# MODELING THERMAL ENVIRONMENT OF A RECIRCULATING AQUACULTURE SYSTEM FACILITY

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## (ABSTRACT)

Economic viability of fish production in recirculating aquaculture system (RAS) facility depends on minimizing the energy requirements of operating such facilities. The fish growth and water quality aspects of RAS have been studied in considerable details. However, the understanding of the thermal environment of RAS lags behind. A step-wise steady-state thermal model was developed to simulate the daily heating, ventilation, water pumping, biofilter operation, and lighting energy requirements over a production cycle.

The model was validated using temperature and energy data collected from RAS facility of Virginia Tech during 1992. Model simulations were performed with various production scenarios. The energy cost of fish production ($/kg) was used to evaluate different scenarios with and without heat recovery from discharged system water.

Building heating required the most (40 % - 70 % of total) energy followed by water pumping, biofilter operation, lighting, and ventilation. Water replacement was the most dominant factor in determining the facility's heating energy requirement. Heat recovery from discharged system water indicated significant drop (up to 40 %) in energy cost of fish production.

**Acknowledgements**

This thesis is dedicated to my parents, who have made numerous sacrifices to see their son make progress. I am indebted to my wife, Ampawan, for her invaluable support. I would like to thank Drs. Marsh, Vaughan, Thomson, and Libey for their constructive criticism of my work at various stages of this research. Last but not least thanks to the American tax payers, who financed my education in the US.

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# 1. INTRODUCTION

Increasing consumer demand and diminishing capacity of natural fish harvest systems coupled with alarming contaminant levels in natural fish stocks are making the intensive production of fish in closed aquaculture systems feasible. Widespread concern over water conservation is also responsible for increased attention to closed systems.

Closed system technology is relatively new and is still developing. Closed system aquaculture allows adequate environmental control in terms of water temperature and quality to provide optimum conditions for fish growth and disease control. Other major advantages of closed systems over fish production in conventional pond, raceway, and ocean systems are freedom from site constraints, high security, controlled feed rate, and the potential for better management of production activities.

However, the capital and operating costs involved in intensive production of fish, particularly by recirculating or water-reuse aquaculture systems (RAS), prohibit easy acceptance of this technology in the existing aquaculture industry. Design and operational complexities associated with recirculating systems further add to their unpopularity.

Biological filtration, water aeration, and proper control of water temperature are necessary to provide optimum conditions for fish growth in recirculating systems. The water temperature can be maintained at any desired level to suit the fish species under production. Water temperature control is achieved either by controlling room air temperature, or by direct heating or cooling of the water. The activities of a recirculating system are performed by electrical and mechanical equipment such as motors, pumps, heaters, and ventilation fans. These equipment require commercial energy inputs in the form of electricity and fuel. The failure of the aquaculture industry to transform the advantages of closed systems into economic benefits is, in large part, due to inadequate research concerning the energy requirements of a closed-system design. Comparatively, fish growth, water treatment, and aeration have received much more attention than the energy inputs required to successfully operate a recirculating aquaculture system facility. This unfortunate neglect of the energy aspects of recirculating system design is the primary motivation behind this research endeavor.

To help recirculating systems become economically competitive with conventional fish production systems, it is necessary to explore the possibility of reducing energy inputs without affecting production. Such a study could be a basis for either recommending better management practices to existing commercial recirculating facilities, or providing the necessary understanding of energy aspects of recirculating systems for future designs. The first step of any effort in this direction should be to gain a clear understanding of the thermal environment of recirculating aquaculture systems to establish the relationships between the system's operating parameters and its energy requirements. Computer modeling of RAS's thermal environment can provide an analytical tool to study the effect of system parameters on energy requirements and energy costs of fish production. Also, an analytical tool can facilitate evaluation of improved system configuration with respect to energy requirements and costs.

## 1.1. Recirculating Aquaculture System Facility

The single stage RAS facility at Virginia Tech uses nine independent recirculating systems for fish production. Fig. 1.1 illustrates a schematic of the recirculating system. Each system has six major components described below.

**Fish Tank:** One 8,330 L rectangular tank is used for fish culture. The tank is constructed of 3 cm thick fiberglass.

**Sump Tank:** One 1,970 L sump or multi-tube clarifier is connected to the fish tank. The sump tank, made of the same material as the fish tank, is used for the removal of suspended solids from fish tank water. A less dense media (BIOdeck) is also being used as a multi-tube clarifier in the sump tank.

