308	60	6	393	264

Use of renewable energy is one solution to solve the environmental problems. Solar energy, geothermal energy and biomass could be taken as heat source for electricity generation. The CO_2 emissions from these power plants were shown in Table 1.2 and it was found that the CO_2 emissions from coal and natural gas power plant were 960 and 443 gCO_2/kWh_e which were higher than those from renewable energy of which the emission was less than 38 gCO_2/kWh_e.

Table 1.2 Life cycle estimations for electricity generators.

Technology	Capacity/configuration/fuel	Estimate (gCO_2/kWh_e)	Reference
Wind	1.5 MW, onshore	10	Pehnt, 2006
Hydroelectric	3.1 MW, reservoir	10	Pehnt, 2006
Hydroelectric	300 kW, run-of-river	13	Pehnt, 2006
Solar thermal	80 MW, parabolic trough	13	Pehnt, 2006
Biomass	Waste wood steam turbine	31	Pehnt, 2006
Solar PV	Polycrystalline silicone	32	Fthenakis et al., 2008
Geothermal	80 MW, hot dry rock	38	Pehnt, 2006
Nuclear	Various reactor types	66	Sovacool, 2008
Natural gas	Various combined cycle turbines	443	Gagnon et al., 2002
Diesel	Various generator and turbine types	778	Gagnon et al., 2002
Heavy oil	Various generator and turbine types	778	Gagnon et al., 2002
Coal	Various generator types with scrubbing	960	Gagnon et al., 2002

At present, concentrating solar power (CSP) technology has been exploited through three different systems: the parabolic trough system, the tower system and the dish/Stirling engine system. Anyhow, all of these are appropriate for countries having high direct normal solar radiation (>1,500 kWh/m^2-yr) (IEA, 2003, Bravo et al., 2007, Purohit and Purohit, 2010). Investment and electricity generation costs for CSP technologies at high direct normal solar radiation are shown in Table 1.3 (IEA, 2003). It could be seen that the parabolic trough system afforded the lowest investment and the electricity generation cost.

Table 1.3 Investment and electricity generation costs for CSP technologies (IEA, 2003).

System	Investment cost (€/kW)	Electricity generation cost (€/kWh)
Parabolic trough system	2,800-3,200	0.12-0.15
Tower system	4,000-4,500	0.15-0.20
Dish/Stirling engine system	10,000-12,000	0.20-0.25

For Thailand, the annual direct normal solar radiation was in a range of 1,350-1,400 kWh/m^2-yr (Department of Alternative Energy Development and Efficiency, Ministry of Energy, 2006) which was rather low for the CSP technologies. Ketjoy and Rakwichian, 2006 studied techno-economic feasibility of a solar parabolic power generation in Thailand. The required maximum electrical power was 800 kW. It was found that the cost of energy (COE) was 25.52 Baht/kWh which was rather high compared with the electricity cost from the conventional power plant.

Recently, organic Rankine cycle (ORC) has been developed and heat source temperature could be in a range of 90 – 120 ^{o}C or over. At this temperature range, flat-plate and evacuated-tube solar collectors could be implemented thus both direct and diffuse solar radiation could be utilized.

The ORC works like a Clausius-Rankine steam power plant but organic working fluid is used instead of water. The ORC is a promising process for conversion of low and medium temperature heat source to electricity thus there is a wide range of heat source which can be applied to the ORC system such as waste heat, solar thermal energy, biomass energy, and geothermal energy, etc.

For solar organic Rankine cycle (SORC), the system cannot operate at low solar radiation then an auxiliary heat is needed. In this study, biomass is a heat source to generate heat through a direct-burnt furnace.

1.2 Literature Review

The literature review is divided into 3 sections. The first section reviews the organic Rankine cycle and working fluid. The second section presents application of solar collector and waste heat with organic Rankine cycle and the last section presents application of biomass energy.

1.2.1 Organic Rankine Cycle and Working Fluid

Saleh et al., 2007 examined and analyzed performance of organic Rankine cycles (ORCs) for geothermal heat recovery. With 31 working fluids and with different types of ORCs, the systems were simulated at a maximum turbine inlet temperature and condensing temperature of 100 and 30 ^{o}C, respectively, and the maximum cycle pressure of 20 bar. The required turbine power was 1 MW. The heat transfer from the heat carrier fluid to the working fluid in the ORC cycle was also described by assuming a maximum temperature of the heat carrier at 120 ^{o}C and the set pinch-point temperature difference (ΔT_{pp}) at 10 ^{o}C. It could be found that R236ca, R245ca, R245fa, R600, R600a, R610a, RE134 and RE245 were suitable working fluid. High thermal efficiency, low volume flow rate at the entrance of the turbine and low turbine outlet/inlet volume flow ratio were obtained. Moreover, with an internal heat exchanger, the thermal efficiency of the cycle could be improved under the same working conditions.

