CHAPTER 1

Introduction

1.1 Statement and Significant of the Problem

In recent years, the world energy demand has been increasing steadily and more demand continuing to the future. The International Energy Agency (EIA) predicted for the incoming 13 years (2030), the global energy demand increase corresponds to two thirds of current primary energy demand which was 9,179 Mtoe and fossil fuels will still account for the largest part of the energy demand. The demand is growing up by 2.4% per year and that most of the new power generating capacity will be Natural gas-fired combined cycles. Therefore, it is important to find improved technologies for power generation with high efficiencies, high specific power outputs, low emissions of pollutants, low cost of investment, operating and maintenance for a sustainable use of available fuels. (Chaitep *et al.*, 2006)

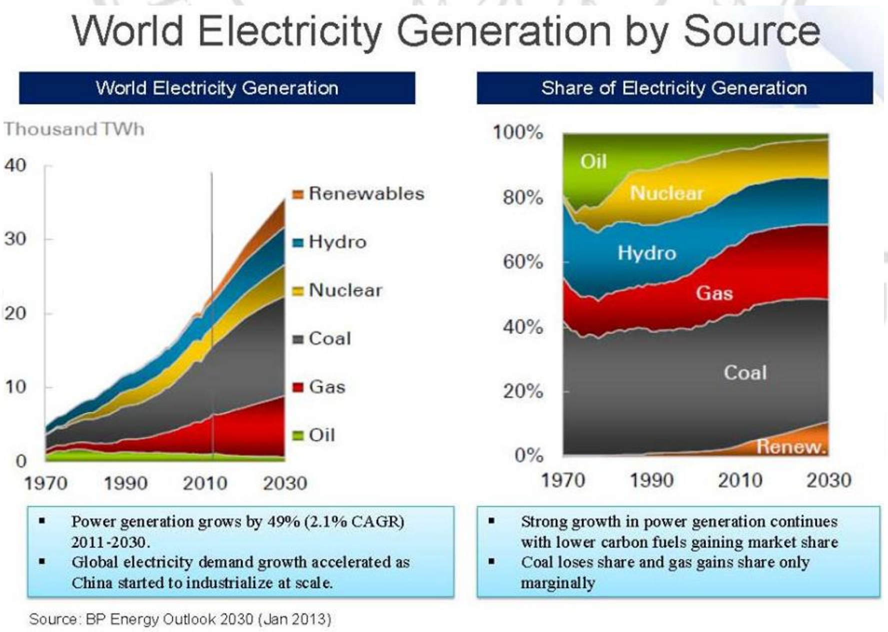

Figure 1.1: World marketed energy consumption: 1980 – 2030

(BP's Energy Outlook, 2013)

Alternative energy conversion technologies are required to utilize energy resources suitable for power generation without causing environmental pollution, such as atmospheric pollution, global warming, and ozone destruction. Low-temperature heat sources are considered as candidates for the new energy sources. Waste heat, solar thermal and geothermal energy are typical examples for low-temperature heat sources with their available temperatures ranging between 50 – 250°C. The use of such low-temperature heat sources as an alternative energy source to generate electricity has long been investigated using organic Rankine cycles (Yamamoto *et al*., 2001). The exhaust heat from most industrial sources and electrical power plants are less than 400^{o}C. If this kind of waste heat is let into the environment directly, it would not only a waste but also cause heat pollution to the environment (Ziapour, 2009).

Figure 1.2(a): Geothermal

Figure 1.2(b): Industrials waste heat

Figure 1.2(c): Solar energy

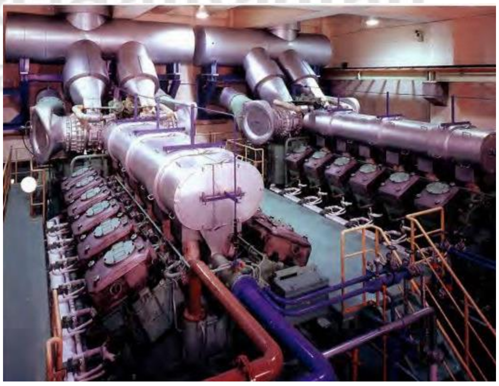

Figure 1.2(d): Exhaust gas engine

Figure 1.2: Low–temperature heat sources (Thirunavukarasu, 1997).

