

CHAPTER I

INTRODUCTION

1.1 Statement and significance of the problem

The economic reality of Thailand's production in all sectors is very much steered by energy efficiency because of the limitation of energy resources. Temporal variation of energy consumption in the form electricity or heat follows increasing trend as it is the case in other parts of the world (Figure 1.1). Hence energy is a crucial factor in the development of the country as well as the quality of life of the people. Thai government has formulated a policy to promote efficient use of energy and the use of heat recovery as waste heat to ensure energy conservation so that it is sufficient to meet the demand of the country.

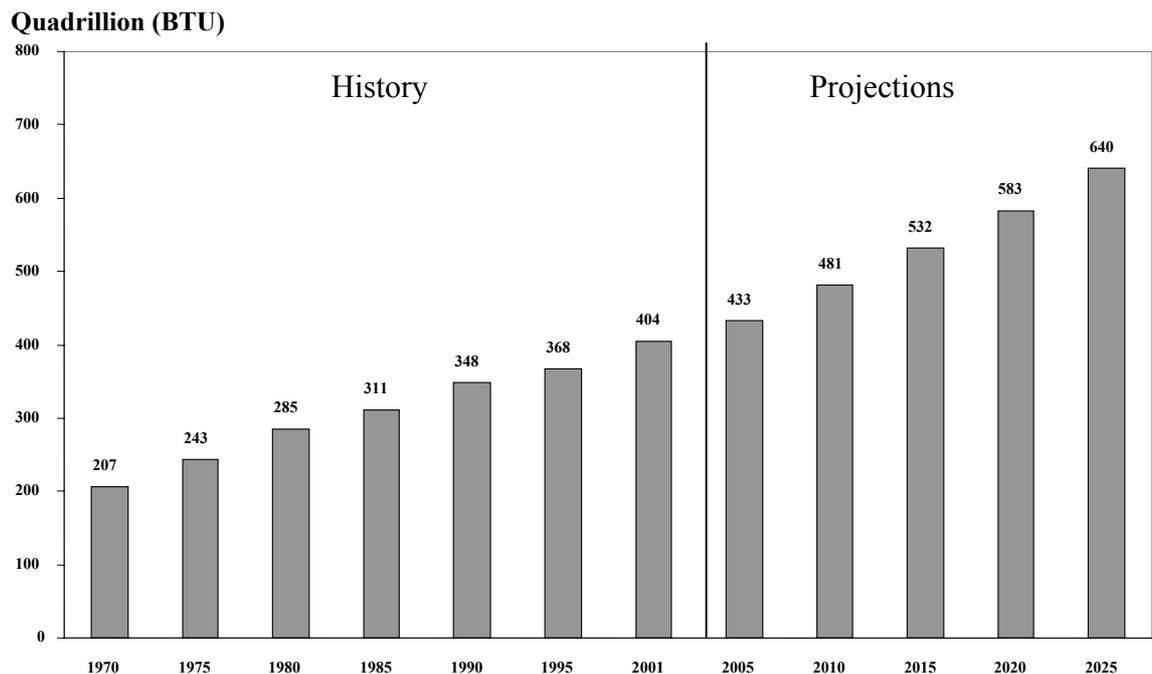


Figure 1.1: World energy consumption, 1970-2025
(International energy outlook, 2002)

The energy demand of Thailand is shown in Table 1.1. The final energy demand by fuel type is also presented in Business As Usual (BAU).

Table 1.1: Final energy demand in the BAU case, Unit: Mtoe (NEPO, 2001)

Sectors	1995	2000	2005	2015	2025
Transport	18.8	21.3	26.2	40.7	64.7
Residential	10.3	12.7	14.3	17.0	19.8
Industrial	16.0	17.6	23.9	39.6	65.3
Agricultural	1.6	1.8	1.9	2.5	3.5
Commercial	2.1	2.3	2.7	3.9	5.7
Total	48.7	55.7	68.9	103.6	158.9

The government is forced to take the leadership role in promoting heat recovery energy technology development and the use of waste heat while allocating funding for research and development of energy conservation technologies. Conservation technologies include both increased efficiency and improved procedural methods. To save or reduce energy use, one way is to consider waste heat recovery wherever it is possible. One of the most efficient systems in use today is heat exchanger. The heat exchangers that are most commonly applied in industrial use can be divided into many types such as a recuperative heat exchanger, heat pump heat exchanger, regenerative heat exchanger, etc.

