CHAPTER 1

INTRODUCTION

1.1 Passive Cooling in Building

Energy consumption for residential use is one of the main energy aspects stated by World energy resources and consumption (2008). In the equator zone like Thailand, one of the most energy consumption is from building air-conditioning which is around 50% of the consumed total energy, especially in summer. For modern buildings, recent environmental concerns have however, led to a greater focus on traditional passive methods of solar control, natural ventilation and other passive cooling methods. Designers, architects and engineers have adapted many traditional basic principles to fit in with the modern office environment, both in terms of building practices and materials and in the way in which we work today, often resulting in innovative design solutions. Nowadays, there are many passive cooling techniques which are shading, solar chimney, earth cooling tube and passive cooling with long-wave radiation.

1.1.1 Shading

Shading a building from solar radiation can be achieved in many ways. Buildings can be orientated to take advantage of winter sun while shading walls and windows from direct hot summer sun. This can be achieved by designing location-specific wide eaves or overhangs above the equator-side vertical windows (south side in the northern hemisphere, north side in the southern hemisphere). Passive solar buildings should not use large glass areas directly into the living space.

1.1.2 Solar Chimney

A solar chimney as stated by Solar Chimney (2008), often referred to as a thermal chimney, is a way of improving the natural ventilation of buildings by using convection of air heated by passive solar energy. A simple description of a solar chimney is that of a vertical shaft utilizing solar energy to enhance the natural stack ventilation through a building. The solar chimney has been in use for centuries, particularly in the Middle East, as well as by the Romans. In its simplest form, the solar chimney consists of a black-painted chimney. During the day, solar energy heats the chimney and the air within it, creating an updraft of air in the chimney. The suction created at the chimney's base can be used to ventilate and cool the building below.

1.1.3 Earth Cooling Tube

Earth Tubes as stated by Ground-coupled heat exchanger (2008), also known as ground-coupled heat exchangers, earth cooling tubes or earth warming tubes, use the earth's near constant subterranean temperature to warm or cool air for residential, agricultural or industrial uses. They are often a viable and economical alternative to conventional heating, cooling or heat pump systems since there are no compressors, chemicals or burners and only blowers are required to move the air. Earth Tubes are regularly used in Europe and slowly being adopted into North America.

1.2 Passive Cooling by Nocturnal Long Wave Radiation

Nocturnal long wave radiative cooling is one passive cooling technique that can be used to decrease the residential energy consumption. Night radiation cooling can draw away heat accumulated during the day to the cool night sky through a radiator. Based on the fact that every object emits energy in the form of electromagnetic radiation, a radiation flux will occur if two surfaces are facing each other. Infrared radiation exchanges occur continuously between the lower layers of the atmosphere and the objects at the Earth's surface. Since the effective sky temperature is lower than the terrestrial surface temperature, a net heat loss occurs for terrestrial surfaces. It can provide night cooling in some climatic zones (Kreith and Kreider, 1978).

However, some of the constituents of the atmosphere, especially water vapor, CO_2 and dust, absorb and re-emit long wave radiation. Thus during nighttime there is a balance between the radiation emitted by the terrestrial surfaces toward the sky and the downward radiation from the atmosphere. Only the net radiation heat loss is effective in the cooling applications (Givoni, 1979)

The advantage of nocturnal long wave radiative cooling is expected to be less expensive in operating cost because it consumes very little energy in the pumping system. Moreover, principles of operation and maintenance are simple and little technical knowledge will be required. In the other hand, this system always has some limitations. It will be strongly affected by local weather condition. A good cooling performance for the same system under certain conditions may not have the same good performance under different weather conditions.

In Thailand, former study (Vimolrat and Kiatsiriroat, 2004) proposed a new concept of nocturnal cooling by using a thermosyphon-radiator for producing cool water in a Trout farm. For this research, the evaporation part of the thermosyphon heat pipe is dipped in a water tank and the condenser part is exposed to the ambient air. During the nighttime, the condenser is cooled by convection with the surrounding air and by radiation to the sky. Then the water temperature in the tank could be reduced by transferring heat to the evaporator of the thermosyphon.

1.3 Literature review

There are many related works about enhancement this kind of the passive cooling systems.