Low-temperature heat sources that between 80 – 200°C in the industrial waste heat stream, solar heat trapped by collectors with low to medium ratios of concentration, low-temperature geothermal sources, and cooling water streams of stationary engines are some of the sources that have been proposed which can effectively used in organic Rankine cycle (ORC), as shown in Figure 1.2.

The ORC system shows great flexibility, high safety, and low maintenance requirements in recovering waste heat. Integrating the ORC to the energy system, such as power plants, could achieve using low-temperature heat source to generate electricity, easing the power burden, and enhancing system efficiency (Wei *et al*., 2007). Since the ORC consumes virtually no additional fuel, for the same added power, the emission of environmental pollutants such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and so on will be decreased.

This application system is an appealing option for remote areas, low power applications. One of the main advantages of ORC lies in mechanical simplicity. As mentioned before, ORC typically consist of a single stage expander which consists of a single rotating component for the entire system. For the past several decades, thousands of ORC have been developed and used for remote terrestrial applications with power outputs ranging from 1 kW to 1 MW. A few examples of remote applications that have used efficient, reliable, unattended ORC power sources include communication stations, data gathering buoys, satellite communication power supplies, as well as irrigation pumps, air conditioners, and turbo–generators (Somayaji., 2008).

1.2 Potential of Low-Temperature Heat Source

The low-temperature heat sources are 4 main categories of applications are conceivable for the ORC or more generally for the low-temperature Rankine cycle.

1.2.1 Combined Heat and Power (CHP) Plants

Where the ORC is most useful is in the recovery and use of waste heat. Two primary applications include combined heat and power (CHP) plants and general heat recovery applications from many potential sources. A combined heat and power plant can for example be a small scale cogeneration plant on a domestic water heater. In this perspective, two options are conceivable: the priority can be given to the power cycle, the latter recovering the heat produced directly in the boiler and the hot water being produced at the condenser of the ORC at a lower temperature, or the priority can be given to the hot water, in which case the heat source of the cycle is the heat recovered on the gases at the exhaust of the combustion chamber. Heat recovery can also be performed on industrial or farming processes such as organic products fermentation, hot exhausts from ovens or kilns, exhaust gases from vehicles, inter-cooling of a compressor, condenser of a power cycle, etc (Dong *et al*, 2009)..

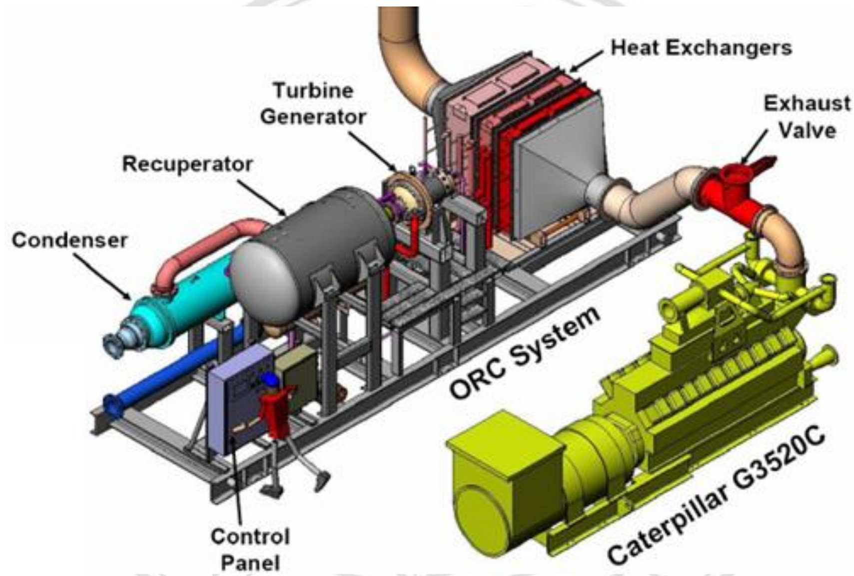

Figure 1.3: Power generated from internal combustion engine heat rejected (Thirunavukarasu, 1997).