Drying is one of the most energy intensive unit operations in food industry. In many applications of drying, dehydration is one of the oldest and most widely used methods of food preservation. In tropical countries, the existing dehydration techniques involve solar and hot air drying methods. Solar drying is now considered, but it generally requires longer drying time. On the other hand, conventional hot air drying involves higher drying temperatures. Drying at high temperatures may cause thermal injury leading to inferior product quality. Both methods have failed to effectively produce good quality product due primarily to the limitation of drying air having an inherent lower capacity to remove moisture. This limitation has led to the idea of development of a low relative humidity dehydration system.

Longan is an important economic fruit for Thailand and the country has one of the most extensive longan production and marketing industries in the world. The export of longan amounts to 114 500 tons (3 651 million Baht) each year (Office of Agricultural Economics, 2002). The structure of longan market has three sources of product consumption. These are fresh consumption in the country about 30%, export of fresh longan about 20%, export of dried longan about 40% and canned longan about 10%. Dried longan production is considerably large with a value of about 45 800 tons (1460 million Baht) and it is rising. The marketing supply for longans in Thailand is very unstable, resulting in fluctuations in market price (Klongpanich, 1991). To stabilize market price, different methods of value addition are important. Drying allows for longer preservation of longan, enabling its ability to possibly capture better market prices. Furthermore, the volume and the weight of longan are reduced leading to lower storage and transportation costs. In longan drying, hot gas from the combustion of fuel (usually natural gas) in the burner is passed through the drying bed. The size of conventional longan dryers in northern Thailand usually measures $2.35 \times 2.35 \times 0.96 \text{ m}^3$. The dryer contains one large tray to handle 2,000 kg of longan fruit for each batch. The air (80°C , velocity of 1.0 m/s) will remove moisture as it pass through the bed (Klongpanich, 1991). In most practices, the exhaust air will be directly released to the ambient air. Recovering the waste heat from exhaust gas can be a creative method as for as energy savings is considered.

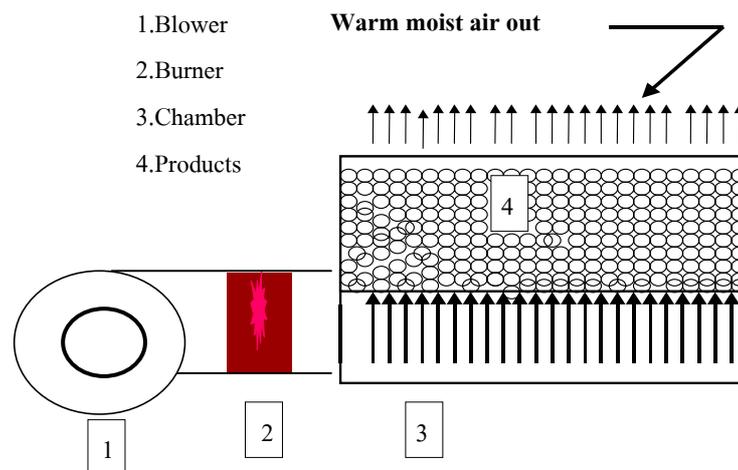


Figure 1.2 Conventional Dryer

Energy availability is a major problem in production sector of Thailand. Furthermore, conventional hot air drying may cause thermal injury leading to inferior product quality. The combination of lower drying temperature, recycling of waste heat, and decreasing the inlet relative humidity of the inlet air can lead to a better drying system, with the possibility of lower energy consumption, better product quality, or both (Achariyaviriya *et al.*, 2000). A drying system with a heat pump is worthy of consideration in an attempt to achieve these goals. It can simultaneously raise the temperature and lower the humidity from that of the waste heat stream. Heat pump have been shown to be energy efficient when used in the drying operations (Jolly *et al.*, 1990). The condenser of the heat pump releases heat to the inlet air and increases its temperature. A heater (or burner) could be used to further increase the air temperature as required to maintain the target inlet temperature. After passing through the drying bed, some of the exhaust air will be drawn through the evaporator, where moisture will be removed from the air. The air can either be sent directly back to the condenser or mixed with a portion of fresh air prior to recirculation. By using this method, the drying quality of the inlet air can be increased. In this work, this system will be referred to as a heat pump dryer (HPD).