Mago et al., 2008 presented regenerative organic Rankine cycles using dry organic fluids, to convert low-grade heat sources or waste energy to power. Regeneration ORC was analyzed and compared with the basic ORC (without internal heat exchanger). Four dry organic working fluids selected for this investigation were R113, R245ca, R123 and isobutene. For basic and regenerative ORC, the condenser temperature was kept constant at 298 K while keeping the turbine inlet temperature at saturated conditions. The isentropic efficiencies of the turbine and pump were 80 and 85%, respectively. It was shown that the regenerative ORC not only gave higher thermal efficiency than the basic ORC but it needed lower heat input to produce the same power. For both configurations, the fluid with the best thermal efficiency was R113, which had the highest boiling point among the selected fluids, while the worst thermal efficiency came from isobutene, which had the lowest boiling point temperature. Dry organic fluids do not need to be superheated since the cycle thermal efficiency remains approximately constant.

Tchanche et al., 2009 investigated the most suitable working fluid for a low-temperature 2 kW solar organic Rankine cycle (SORC). The system performances such as thermal efficiency including safety and environmental data were evaluated from 20 working fluids. The condensing temperature and the evaporating temperature were 35 and 75 ^{o}C, respectively, while the turbine inlet temperature was at saturated condition. The isentropic turbine efficiency and the turbine mechanical efficiency were 70 and 63%, respectively, and the pump efficiency for all cases was 80%. Hot water serving as heat source at a maximum temperature of 90 ^{o}C produced by a set of solar collectors and the set pinch-point temperature difference (ΔT_{pp}) between the heat source and the ORC evaporator was 6 ^{o}C. It was found that R134a was the most suitable working fluid for low-temperature applications driven by the heat source temperature below 90 ^{o}C. R152a, R600a, R600 and R290 offered attractive performances but these needed safety precautions, owing to their flammability.

Drescher and Bruggemann, 2007 selected fluids for an ORC in biomass power plants. Thermodynamic properties of the working fluid had been evaluated from the database of the Design Institute for Physical Properties, DIPPR (DIPPR, 2004) which included nearly 1800 substances.

Wei et al., 2007 studied performance analysis and optimization of an ORC for waste heat recovery utilizing R245fa as working fluid. The power of ORC system was 100 kW. An exhaust heat from a gas turbine in a range of 610-650 K acted as a heat source for the ORC. R245fa was the working fluid calculated by REFPROP 6.01 (National Institute of Standards and Technology, NIST, 2000).

1.2.2 Use of Solar Collector and Waste Heat as Heat Source for ORC

Wang et al., 2010a reported experiment investigations of a low-temperature solar Rankine cycle system utilizing R245fa as working fluid. The maximum allowable cycle pressure was not over 1.5 MPa. 10 m^2 evacuated-tube solar collectors and 12 m^2 flat-plate solar collectors were used in the experiment system. The experiment was carried out from 11:20 AM to 15:10 PM on October 24th, 2008, a typical sunny day in autumn, in Tianjin, China. Based on these experiment data, the enthalpy values at the different monitoring points could be calculated by REFPROP 8.0. It could be seen that the evacuated-tube solar collector was much more efficient and stable than the flat-plate solar collector due to its higher efficiency. The average collector efficiency of the evacuated-tube solar collector was 71.6%, while the latter was 55.2%. The overall power generation efficiencies were 4.2% and 3.2% for evacuated-tube solar collector and flat-plate solar collector, respectively.

Wang et al., 2010b experimentally tested a low-temperature solar Rankine cycle system with R245fa pure fluid and zeotropic mixtures. The cycle performances with pure fluid M_1 (R245fa) and zeotropic mixtures M_2 (R245fa/R152a, 0.9/0.1) and M_3 (R245fa/R152a, 0.7/0.3) were experimentally studied. The maximum and minimum cycle pressures were 2 and 0.2 MPa, respectively. 0.6 m^2 flat-plate solar collector was used in the experimental prototype. It could be seen that the collector efficiency and thermal efficiency of zeotropic mixtures were higher than those of the pure fluid R245fa. This indicated that the zeotropic mixtures gave potential for over efficiency improvement. The average overall efficiency of M_1, M_2 and M_3 were 0.88, 0.92 and 1.28%, respectively.

Wang et al., 2011 presented an experimental investigation on the low-temperature solar Rankine cycle system using R245fa. A 0.6 m^2 flat-plate solar collector acted as the ORC evaporator. A diaphragm metering pump was used to circulate liquid R245fa. This metering pump could provide a maximum operating pressure of 1 MPa and flow rate could be adjusted up to 6.5 L/h. The enthalpy values at the different monitoring points were calculated by REFPROP 8.0. The experiment was carried out from 8:30 AM to 16:00 PM, on October 15^{th}, 2007, a typical sunny day of fall, in the city of Tianjin of China. It could be seen that the best heat collection efficiency of the flat-plate solar collector for R245fa was found to be around 55% during 12:50-13:50, when the volume flow rate was 2.275 L/h. During the experiment, the time-average Rankine cycle efficiency was found to be 2.8% in the morning and 5.3% in the afternoon, the corresponding net power output was around 10 W.