**Biofilter Tank:** A 1,990 L fiberglass tank with a three stage rotating biological contact filter (RBC) is used as a biofilter for restoring the water quality in the fish tank.

**Pump:** Two pumps (GOULDS Model 3871) each rated at 0.186 kW and 170 L/min, are used for pumping water from the sump tank to the biofilter tank.

**Motor:** One 0.186 kW electric gear motor (DAYTON) turns the RBC at 4 r/min.

**U-tube Aerator:** One U-tube aerator of 0.32 m diameter and 13.6 m depth is attached to the pipe connecting the biofilter tank and the fish tank. The U-tube aerator uses pure oxygen injection for aeration of fish tank water.

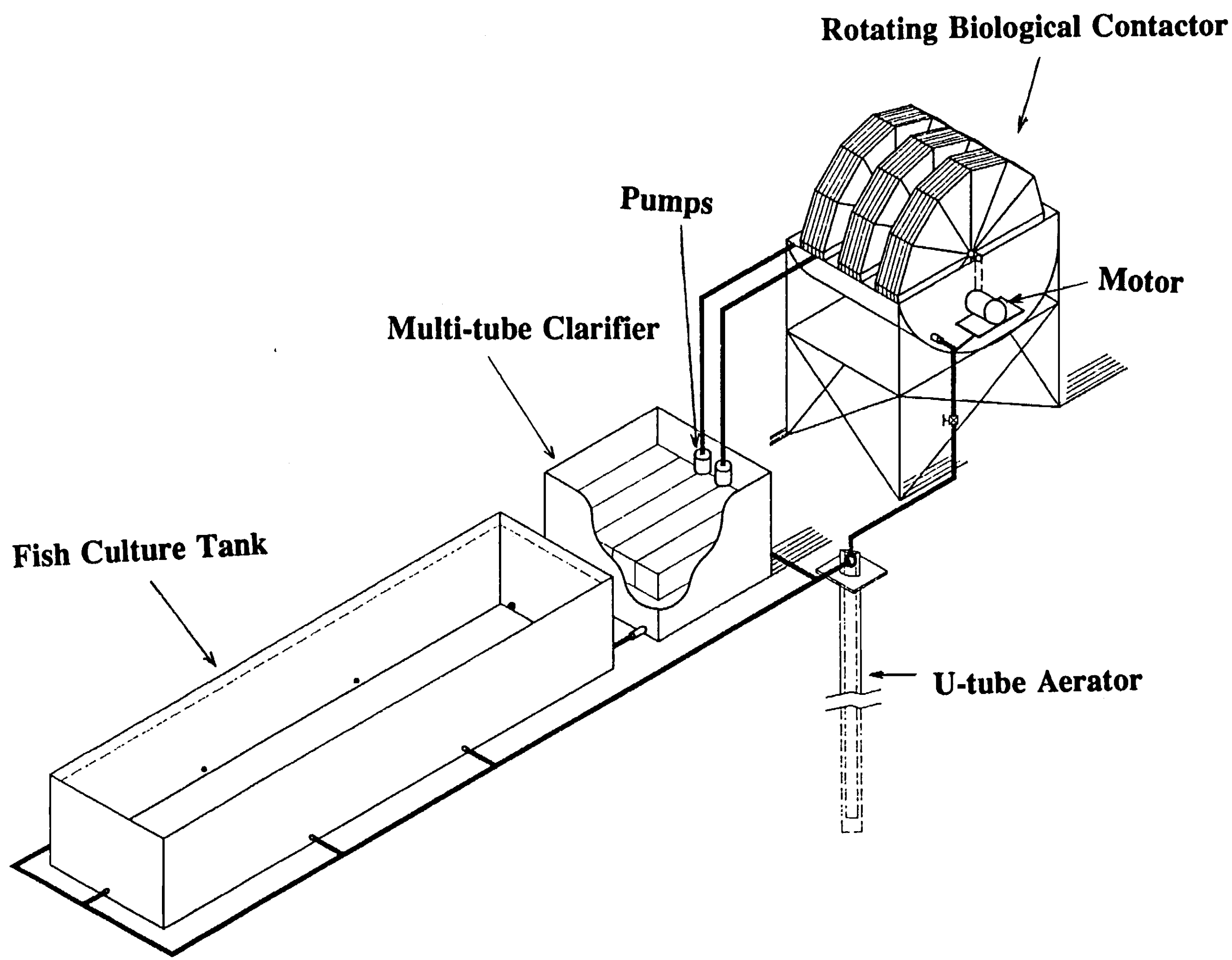


FIG. 1.1 Recirculating aquaculture system design

The nine independent recirculating systems are housed in a post-frame type utility building. The building is 33.5 m long, 15.2 m wide, and 4.8 m high at the ceiling. Corrugated aluminum siding of 19 gauge covers the interior and exterior of the building. Insulation is provided by R-19 fiberglass blanketing in the walls and R-30 in the ceiling.