Heat pipes are devices with very high thermal conductance (Dunn and Reay, 1982). The heat pipe employs evaporating and condensing process of working fluid. Generally, it is a closed end pipe, which comprises of an air-evacuated hollow tube and some amount of working fluid sealed within the tube. A loop thermosyphon (LTS) is a type of heat pipe, which operates under gravitational force. It can be divided into three sections: i) evaporator, ii) condenser, iii) adiabatic pipe connecting evaporator and condenser section, the working fluid will be evaporated and rapidly moves to the condenser section. The vapor condenses and the condensate returns to the evaporator section by gravity through the connection of pipes, which are set at some inclination. The LTS is an effective method to transfer heat by means of the use concept of latent heat of evaporation and condensation. The applications of the loop thermosyphon in the heat pump dryer is through transfer of heat from the hot air in the evaporator section of LTS before entering the evaporator of heat pump and exit the evaporator of heat pump dryer after losing moisture. These are pre-cool and reheat processes. So, the heat pump with the LTS has potential to reduce energy consumption when compared to the conventional heat pump dryer. In order to

alleviate some of the energy requirement for the HPD, LTS has been introduced into a drying system (Terdtoon *et al.*, 1999).

A mathematical simulation of fruit drying with heat pump assisted continuous dryer has been studied to investigate the effect on the specific energy consumption and the performance of heat pump (Jolly et al. 1990, Jai et al, 1990, Prasertsan et al. 1996). It was found that drying air temperature, recirculation air ratio (RAR), by-pass air ratio (BAR), airflow rate, all influenced the performance of HPD, quantified by the specific energy consumption (SEC, the energy use per water remove from product). Thermal effectiveness of a LTS was studied in air preheating by using a loop thermosyphon as one way of the energy reduction method in longan drying (Terdtoon et al. 1999). Based on a thermal effectiveness of 0.34 from laboratory tests, they concluded that the pre-heater unit was suitable for industrial scale application.

Based on the previous research and before commercial application, LTS with HPD need to be further studied. This study will be focusing on the application of the LTS as an energy saver for a heat pump dryer.

1.2 Literature Review

1.2.1 Drying

Drying is removal of moisture to safe moisture content and dehydration refers to the removal of moisture in liquid form. Generally, drying is defined as the removal of moisture by the application of heat and drying is practiced to maintain the quality of fruits during storage by preventing the growth of bacteria, fungi and the development of insects and mites. The safe moisture content of fruits is usually under 15 % moisture on a wet basis. Heat is normally supplied to the fruits by heated air, by natural means or artificially and the vapor pressure or concentration gradient thus created causes the movement of moisture from inside to the surface. The moisture is evaporated and transported by the air. Drying rate depends on drying air temperature, moisture content of the products, the relationship between the moisture content of the products and the relative humidity of the drying air, product type and maturity. There are two methods for expressing moisture content, viz., wet basis and dry basis. Moisture content on a wet basis is expressed as the ratio of mass of water present to

the total mass of the material. Moisture content on a dry basis is expressed as the ratio of mass of water present to the bone dried material. The equilibrium moisture content (M_{eq}) of any material is defined as the moisture content of the material after it has been exposed to a particular environment for an infinitely long period of time. The M_{eq} is dependent upon the relative humidity and temperature conditions of the environment as well as on the species, variety and maturity of fruits or food products. The relationship between the moisture content of any material and its equilibrium relative humidity and temperature can be expressed by mathematical equation. For whole longan (Vongnichakul, 1997) developed from Oswin model and can be used for drying whole longan. Longan is one of the major cash crops that bring significant income to farmers in the Northern part of Thailand. The Ministry of Agriculture and Cooperatives has selected this as one of the nine cash crops in Thailand planned for export promotions. The information provided by National Statistical office shows that, longan is exported for over 13.5 Billion Bahts per year (Suadee, 1998).

1.2.2 Heat Pump

The performance of an experimental heat-pump dryer under operating condition is of some practical interest and it has been reported by Pendyala *et al.* (1990). The system was operated using R-11 and R-12. The approach velocity of air to the evaporator and the superheat of the working fluid at the exit of the evaporator were identified as the critical parameters for optimization. The system was evaluated with respect to coefficient of performance (COP) and specific energy consumption (SEC). The (COP) and (SEC) values obtained using R-11 were 3.5 and 3500 kJ/kg, respectively, and the corresponding values for R-12 were 2.5 and 1800 kJ/kg. In spite of the lower (COP) for R-12, the corresponding (SEC) values were better because the system could be operated without any additional electrical heating with the use of R-12. The R-22 heat pump dryer characteristics were studied by Prasertsan *et al.* (1996), for both open and closed system using a computer simulation technique. The cooling capacity was 11.4 kW. Two layers of wet clothes simulated the drying load in the dryer. Each layer consisted of 15 sheets of 41 x 65 cm². The airflow rate was 0.23 kg/s. The maximum working air temperature was 70°C. In closed cycle, the energy consumption was 0.837 – 1.135 MJ/kg or specific moisture extraction rate (SMER) was about 3.2 – 4.3 kg/kW-h which depended on the ambient condition and the