Wei et al., 2007 studied system performance and optimization of an ORC system using R245fa as working fluid driven by exhaust heat. The properties of the working fluid R245fa were calculated by REFPROP 6.01. The simulation software of the ORC system was validated with the experimental data of a 100 kW ORC system powered by exhaust heat of a gas turbine operating between 610-650 K. It could be seen that the net power output and the efficiency were smoothly and linearly increased with the increase of exhaust flow rate and temperature while those decreased evidently and linearly with the increase of the ambient temperature.

Roy et al., 2010 investigated performance analysis of an ORC using R12, R123 and R134a as working fluids for power generation from waste heat. Flue gas from exhausts of ID fans at 140 ^{o}C and 312 kg/s of 4 power plant units each of 210 MW was heat source. The pinch point, which was the least temperature difference between the working fluid of ORC and the heating flue gas, was 5 ^{o}C. It could be seen that R123 gave the maximum work output and the maximum thermal efficiency among all the selected fluids and the thermal efficiency of 25.30%.

Dai et al., 2009 explored working fluids for ORC with IHE to recover waste heat. The fluids of the cycle were ammonia, butane, isobutene, R11, R123, R141B, R236EA, R245CA, R113 and water. Hot air at 145 ^{o}C, and a mass flow rate of 15.951 kg/s was a heat source at the ORC evaporator. The pinch temperature difference in the evaporator was assumed to be 8 ^{o}C and the thermodynamics properties of the working fluid were calculated from REFPROP 6.01.

Chen et al., 2006 studied performance of a CO_2 transcritical power cycle compared with an ORC using R123 as working fluid. Both cycles took exhaust gas at a temperature of 150 ^{o}C with a mass flow rate of 0.4 kg/s as a heat source. The pinch point, which was the least temperature difference between the working fluid of ORC and the exhaust gas was 10 ^{o}C.

1.2.3 Application of Biomass Energy

Pui-ock et al., 2007 studied a potential of agriculture residue (biomass) in Thailand for electricity generation. Five types of biomass, fuel wood, paddy husk, cassava root, bagasse and shell oil palm, were energy sources for power generation. It could be seen that in 2007 and 2011, the agriculture residue potential for electricity generation were approximately 2000 and 3000 MW, respectively.

Sasujid et al., 2007 studied an application of biomass energy for box-type Longan drying. A biomass furnace was a cylinder having an inner diameter of 0.77 meter and height of 2.40 meter. Air and rice husk entered the combustion chamber in tangential direction with vortex rotation. Experiment results showed that the thermal efficiency of the rice husk cyclonic furnace was about 70% at a rice husk feed rates of 53.8 kg/h. The temperature of flue gas released from the combustion chamber was approximately 450 ^{o}C. After that it that was led to a cyclonic filter and blended with a fresh air to a suitable temperature for drying.

Wannagosit and Charoensawan, 2009 presented thermal performance modeling of a hybrid water heater having evacuated-tube solar collector and flue gas from rice husk combustion. The combustion gas of rice husk at around 20 kg/h and the efficiency of 75% after cyclone filtration at a gas temperature and flow rate were constant at 150 ^{o}C and 50 m^3/min, respectively was used as an auxiliary heat.

For Thailand, as notified in the previous studies, it could be seen that there was a high potential to generate power through an ORC with heat sources from solar thermal energy and biomass. In this study, solar energy from flat-plate and evacuated-tube solar collectors was taken as a heat source for ORC. Selection of working fluid in the cycle was also found out. Biomass, rice husk and wood chips, was direct burnt to generate exhaust gas as an auxiliary heat when the solar radiation level was not high enough. CO_2 emission at various ratio of solar energy and biomass energy was also investigated.

1.3 Objective of the Present Study

1.3.1 To study the effects of working fluid types and evaporating temperature to thermal efficiency of ORC for electricity generation.

1.3.2 To develop a mathematical model to evaluate an ORC performance on power generation with hybrid solar and biomass energy.

1.3.3 To evaluate the levelized electricity cost of an ORC with hybrid solar collector and biomass energy including CO_2 emissions from the system.

1.4 Scope of the Study

1.4.1 Flat-plate and evacuated-tube solar collector were used in simulation.

1.4.2 ORC capacity was not over 280 kW_e.

1.4.3 Evaporating temperature was between 75-135 ^{o}C.

1.4.4 The parameters of this study to find the efficiency and levelized electricity cost of an ORC were the ORC evaporating temperature and the solar collector area.

1.4.5 The weather data of the northern, the central, the northeastern and the southern parts in Thailand were taken as the input information for the simulation.

1.4.6 Rice husk and wood were biomass used in the simulation.

1.4.7 For experiment, the solar water heater system with evacuated-tube was investigated to find out the temperature of hot water for supplying to the ORC. The results were compared with those from the experiments.

1.5 Benefit of the Study

1.5.1 A new concept in using hybrid solar and biomass energy with ORC for power generation was presented.

1.5.2 Levelized electricity cost of an ORC with hybrid solar and biomass energy could be investigated including the CO_2 emissions evaluation.

1.6 Keywords

Organic Rankine cycle, Solar collector, Biomass, Power generation, Levelized electricity cost