Air inside the building is heated by four propane heaters (GRAINGER # 3E241, 29.3 kW Input; 22.561 kW Output). One such unit heater is suspended from the ceiling in each corner of the building. Tank water temperature is controlled by the building air coming into contact with the culture water through large surface area of the RBC. A water temperature of 25° C is considered optimum for fish growth but is allowed to fluctuate between 22 and 28° C. The building air temperature fluctuates between 20 and 30° C. During warmer seasons the building doors are opened whenever the environment inside the building becomes too humid. Ventilation is also provided by a large exhaust fan (GRAINGER # 7C209, 7174.4 L/s) located in the production area of the building and a small exhaust fan (GRAINGER # 7F667, 410.64 L/s) located in the attic. The unit heaters and attic exhaust fan are controlled by thermostats (GRAINGER # 1A021) and humidistats (GRAINGER # 2E728) located within the production area and the attic of building. However, the exhaust fan located in the production area is switched on or off manually.

Lighting in the building is provided by six (150 W each) incandescent lamps. Light intensity is being manipulated by a wall mounted rheostat located in the production area.

# 2. OBJECTIVES

This research was initiated to obtain an understanding of energy requirements of recirculating aquaculture systems through a mathematical model of energy inputs and thermal processes associated with the RAS facility at Virginia Tech. The main purpose of this model is to estimate various energy requirements for an entire production cycle. This is achieved by accurately quantifying the daily thermal processes, and then calculating the energy requirements of different activities of the recirculating system for a complete production cycle. Based on current energy prices, the model should then be able to estimate the energy costs of different activities for each kilogram of fish produced in the facility. Further, the model simulations can be used for evaluating a range of management alternatives with respect to system's energy requirements and monetary energy costs of fish production.

The specific objectives for this research were as follows:

1. Develop a thermal model of RAS for simulation of energy requirements;
2. Study the effect of major production parameters on energy requirements; and
3. Establish a general relationship between energy input costs and fish production.

# 3. REVIEW OF LITERATURE

The design and operation of recirculating aquaculture systems involves integration of technologies used in many different fields as diverse as fisheries and thermal engineering. Since this research concentrates on modeling the energy aspects of recirculating systems, related literature was reviewed. Few studies have focused on energy aspects of recirculating systems. Consequently, little information is available on the behavior of recirculating systems with respect to their energy inputs.

The use of a reliable weather generator to obtain daily values of weather variables like ambient temperature and solar radiation is essential to accurately quantify the heat transfer processes across the recirculating aquaculture system. In contrast with energy inputs in recirculating aquaculture systems, a substantial number of studies are available on weather generators. This literature review is categorized into two major groups namely, energy in recirculating aquaculture systems and weather generators.

## 3.1 Energy in Closed Aquaculture Systems

Huner and Dupree (1984), in their "Third Report to The Fish Farmers" prepared for U.S. Department of Interior's Fish and Wildlife Service, suggest that fish growth and activity are directly related to water temperature. Over the range of 0 to 35° C, the metabolic rate of catfish doubles for each 10° C rise in water temperature. This report further states that most warmwater fishes grow best at temperatures somewhere in the range of 21 to 32° C. Channel catfish grow best at 23 to 29° C. The length of their optimal growing season thus equals the number of days that water temperatures exceed 23° C. Typically, a growing season of 150 to 210 days is needed for 15- to 20-cm channel catfish fingerlings to reach market sizes of 0.35 to 0.6 kg.

Stickney (1979) identifies temperature as the most important physical parameter affecting growth of aquatic animals. He also states that it is possible to control temperature in any type of aquaculture system, but in most cases attempts to alter ambient temperature will lead to financial disaster.