1.3.1 Reviewed Study

Etheridge et al. (2006) reviewed the studies of reducing air conditioning load in building by phase change material (PCM)/heat pipe cooling techniques. A novel system for reducing or eliminating the need for air conditioning was developed to the proof-of-concept stage under an earlier project at the University of Nottingham. The system made use of heat pipes to transfer heat into and out of a phase change material which was ‘frozen’ during the night and ‘melted’ during the day. This paper described a number of concepts for ‘free cooling’, and the background to the current concept, before detailing field tested on the system that had recently been completed and which demonstrated its effectiveness under real operating conditions. Systems were installed in two offices and detailed monitoring of their performance was carried out during the summer months. On the basis of the results obtained it was concluded that the system functioned very well and was practically and technically the most attractive of the available alternatives to air conditioning. The fact that it was suited to retrofitting in existing buildings meaned that both the potential market and the CO_2 reductions were large. In practical application, the paper also described a novel system that was intended to provide passive cooling in naturally ventilated buildings. The novelty lied in the use of heat pipes and a fan to enhance the heat transfer to and from the PCM and the air. This was successful shown by the ability of the system to exercise a degree of control over the room air temperature that was comparable to that of a conventional air conditioning system. The review provided in the paper might also be of use to other workers on PCMs and night cooling of naturally ventilated buildings.

1.3.2 Experimental Studies

Boon-loang et al. (1982) carried out the experimental studies at the site of three mountain, Doi Ang-Khang, Huay Thung Chao and Doi Pui, located in Chiang Mai. A model of solar-assisted dehumidification system was designed and built. The results showed that during rainy months, July to October, the average heat fluxes were around 10-20 W m^{-2}. And the water temperatures from each site were generally 0-2 °C below ambient or 15-20 °C during the rainy season.

Kiatsiriroat et al. (1983) carried out the experimental work about night heat loss from the radiator plates at Bangkok and compared with theoretical studies. The results shown that, in the equator zone, the sky temperature was found to be lower with decreasing in the surrounding temperature and relative humidity. The sky temperature from the experimental work was found to be lower than that of the theoretical model.

Hamza et al. (1995) carried out experimental and theoretical studies of nocturnal cooling by flowing water through the night sky radiator unit. Their system was two parallel plates night sky radiator, the top one was a black-painted aluminum plate. This radiator plate was covered by a polyethylene windscreen cover. The experiment study was conducted for a gravity flow open loop system. The first study was to let flowing water direct contact with the ambient air when the second one was to cover flowing water by a wind screen. The effect of wind screen thickness on the cooling performance was also studied. The results showed that for typical hot dry summer nights in Assuit, with this gravity-flowed system, the lowest water temperature was obtained at the lowest water flow rate as expected. And the evaporation, that took place in case of open water supply tank, produced a slight enhancement in performance of the whole system. Moreover, when decreasing the thickness of the cover, increase in average cooling power was obtained and then average outlet temperature was also decreased.

Lin et al. (2003) presented an energy storage system, which could be readily integrated with the building structure. It stored heat supplied by solar energy via the two-phase closed loop thermosyphon to storage tank and released stored heat in energy storage material via two-phase closed thermosyphon to the heat exchanger through the flow of transport fluid. The functions of such energy storage system had three operating modes: heat charge, heat discharge, and simultaneous charge and discharge. The thermal performance of the system with alcohol and water as working fluid was experimentally investigated. The results showed that the storage system employing alcohol as working fluid in the loop thermosyphon provided better performance; the system gave optimum heat charge and discharge performance under 35–40% fill ratio, regardless whether the working fluid was water or alcohol. The system displayed optimum charge efficiency of 73% and optimum discharge efficiency of 85% with alcohol as working fluid.

Vimolrat and Kiatsiriroat (2004) produced cool water by thermosyphon attached to the radiator. The evaporator of the thermosyphon heat pipe was dipped in a water tank when and the condenser was exposed to the ambient air. During the nighttime, the condenser was cooled by convection with the surrounding air and by radiation to the sky. Then the water temperature in the tank could be reduced by transferring heat to the evaporator of the thermosyphon. This new concept of nocturnal cooling used this thermosyphon-radiator for producing cool water in a Trout farm. Following their technique, the can produced cool water around 20 °C by the nocturnal long wave radiative cooling. Their system had ratio of radiator area to water volume, (A/V) = 1.39. From their study in Chiang Mai, the water temperature can be cool down about 2°C for one night. This system can work well in the winter of Thailand.