recirculation air ratio (RAR). While in open cycle, the energy consumption was 0.960 to 1.384 MJ/kg or specific moisture extraction rate (SMER) of about 2.6 to 3.7 kg/kW-h. In comparison, the closed cycle tended towards better performance than the open cycle depending on the ambient condition and RAR. From the results, it was obvious that the RAR influenced the closed cycle system performance. Higher RAR resulted in higher moisture content in the working air, and less latent heat was removed at the evaporator (because of relatively high air temperature at high recirculation air ratio), thus higher relative humidity air entering the dryer, consequently lowered the system performance. Simulation of R-22 heat pump assisted continuous dryer was studied with air mass flow rate of about 0.2 – 0.6 kg/hr by Jia *et al.* (1990). The system was a closed cycle. In this study, the energy consumption was 0.900 to 1.280 MJ/kg or specific moisture extraction rate (SMER) of 2.8 – 4.0 kg/kW-hr depending on the air mass flow rate. The influence of recirculation air ratio (RAR) on the performance of the heat pump dryer was investigated. When less warm air was vented, the system operating temperature rose and also the temperature between the condensing and evaporating temperatures increased, thus reducing the coefficient of performance (COP) of the heat pump. From the results, 10% reduction of vented warm air could increase SMER by 15% and product throughput by 50%. Clements *et al.* (1993) studied R-22 heat pump assisted continuous dryer with an air flow rate of 0.2 to 0.6 kg/hr in a closed system. The drying load in the dryer was a set of foam rubber blocks of about 40x40x 30 mm. The throughput of the dryer was about 20 kg/h. The maximum working air temperature was 70°C. In this study, the energy consumption was 1.440 to 2.400 MJ/kg or specific moisture extraction rate (SMER) of 1.5 to 2.5 kg/kW-h. From the results, they suggested that a heat pump dryer for constant drying should be designed to operate in two modes. In winter, the dryer should operate as a closed system to keep energy within the system and in summer the open system was suggested. Prasertsan *et al.* (1996) added that the system performance would depend on the dryer type and the dryer efficiency as well. If the dryer efficiency were substantially lower, the closed system would be better than the open system because the low humidity air was recirculated in the system instead of venting off. Achariyaviriya *et al.* (2000) studied mathematical model of a heat pump fruit dryer. Using the experimental data of papaya glaze moisture content, the model was verified. It was found that ambient condition, the specific airflow rate, the recirculation air ratio and the by-pass air ratio affected markedly the performance of

all heat pump dryers. The optimization results of drying papaya glaze of 100 kg-initial mass are; drying air temperature of 56 °C, airflow rate of 1000 kg-dry air/h, the bypass air ratio of 70 to 80%, the recirculation air ratio of 80 to 100% and heat transfer area of condenser of 4 m².

1.2.3 Loop Thermosyphon (LTS)

Two novel applications of heat pipes in air conditioning systems, which enhanced dehumidification capabilities and dramatically reduced operating costs were studied by Beckwith (1996). Variation of one of the systems was used to save energy by providing heat recovery between exhaust and make-up air streams of a building, and for better comfort control free terminal reheat was provided in individual zones within a building. The Controllable Wrap-Around Heat Pipe transfers heat out of the air entering a cooling coil to pre-cool the air and allow the cooling coil to condense more moisture. The heat is transferred to the air leaving the cooling coil to provide free re-heating for comfort. Both cooling and reheat energy consumption are reduced compared to a traditional reheat system. In the subcool and desuperheat reheat system, liquid refrigerant is subcooled in the supply air prior to entering the evaporator to increase moisture removal and provide free reheat. In addition, heat is transferred from the hot gas discharge line of the compressor to supply air to provide additional reheat through a controllable heat pipe loop. The thermal characteristics of the heat pipe dehumidifier for an air-conditioning system of the clean room of which temperature and relative humidity are controlled at 25°C and 50% respectively were investigated by Waikual (1997). The system consisted of 1-ton of cooling capacity air conditioning system and a 0.4 kW electric heater, a constant total room heat load of 1.21 kW. The blower speed was selected at maximum level which corresponded to the air flow rate of 260 m³/h. In this experiment, three experimental cases were conducted without using thermosyphon, using 4-loop thermosyphon, and then using 8-loop thermosyphon. The results suggested that the 4 coil-loop thermosyphon saved electric power consumption at the rate of 0.76 kW-h per day or 6.6 % when compared with the system which did not use themosyphon. The efficiency of thermosyphon was about 75%. Terdtoon *et al.* (1999) designed and constructed an LTS for an ice storage system (ISS) from the normally available air conditioning system (ACS). The LTS