Wheaton (1977) indicates that water temperature can be controlled much more economically in a closed system than in a semi-closed system because large amounts of heat (or cold) are not discarded with the water. Thus the energy requirements of a closed system may be less than those of a semi-closed system even when more pumping is necessary. Wheaton further states that the need to heat and cool water accounts for one of the major operating expenses in semi-closed and closed systems.

Ogle (1980) maintains that the cost of energy for recirculating systems is the highest of all types of fish culture. He suggests that energy costs can be reduced by utilizing solar and low energy technologies.

Muir (1981) quantifies pumping, aeration, and heating costs and presents them graphically in his study of management implications in recirculating water systems. Muir predicts that the pumping costs vary between $100 and $1000 per Mg production capacity of recirculating system at 1979 energy prices, depending on design water head as shown in Fig. 3.1. He assesses heating costs on the basis of temperature difference and degree of recirculation as shown in Fig. 3.2. He concludes that pumping and heating costs in recirculating systems can be significantly greater than the possible savings over other production systems. This is supported by Edwardson's analysis (cited by Muir, 1981), in which fuel contributes 86.9% of total energy inputs in a recycled system, and totals in terms of GJ/t were 15 times as high as those in flowing-water intensive systems.

MacKay and Toever (1981) find that cage, pond, raceway, and closed systems utilize more energy than is contained in the fish they produce. They compare the energy ratios (output/input) for these systems and find that the ratios vary from 0.28 - 2.5 for cage culture; 0.05 - 0.77 for pond culture; and 0.02 for closed systems. Taking into account the energy required for manufacturing the materials, for construction, for heating, and for pumping the water, 7 calories are needed for every calorie of fish produced in a recirculating system.

In a feasibility study carried out for fish production in recirculating aquaculture systems, Losordo et al. (1989), concludes that the cost of fish production is sensitive to the amount of energy used to heat or cool the system; the heating/cooling energy alone comprised 8 to 15 percent of the total production cost for various fish species under production.