1.2.2 Solar Thermal Power Plant

An ORC can be used in the solar parabolic through technology instead of the usual steam Rankine cycle. The ORC allows a lower collector temperature, a better collecting efficiency and hence the possibility of reducing the size of the solar fields. Several examples of parabolic troughs using ORC are available in the literature: S. Canada (2005) presented a parabolic trough ORC solar power plant, using n-pentane as working fluid and with an inlet temperature of 204°C and Kane (2002), studied the integration of two superposed ORC on a parabolic though solar collector, the topping cycle using CFC-123 as working fluid, and the bottoming cycle using HFC-134a.

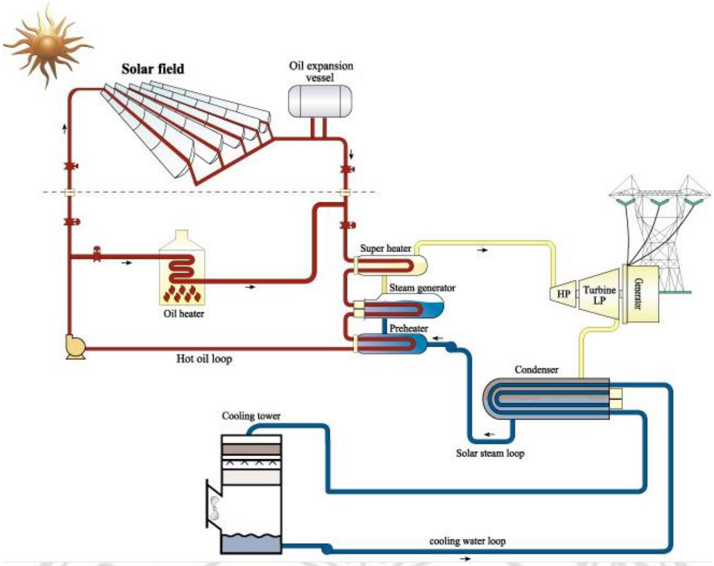

Figure 1.4: Solar power plants for electric generating (García-Rodríguez *et al*, 2007)

1.2.3 Biomass Power Plant

The biomass is the term used to describe all the organic matter produce photosynthesis that exists on the Earth. The prime source of all energy in biomass is the sun, the biomass acting as a kind of chemical energy store. Biomass is constantly undergoing a complex series of physical and chemical transformations and being regenerated while giving off energy in the form of heat to the atmosphere. For millennia, direct combustion is in the simplest form of an open fire used to provide heat for cooking, heating water or heating the air in a home. More sophisticated technologies also exist for extracting biomass energy and converting it into useful heat or power in an efficient way (Hattiangadi, 2013 and Drescher *et al*, 2007).

The biomass fuel ORC have advantages: low-temperature and low-pressure levels, higher plant performance in comparison to pure heat production, higher electrical efficiency, small space required, higher cost effectiveness, and good partial load behavior. Small scale turbines for organic working fluids are well developed and optimized with respect to their efficiency. This increase in efficiency increases the electricity production in comparison to conventional steam turbines. Waste heat is another energy source that can be converted to useful energy by using expanders in an ORC system. Potential heat sources include: tail gas from industrial furnaces or combustion engines, waste vapor from chemical and petrochemical processes, and solar heat from flat or parabolic reflectors and collectors.

1.2.4 Geothermal Power Plant

Geothermal source vary in temperature from 50 – 350°C. For low-temperature geothermal sources, the power plant efficiency is very dependent on the ambient temperature that determinates the heat sink temperature.

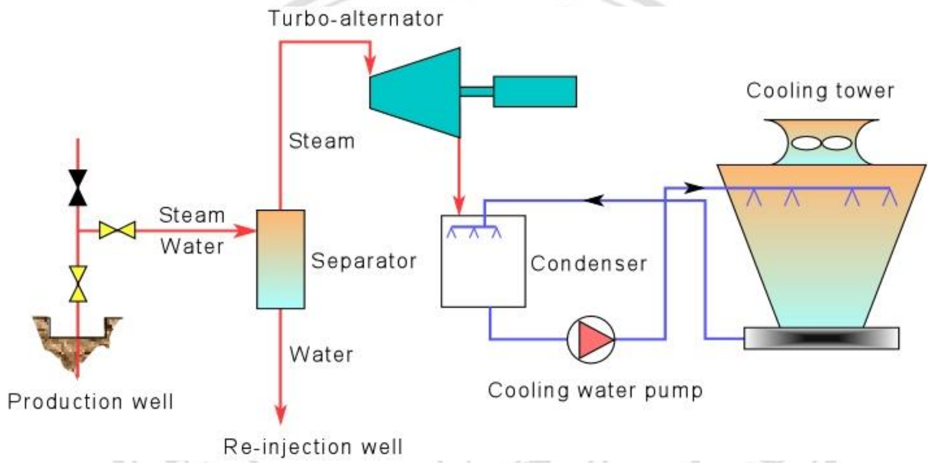

Figure 1.5: Geothermal electric generation diagram (http://www.pre.ethz.ch/research/projects/?id=powersol, 2007)