Bassindowa et al. (2007) presented the work on three experiments which were designed and tested to study the feasibility of using radiative cooling in Jeddah, Saudi Arabia, which was a coastal city. The first experiment was made on recording the temperature history of two plates, one of them in horizontal position and the other inclined 45° with the horizontal and facing North. Both plates were painted black. In the second experiment, a plate was covered with a plastic sheet of 100 mm thickness, and insulated from the back. The third experiment was designed to test the effectiveness of radiative cooling to cool a shelter. Two identical shelters were fabricated, one with a radiator and the other served as a reference. In all experiments, ambient temperatures were measured and recorded. It was concluded from these experiments that radiative cooling concept was an attractive idea that can be utilized in general for lowering the sink temperature even for a coastal city like Jeddah, Saudi Arabia. The concept could be used for example to increase heat engine efficiency or to improve the coefficient of performance (COP) of a refrigerator. Other applications and ideas to utilize this concept were also possible.

El-Baky and Mohamed (2007) presented the heat pipe heat exchangers which were used in heat recovery applications to cool the incoming fresh air in air conditioning applications. Two streams of fresh and return air were connected with heat pipe heat exchanger to investigate the thermal performance and effectiveness of heat recovery system. Ratios of mass flow rate between return and fresh air of 1, 1.5 and 2.3 were adapted to validate the heat transfer and the temperature change of fresh air. Fresh air inlet temperature of 32–40 °C were controlled, while the inlet return air temperature was kept constant at about 26 °C. The results showed that the temperature changes of fresh and return air were increased with the increase of inlet temperature of fresh air. The effectiveness and heat transfer for both evaporator and condenser sections were also increased to about 48%, when the inlet fresh air temperature was increased to 40 °C. The effect of mass flow rate ratio on effectiveness was positive for evaporator side and negative for condenser side. The enthalpy ratio between the heat recovery and conventional air mixing was increased to about 85% with increasing fresh air inlet temperature. The optimum effectiveness of heat pipe heat exchanger was estimated and compared with the present experimental data. The results showed that the effectiveness was close to the optimum effectiveness at fresh air inlet temperature near the fluid operating temperature of heat pipes.

Wannaree and Kiatsiriroat (2007) experimentally tested a nocturnal water cooling system for reducing cooling load of an air-conditioned room. The experiment was carried out 7 days consecutively under the climate of Chiang Mai. The system consists of a 180 liter vessel, a sky radiator and a cooling coil each of 2 m^2. It could be found that the water temperature in the storage tank could be dropped down, around 2.3 °C for one night, and the main heat rejection is due to sky radiation. During the day time the cooling load could be reduced around 40.5 watts by the system and the inside room temperature is 4.1-4.5 °C lower than ambient temperature.

1.3.3 Simulated Model with Experimental Studies

The correction model by Unsworth and Monteith (1975a and 1975b) for the radiator having inclined angle, impacting on the mean reservoir temperature, were presented and simulated by a computer program. Finally, this work showed the impacting of the ratio between the radiator's aperture area and the reservoir volume (A/V) on the reservoir temperature.

Dan and Chinnappa (1989) clearly showed the details of energy balance on a radiation unit which consisted of both convection and radiation. Water was trickled over the cover glass of a solar collector. The collector was mounted on a roof of 3m height and at a slope of 19° facing north. Two tanks of about 400 1itres total capacity were used for water storage. Water was drawn from the bottom of one tank and pumped up to a horizontal spreader pipe located above the upper edge of the collector. Holes were drilled along the length of the spreader pipe, and water sprayed onto the cover glass surface. A trough collected the water at the bottom edge of the collector and directed it through a downward pipe back to the second tank. Water in the two tanks was well-mixed by providing re-circulation; and this ensured the same temperature in both tanks. The predicted water temperature and heat flux, established by this model seems to be reliable because they could fit well with the experimental results.

Erell and Etzion (2000) adapted an analytical model originally for heating applications of the solar collector to the description of the nocturnal long wave radiative cooling apparatus. The radiators used in most previous experiments were based on flat-plate solar collectors adapted to cooling, generally by removal of the glazed cover plate. The temperature distribution in the flow direction is a key parameter in the design of a cooling radiator. The calculation of the fluid temperature at any given point along the cooling pipe may be derived from the following expression, proposed by Duffie and Beckman (1991). The model calculations were compared with experimental results for all three radiator types, operating under a variety of flow regimes. The calculated outlet temperature was in very close agreement with the experimental value. In each case, the model of adaptation a solar collector model to use as a night sky radiator seemed to be acceptable and allowed accurate prediction of the fluid outlet temperature. Moreover, the effect of additional fins at the risers be discussed and seems not appropriate for the cooling applications especially when stored water temperature below ambient temperature.