had been tested with one ton cooling capacity of diluted brine. The result revealed that the average heat transfer rate to be 4,720 watts in the condenser which was the highest. The maximum effectiveness was 0.809. Terdtoon *et al.* (1999) designed and constructed an LTS for the normally available Longan dryer in northern Thailand. The LTS had been tested under the working condition of the Longan dryer. It was found that at the inlet where temperature and velocity of the hot gas were 60 °C and 1.8 m/s respectively, the LTS could recover heat from the hot gas by an amount of 2,404 W. The LTS could be produced economically. The thermal performance of a loop thermosyphon heat exchanger (LTHE) using effectiveness-NTU method has been studied by Noie-baghban *et al.* (2000). A LTHE was designed, constructed and tested under medium temperature conditions. Distilled water was chosen as the working fluid and filled at 60% of the evaporator height. A natural gas heater heated the atmospheric air. The air velocities at the condenser section were varied between 2.9 and 3.6 m/s and at the evaporator section between 0.9 and 3.24 m/s. The heat absorbed by to the evaporator was around 15 kW. The condenser and evaporator sections had two rows consisting of 12 plate-finned tubes. It was concluded that a low cost and more efficient loop thermosyphon heat exchanger is to be developed to allow a substantial proportion of waste heat to be recovered. An important limitation, sonic limit, to heat transfers for heat pipes was eliminated. Since the vapor flow and the returned condensate travel in different pipes, the possibility of vapor flow at high velocity causing choking of return condensated is not a problem. The base performance is 46% effective for 1 m/s air velocity through the condenser section and 2.9 m/s air velocity through the evaporator section. The overall evaporator effectiveness is nearly constant, as the variation of air velocity through the evaporator section is low. The decrease of air velocity through condenser section led to the increase of overall effectiveness of loop thermosyphon heat exchanger, while the effectiveness of condenser section decreased. Dobe *et al.* (2000) investigated a successful application of the waste heat recovery from flue gases in a bakery, using a loop thermosyphon heat exchanger (LTHE) with water as working fluid. The effectiveness of each LTHE was found to be 51% and the average heat recovery from the flue gases by each LTHE was 19.3kW. Dobe *et al.*(2002) studied the effect of Non-Condensable gases (NCG) on the performance of loop thermosyphon heat exchanger (LTHE) which is used in industrial waste heat recovery systems. It was shown that NCG affects the performance of the LTHE and reduces their effectiveness.

The effect of the presence of the NCG is more pronounced at low temperatures and as the temperature of the operation increases, the LTHE performance improves. The effect of the presence of the NCG can be reduced if some space is provided for their collection. This can be done by installing reservoirs at locations where NCG has the maximum tendency to accumulate. From the previous research, it is evident that the application of LTS in heat pump dryer has great potential. However, further investigation is desired both in terms of modeling and experimental evaluation.

1.3 Research Objectives

- 1.3.1 To construct a simulation model, which can be used to simulate variable data for design and construction HPD.
- 1.3.2 To simulate HPD for minimum energy consumption at any specified condition and optimization data for design and construction loop thermosyphon.
- 1.3.3 To construct a simulation model, which can be used to simulate the LTS and construct the LTS.
- 1.3.4 To experimentally investigate the heat transfer characteristics of the LTS in conjunction with HPD.
- 1.3.5 To compare result from the experiments with the ones from simulation program (validation).
- 1.3.6 To conduct an economic analysis of the HPD with and without the LTS.

1.4 Usefulness of the Research

- 1.4.1. System data obtained from this research will be used in the prediction of the condition of the optimum energy consumption of HPD for longan drying process.
- 1.4.2 A suitable simulation program for the HPD with and without the LTS be obtained.

1.5 Research Scope

1.5.1 Simulation programs are

- Airflow rate from 400 to 750 m³/hr, in step of 50 m³/hr.
- Drying temperature from 70 to 80 °C, in step of 5 °C.
- Ambient air temperature from 25 to 40° C, in step of 10°C.
- Relative humidity from 20 to 80%, in step of 10%.
- Recirculation air ratio (RAR) from 0 to 100%, in step of 10%.
- By-pass air ratio (BAR) from 0 to (RAR-5%), in step of 5%.
- Heat pump system with R-12 as working fluid
- Loop thermosyphon is copper tube.
- Working fluid is R-123 with filling ratio of 75% of evaporator section (17 % of total volume).

1.5.2 Experimental work

There are two groups of experimental work; (1) experimental work to study heat transfer characteristics of the loop thermosyphon and their effects on the heat pump dryer, (2) experimental work to validate the simulation program developed. The parameters to be selected are three values of each parameter that will be employed as the experiment parameter. The other parameters were controlled.