A large amount of energy in the form of medium to low-temperature gases or low-temperature liquids less than about 250°C is released from process heating equipment, and much of this energy is wasted.

Conversion of low-temperature exhaust waste heat, the making efficient use of the low-temperature waste heat generated by prime movers such as turbines, internal combustion engines, fuel cells and other electricity producing technologies. The energy content of the waste heat must be high enough to be able to operate equipment found in cogeneration and tri-generation power and energy systems such as absorption chillers, refrigeration applications, heat amplifiers, dehumidifiers, heat pumps for hot water, turbine inlet air cooling, and other similar devices.

The steam Rankine cycle is the principle method used for producing electric power from high temperature fluid streams. For the conversion of low-temperature heat into the power, the steam Rankine cycle may be a possibility, along with other power cycles, such as the ORC. Most alternative thermal energy is found at a temperature below that of boiling water at below 100^{o}C. Solar energy is most economically collected at 40 – 65^{o}C; a geothermal temperature of 70^{o}C exists only 200 feet underground and industrial waste heat is most prevalent at temperatures between 60 - 120^{o}C (Somayaji et al., 2008).

1.3 Literature Reviews

1.3.1 ORC System for Low Temperature Heat Sources Studied

Gurgenci *et al*., (1986) suggested the limitation on the properties applies to both working fluids and the heat sources. Low-temperature heat source between 50 – 250°C as in the industrial waste heat stream, solar heat trapped by the collectors with low to medium ratios of concentration, low-temperature geothermal sources, and cooling water streams of stationary engines are some of the sources which can be effectively used in ORC. The amount of heat energy that can be extracted depends on the waste steam temperature and on the temperature of the cooling medium. The main advantage of the ORC is its superior ability in recovering waste heat with low to medium temperature. On the negative side, the temperature range limits the available heat sources dramatically.

Hung *et al*., (2001) and Lee *et al*., (1996) studied typically solar and geothermal sources which are usually available at low-temperature make up to 80% of the ORC heat source (Hung *et al*., 2001). The effect of the temperature of the heat source was also provided by (Lee *et al*., 1996) in their investigation. They performed a system parametric analysis on an ORC using CFC-113 as working fluid and proved that the recovery of low temperature, low pressure waste steam by an ORC provided a high potential for moderate capacity plants. They also indicated that the effects of the condensing and vaporizing temperatures on the system’s economic feasibility were significant.

Niggeman *et al*., (1978) studied of low-temperature heat sources have 50% of the total heat generated in the industry. The recovery of the waste heat energy of different sources has been examined by many researchers. An ORC system combined with a space nuclear reactor in order to achieve higher efficiency. Hung *et al*., 1996 studies have also taken place to recover waste heat at temperatures around 370 – 538^{o}C in the chimney of a furnace. Utilization of heat rejected from a condenser was examined by Angelino *et al*., (2000) who concluded that a combined cycle with an ORC system as a bottoming cycle that utilizes the waste heat at a temperature greater than 200°C from the condenser has a return of investment less than conventional cycles. Some typical industrial waste heat sources are hot gases from blast furnaces in steel industry, exhaust gases of gas turbine and diesel engines, hot gases from kilns in ceramic industry and hot liquids in paper and pulp industry (Larjola *et al*., 1995).

The thermodynamic modeling of a binary cycle with geothermal energy being used as the heat source was also investigated (Kohler *et al*., 2003). The possibility of using low-temperature, liquid-dominated geothermal sources was explored (Desidiri *et al*., 1997). The scope for optimization of the performance, by modifying the main parameters such as turbine inlet pressure and type of fluid being used was also studied. Much research work has been done on the parameters analysis on an ORC energy recovery system. Thermodynamic analysis, economic evaluation, sensitivity analysis, and economic design parameters study is widely covered (Yamamoto *et al*., 2001).