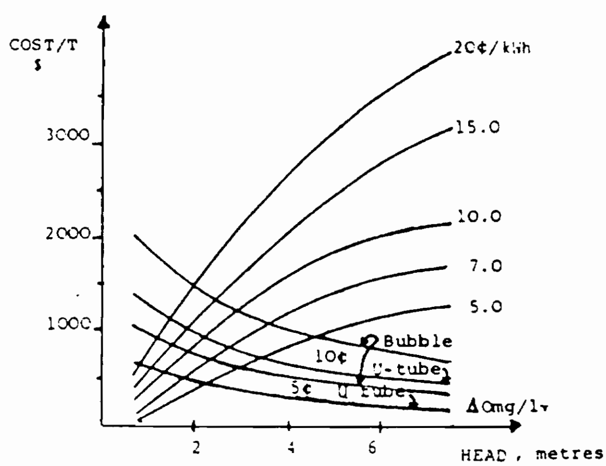


**FIG. 3.1** Energy costs: pumping and aeration
(Source: Muir, 1981)

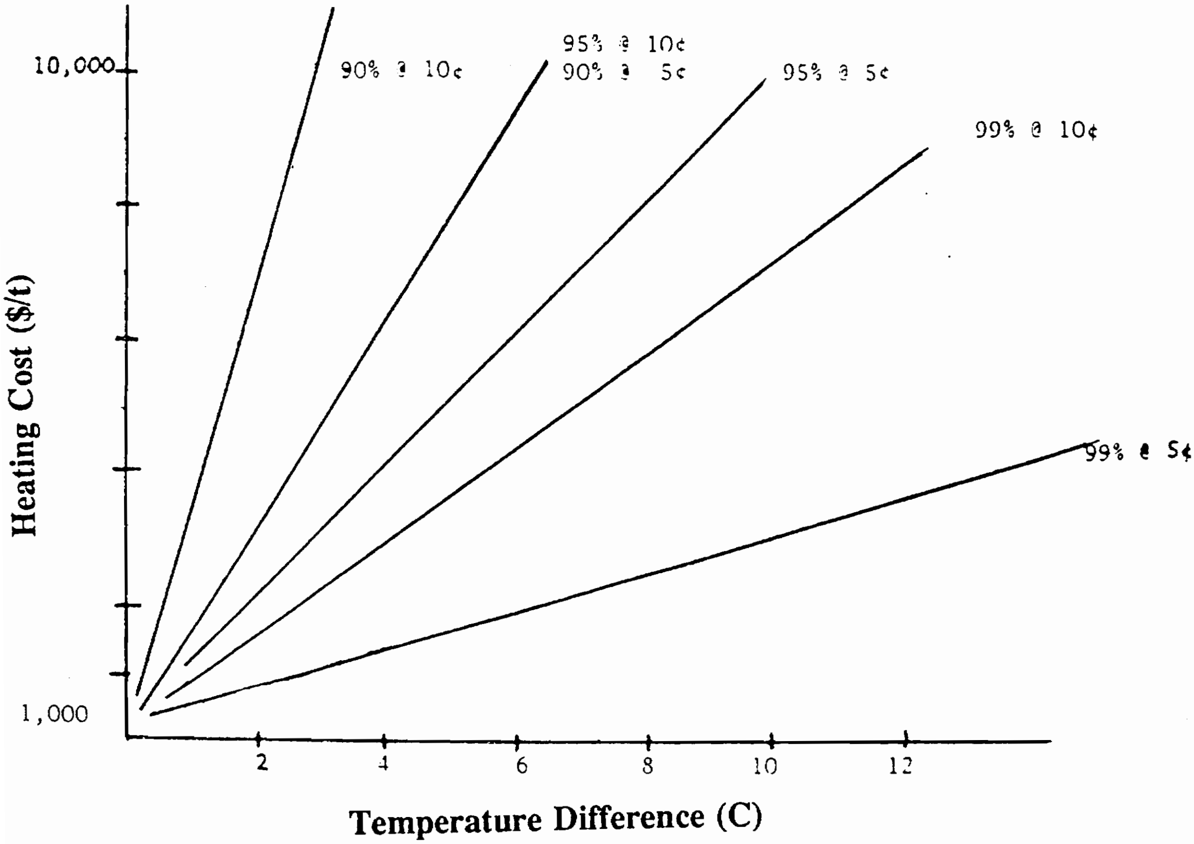


FIG. 3.2 Heating costs: production to capacity ratio (Source: Muir, 1981)

The Cornell Aquaculture Program compared the energy inputs required to produce various species of fish and other meat products and found that intensive fish culture did not offer any competitive advantages over commercial meat production methods. The energy costs were found to be 35% of the total of capital and operating costs for producing trout in a reuse system under expert management and maximum densities.

Gorder (1990), in his discussion of design strategies for recirculating aquaculture systems, suggests that the methods used to heat water (relating also to the % recirculation) and to conserve heat are vital to an economic and energetic analysis of a closed fish culture system. Most commonly used method is to heat the building air and insulate the room. This is expensive and can result in an uncomfortable working environment, since the room must be at least 2° C warmer than the desired water temperature to compensate for evaporative cooling. It is also possible to heat the water and insulate the culture tanks (as well as the room). This is also expensive and requires the covering of all water surfaces to maintain the heat within the water. The expense of meeting these requirements will vary in every situation, but this is a vital category of operational cost that is often ignored or given little importance. Some system designs are site specific, requiring some level of co-generated heat to maintain economical operational energy costs. To be economically feasible, other designs require the inclusion of heat exchangers to recover heat from the discharged culture water.

Reinemann and Timmons (1988) developed interactive software (FISHOUSE) for modeling water-reuse aquaculture systems thermal environments. This software predicts energy costs for various enclosed aquaculture housing options. Since this software program is written for complete water-reuse systems, it can not be used when culture water is periodically replaced in the system. Moreover, FISHOUSE has not been evaluated against any real recirculating aquaculture system.

Water replacement is usually associated with enclosed aquaculture facilities (Wood, 1991). From 5 to 15 percent of the water in the system is replaced at one time and the frequency of discharges usually depends upon the amount of fish feed put in the culture tank (G. Libey, pers. comm.). Timmons et al. (1991) suggest that energy costs are minimal when there is negligible water exchange outside the system. They further suggest that water exchange rates exceeding 2% of system volume per day usually preclude water temperature control.

Most of the studies cited above show water temperature as an important factor in fish production and identify energy expenditure as a major component of the overall production cost. However, few attempts have been made to objectively quantify energy inputs in recirculating systems. Development of the interactive software, FISHOUSE seems the only effort on modeling the thermal environment. However, the application of FISHOUSE is limited only to the completely-closed systems; it can not be used with the RAS design based on partial water recirculation. Also, its validation and detailed model documentation are not reported.