Mier et al. (2002) clearly compared the simulated model and experimental work of passive cooling unit having storage tank. Additionally, they presented the effects inclined surfaces and sheltering objects on out going radiation. Moreover, they also present the effects of the sizing of the reservoir. The system utilized water as heat carrier and consisted of a radiator roof, a reservoir, connecting pipes, a pump and a control unit. The radiators were mounted as integrated modules on the roof of a building, normally under a small tilt angle, and replace conventional roof cover materials. The heat carrier was lifted by pumping power into the upper part of the radiator. Driven by the force of gravity, the liquid trickles through the radiator's intrinsic channels, released heat and returned to the reservoir. The system was a drain-back system and the store represented the drain-back reservoir for the heat carrier when the system was not operative. The heat carrier circulated freely between the radiator loop and the storage tank without intermediate heat exchangers. When there was no net cooling power, the circulation was stopped by the controller, the water drained back into the reservoir and unwanted heat gains were avoided.

The data of the experiment showed that the system could produce cool water about 1ºC above the lowest ambient temperature in that night. The work presented the sky emissitivity model for both cloudless and overcast sky, the simulated result from these model could fit with the experimental result.

Liu et al. (2006) presented a looped separate heat pipe as waste heat recovery facility for the air-conditioning exhaust system. A one-dimensional steady-state model was presented for determining the upper and lower operating boundaries of the initial filling ratio of the working fluid, as a function of the separate heat pipe geometry, vapor temperature of working fluid and power throughput, combined with two-phase heat exchange characteristics and distribution of the liquid film velocity along with the liquid film thickness direction. A parametric analysis was performed to investigate the effects of the length of the evaporator, vapor temperature, and power throughput on the critical values of the upper and lower boundaries. Simulation results showed that the length of the evaporator makes almost no influence on the upper boundary, but great effects on the lower boundary. Increasing of the vapor temperature led to the easier arriving of the lower boundary. Moreover, operation ranges of the separate heat pipe varied with the working fluids. Water and methanol were used separately. An experiment was implemented to validate the simulated results. The numerical predictions compared favorably with experimental results.

1.3.4 Applications of Nocturnal Cooling

Givoni (1977) described a system namely roof radiation trap, which was used for nocturnal radiation cooling in summer. The radiation trap consisted of fixed insulating layer separated from a flat roof and glazing, protected by a hinged insulating panel, in the southern gap between the roof and the fixed insulation. This fixed insulating layer was covered by corrugated metal sheets, painted white, which served as nocturnal radiators in summer. In summer, the penetration of solar radiation during daytime was prevented by the hinged insulating panel. At night the painted external metal layer was cooled by outgoing radiation and the air under the corrugations was blown into the space of the radiation trap and cooled the roof, which, in turn, served as a heat sink during the next day. Nocturnal evaporative cooling could supplement the radiant cooling.

Bourne (2001) showed a significance of using night roof spray storage cooling system which provided chilled water to in-slab tubing and fan coils. Nocturnal long-wave radiative cooling unit produced the cool water using in this work. He found that this type of passive cooling was most appropriate for large, low-rise buildings that had low-slope roof areas. It was most effective in dry climate that had clear night sky.

Rincon et al. (2001) showed the advantage of the roof pond architecture over ordinary insulation and also compared the experimental work with the computer program. To obtain the experimental data, two cells with identical external walls but different roofs were built. One of the cells, named the reference cell, had a well-insulated roof. The other cell, named the experimental cell, had an open roof pond as roof. Both were protected during the day with two insulating panels, and exposed to the sky and atmospheric air during the night. All relevant climatic conditions were recorded in the meteorological station, which was part of the experimental platform. The comparison of the internal temperature measurements in both cells allowed to evaluate experimentally the efficiency and the cooling potential of both systems.