1.3.2 Working Fluid for Low Temperature Heat Sources Studied

The working fluid is an important part of Rankine cycle. Thermodynamics properties of the working fluids are key parameter for modeling of the system (Kohler *et al*., 2003). In order to get the maximum required properties out of a refrigerant, the refrigerant should satisfy some very important requirements. For ORC applications, flammable compounds could be employed if appropriate safety measures are permitted. Working fluids which are phased out are neglected owing to their high ozone depletion potential (Angelino *et al*., 1998). Also there are some general criteria (Vijayaraghavan *et al*., 2005) like stability of the fluid, non-fouling nature; non-corrosiveness etc. to improve the heat transfer characteristics, the thermal conductivity of the selected refrigerants has to be high. The latent heat of vaporization should be high which means a smaller flow rate is required for a similar output from the plant. The liquid specific heat should be high meaning that less preheating is required (Vijayaraghavan *et al*., 2005).

Vlaminck *et al*., (1990) studied substance instead of water using readily available property evaluation tools like REFPROP, simple software which is custom made based on the requirements can also be used. A similar attempt was made by Vlaminck *et al*., (1990) in which, the best available equations of state, equations of vapor pressure and the correlations for the prediction of the various properties were used, and software was developed. This software predicts all customary thermodynamic quantities with only a relatively small number of physical parameters of the fluid. As in the choice of the properties of the working fluids, the type of working fluids is also important. The Rankine cycle can be modeled effectively using software like Cycle Tempo, REFPROP, and HYSYS. Yamamoto *et al*., (2001) has offered that, in order to determine the optimum operating conditions, carried out a thermodynamic analysis of an ORC using a process simulator called HYSYS. This simulator is useful for thermodynamic analysis, especially at steady-state conditions. The simulator requires conditions like heat input, turbine inlet and outlet pressure.

Drescher (2007) referred that, in contrast to water, the expansion of an organic working fluid in a turbine ends in the dry state rather than in the wet state. He also points out that organic working fluids are more useful when the maximum available temperature is low and the size of the power plant is relatively small. Although less thermodynamically efficient than the Carnot cycle, the Rankine cycles is practical and adaptable. The Rankine cycles utilizing the organic fluids tend to give higher thermal efficiency compared with water. Maizza *et al*., (2001) reported that the fluid thermodynamic characteristics give rise to thermodynamic limitations to the amount of energy that can be extracted from the heat source. Some refrigerants satisfy the above mentioned criteria more than the others. One such refrigerant is HFC-245fa. An application development guide released by Honeywell gives some of the properties of Genetron-245fa and also some of the applications of this refrigerant as the working fluid (Honeywell, 2000). Somayaji *et al*., (2006) and Mago *et al*., (2006) presented an analysis of the performance of ORC using CFC-113 and HFC-134a in which the use of organic fluids to generate power using low-temperature waste heat was studied. They have also shown that organic fluids must be operated at saturated conditions to reduce the total irreversibility of the system. Liu *et al*, (2002) reported performed a simulation on an ORC with various working fluids for a hot temperature of 150^{o}C and a cold temperature of 30°C. It turned out in this simulation that CFC-123 had a slightly better efficiency than iso-pentane. HFC-245fa and n-pentane were not taken into account in that study. Lemort, (2007) compared three working fluids on an ORC application (hot side temperature 130°C and cold side temperature 30°C). The three working fluids were CFC-123, HFC-245fa, HFC-134a, and n-pentane. The calculated efficiencies were 9.71, 9.30, 7.86, and 9.74% respectively. Madhawa, (2007) simulated a geothermal ORC with a hot source temperature of 70 – 90°C, a temperature difference ranging from 40 – 60°C and various working fluids. Among those working fluids, CFC-123 and n-pentane outperformed the other fluids with a higher efficiency of 9.8 and 9.9% respectively.