## 3.2 Weather Generators

The weather variables of interest for modeling thermal environment of RAS are air temperature and solar radiation because they directly influence the heat transfer processes across the system. In general, there are two different approaches in use for simulating daily weather variables. Stochastic generation is most commonly used by agricultural researchers. The second method, which is deterministic in nature, is based on modeling daily average air temperature and solar radiation as functions of Julian day in the form of sine curves.

Kimball and Bellamy (1986) generate solar radiation, temperature, and humidity patterns for selected locations in U.S.A., New Zealand, and Denmark. They use mean monthly values of total daily solar radiation, maximum and minimum air temperature, and vapor pressure to generate diurnal patterns of solar radiation, air temperature, and humidity. Solar radiation is modeled as a simple half-cosine function. Air temperature is generated using sine and exponential functions. The model for vapor pressure is a constant equal to the daily average.

Reinemann and Timmons (1988), in developing FISHOUSE, employ the second approach, in which daily outdoor temperature and solar radiation are simulated as sine curves and functions of Julian day. This approach is simple and easy to integrate with the models of building thermal environment. It requires average annual maximum and minimum values of air temperature and solar radiation for the site for which the daily values are being generated. The minimal input data requirements of this approach make it easy and quick to implement. However, the validity of this weather generator has not been reported by Reinmann and Timmons (1988).

Bruhn and Fry (1980) construct a computer simulation model to supply daily weather data to a plant disease management model for potato late blight. Monte Carlo techniques is employed to generate daily values of precipitation, maximum temperature, minimum temperature, minimum relative humidity and total solar radiation. Each weather variable is described by a theoretical probability distribution and the values of the parameters describing each distribution is dependent on the occurrence of rainfall. Precipitation occurrence is described by a first-order Markov chain. The amount of rain, given that rain had occurred, is described by a gamma probability distribution. Maximum and minimum temperature are simulated with a trivariate normal probability distribution involving maximum temperature on the previous day, maximum temperature on the current day, and minimum temperature on the current day. Parameter values for this distribution are dependent on the occurrence of rain on the previous day. Both minimum relative humidity and total solar radiation are assumed to be normally distributed. The values of the parameters describing the distribution of minimum relative humidity was dependent on the rainfall occurrence on the previous day and current day. Parameter values for total solar radiation are dependent on the occurrence of rain on the current day. Bruhn and Fry evaluate the generator using actual weather data from three different locations and find close agreement between the actual and simulated values.

Nicks and Harp (1980) also use stochastic generation of meteorological data for daily maximum and minimum temperature and total solar radiation data. Data generated from their models were tested against historical records and were found to be adequate, representing the observed data for 11 of 12 months.

Richardson (1982) studies the dependence structure of daily temperature and solar radiation for 31 weather stations across United States. He finds that the daily weather variables tended to persist in time and are mutually interdependent. Maximum temperature and minimum temperature have an average lag-one serial correlation coefficient of 0.671 and 0.621, respectively. Solar radiation has an average serial correlation coefficient of 0.251.

Nicks and Lane (1989), and Richardson and Nicks (1990) outline the equations and algorithms used in various components of a weather generator employed by a number of soil and water engineering models. This generator is also based on stochastic generation principles. Richardson and Wright (1984) call this generator "WGEN", which stands for Weather Generator, and provide its detailed computer program and values of parameters for application in 48 States. WGEN simulates daily values for precipitation, maximum temperature, minimum temperature, and solar radiation. They compare the generated weather data with actual data for various locations and find a close agreement between the two data sets.

# 4. MODEL DEVELOPMENT

This chapter details the theoretical approach used in developing a computer model of thermal environment and energy inputs of Virginia Tech recirculating aquaculture system facility. General considerations of the thermal model are discussed first, followed by a description of the different steps involved. Lastly, the details of the developed computer model are presented.

## 4.1. General Considerations

Fig. 4.1 illustrates the components of the thermal environment of RAS facility. The RAS facility has two distinctly separate environments: 1) the RAS water in which fish grow, and 2) the air inside the building enclosure of RAS. A third environment, the outside air, surrounds the building. Since fish growth occurs within a narrow temperature range, the RAS water temperature is of primary importance. The building air temperature is also important due to considerations of an acceptable environment for workers and moisture effects on electrical and mechanical equipment operating within the facility. However, there is greater flexibility in selecting the building air temperature and it can be allowed to fluctuate within a wide range. Heat transfer takes place across the