Heat transfer fluxes were specified as boundary conditions in all external surfaces, except for the floor, where soil temperature was specified. At the walls and roof surfaces, the specified unsteady heat fluxes included absorbed solar radiation, convection due to wind and long-wave radiative exchanging between surfaces and the sky. For the passive cooling system implemented in the roof, heat flux by evaporation or condensation from or toward the water surface was taken into account. It could be observed that the trend of the simulation curves was similar to the experimental results, and showed a very good qualitative prediction.

It could be seen that there is a high potential to implement nocturnal cooling for both stand alone or parallel with active cooling. The studies of Vimolrat and Kiatsiriroat (2004) and Wannaree and Kiatsiriroat (2007) are very interesting since their thermosyphon heat pipes could reject heat from stored water in the nighttime without any work input. The cooling water from their techniques could be applied to reject cooling load from any air-conditioned building thus for energy used in its air-conditioning system could be reduced. For our study, a model of cool water production by thermal convective and radiative nocturnal cooling is developed. The simulation studies for both short term and long term storage application are performed.

1.4 Objectives of the Study

1.4.1 To study effect of radiator area and storage tank volume on performance of a convective and nocturnal long wave radiative cooling system by thermosyphon heat pipe radiator.

1.5.2 To develop a model for predicting performance of a convective and nocturnal long wave radiative cooling system by thermosyphon heat pipe radiator.

1.5 Significances

1.5.1 The new technique of passive cooling, using thermosyphon attached to the radiators could be used to reduce energy consumption of air-conditioning system in any building.

1.5.2 Generalized model of this technique could be applied in both active and passive cooling in buildings.

1.6 Scopes

Experiment Work:

1.6.1 The water storage tank is at least 0.5 m^3 in volume.

1.6.2 The working fluid is R-134a inside heat pipe.

1.6.3 The thermosyphon heat pipe is made of copper.

1.6.4 The water storage is thermally insulated by polystyrene insulation.

1.6.5 The outside diameter of thermosyphon heat pipe is 19.05 mm.

1.6.6 The evaporative section and condenser section are 1.5 m length.

Simulation:

1.6.7 The simulation program is based on finite volume method.

1.6.8 The weather data is five-year averaged data of Chiang Mai, Thailand.

1.6.9 The controlled room temperature is not lower than 23 °C.

1.6.10 The cooling load is not higher than 35170 watts.

1.6.11 The radiator area is not over than 100 m^2.

1.6.12 The storage tank volume is not over than 15 m^3.

1.6.13 The sky temperature model is based on Bliss (1961) model.

1.7 Organization of the Thesis

Chapter 1 is the introduction of the motivation for this research and also presents the literature reviews which concerned with both direct and indirect utilization of nocturnal long-wave radiative cooling for the passive cooling propose. The contents of previous studies give us the concepts and ideas for research and development of the nocturnal long wave radiative cooling system in the Chiang Mai, Thailand. This chapter also states the specific objectives, significances and scopes of the study.

Chapter 2 states the principles and theories that concerned with this research. The fundamental contents of heat transfer such as conduction, convection and radiation are explained. The closed-end thermosyphon heat pipe theory from Engineering Sciences Data Unit Item Number 81038 is referred. The former studies of other researchers on the sky temperature are stated. The mechanisms of nocturnal long wave radiation and computational fluid dynamics are also shown in this chapter.

The content of Chapter 3 explains the effect of thermosyphon evaporator length which is the significant designed parameter on this nocturnal cooling system. The thermosyphon evaporator length means to its material and working fluid which can lead to the investment cost on the project. The experiment has been done to find out the heat transfer of each case study. The computational fluid dynamics by finite volume method is used to explain the phenomenon of flow and water temperature.

Chapter 4 shows the significance of nocturnal long wave passive cooling for building. The testing unit of 1.0 m^3 storage tank and 22.5 m^3 room with artificial heater is established. The experimental setup has been done to find the stored water temperature and also the room temperature under each artificial cooling load. A numerical model to find the stored water and tested room temperature has been developed. The percent cooling load reduction of the air-conditioning under each designed room temperature has also been shown in this chapter.

The seasonal scale of the simulation has been explained in Chapter 5 with the last five years weather data from Thai Meteorological Department. The simulation model from Chapter 4 has been used to predict both stored water temperature and percent of energy saving in air-conditioning under each designed room temperature.

Finally, Chapter 6 offers the conclusions that summarize the whole study of this research and the recommendation for future work.