Hung *et al*., (2001) analyzed of system thermal performance also involves thermodynamic optimization of the system. Thermodynamic optimization is the determination and minimization of the thermodynamic factors causing the decrease in efficiency. Irreversibility in a real life thermodynamic system usually leads to inefficient conversion of all the available thermal energy into useful work. From the first and second laws of thermodynamics, we find the efficiency of an ORC can be obtained under various working conditions for a specific working fluid. They conclude in their paper that when the associated state is a saturated vapor, the system thermal efficiency is commonly increased with respect to greater turbine inlet pressure which leads to less irreversibility when the temperature of the source is fixed. When the temperature difference in the evaporator is fixed, higher turbine inlet pressure leads to larger irreversibility. In general they say that the waste heat boiler is a key component to cause irreversibility. The second law efficiency is the indicator for the amount of irreversibility in a system.

Hung *et al*., (1997) studied in their work have done parametric analysis and compared the efficiencies and irreversibility of the ORC using various working fluids such as Benzene, Toluene, P-Xylene, CFC-123, and CFC-113. A 10 MW waste heat source was employed for this purpose. A computer program was developed to simulate the performance of the working fluids under various working conditions. The thermodynamic properties of the fluids were calculated using Peng-Robinson equations. They found that when the associated state is a saturated vapor, the system thermal efficiency would increase with turbine inlet pressure. When the temperature difference in the vapor generator is fixed, higher turbine inlet pressure leads to larger irreversibility.

Somayaji *et al*., (2006) showed that ORC using dry fluids have better performance than ORC using wet fluids.

Chinese *et al*., (2004) studied the diffuse introduction for biomass based power generation in an industrial district has been studied which can improve system efficiency and also at the same time reduce the emissions. They investigated the impact of the introduction of ORC units in an industrial context from a system perspective. With particular reference to industrial districts, which are characterized by the concentration in small areas of a large number of medium and small size firms, to this end, a mixed-integer, linear programming model oriented to economical optimization of the system is developed and a sensitivity analysis is carried out in order to determine the condition for the expansion of biomass based power generation and to evaluate potential CO_2 emissions.

Angelino *et al*., (1998) investigated method the potential role of bottoming ORC in steam power plant stations was studied to reduce emissions and improve system efficiency. A method proposed by which a fraction of the low pressure steam is extracted. This is fed to an auxiliary ORC module of small capacity. This auxiliary ORC module besides being perfectly suited to explore even the coldest cooling agent, improved the working condition of the main turbine by reducing the exhaust volume. With the help of a computer programming, the performance of a typical power station supplemented with an ORC system was analyzed for different cooling situations. In this investigation, attention was focused on turbine optimization.

This research of “Characterization of low pressure micro-turbine using low-temperature heat source” is initiated from the concept of thermodynamics into power generating by turbine with low-temperature heat source into a vaporize working fluid and use its vapor to drive turbine. This method of vapor generating provides good performance when using proper heat ratio of turbine stage. The superheated vapor of working fluid is used in turbine driving as a heat source for power plant. In order to design this system to vapor production by simple Rankine cycle to generate the power.

1.4 Objective of the Study

1.4.1 To design, construct and test a laboratory scale of micro-turbine which is impulse radial type operating under low-pressure and low-temperature.

1.4.2 To investigate the effects of pressure, temperature, torque, and power output of the turbine.

1.4.3 To develop a numerical model to the optimize performance.

1.5 Scope of the Study

1.5.1 This system is based on the ideal Rankine cycle with HCFC-141b (1,1-Dichloro-1-fluoroethane) refrigerant as a working fluid in the experiment.

1.5.2 The micro power turbine to be used in the experiment is radial flow type.

1.5.3 The numerical and experiment analysis to optimize the system performance and operate at temperature of 70–100°C and atmospheric pressure.

1.5.4 The experimental data is used for verifying the numerical model

1.6 Benefit of the Study

1.6.1 The new contribution of this research is the energy production from small size of power generator at low-temperature heat sources.

1.6.2 This research is conducted to utilize low-temperature heat sources and converted to power generation to ensure sufficient electricity production.

1.6.3 This research is a new developed system which is simpler to design, operate, and conduct to micro power generation technology group and sustainable development.

1.6.4 To gain a prototype model of small vapor turbine this can modify and develop continuously in any part of system. Furthermore, to increase the operation efficiency and lead to low-temperature heat source usage.

1.7 Research Location

This research was studied on the Propulsion and Aerodynamics Research and Application Laboratory (PARA Laboratories) in the Mechanical Engineering Department, Faculty of Engineering, Chiang Mai University, Thailand.