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**AN ENGINEERING ANALYSIS OF A CLOSED CYCLE
PLANT GROWTH MODULE**

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ABSTRACT

An engineering computer model has been developed at Battelle to simulate the performance of a controlled environment agriculture system. This computer model, called SOLGEM, was developed to provide a dynamic performance simulation of an enclosed growing system in which the ventilating and air conditioning power required to maintain ideal growing conditions was provided entirely by solar energy. The model is made up of 11 primary subroutines which simulate the performance of the major components of the system, including a plant growth and evapotranspiration model, ventilation and flow model, evaporative cooling and solar-driven absorption cooling, and photovoltaic power generation.

The SOLGEM model has been applied to calculate the performance of a plant growth module similar to the module under study at NASA Ames. The plant growth module is a ground-

based plant growth research facility, intended for the study of bioregenerative life support theories.

This report presents the results of a performance analysis of the plant growth module. The estimated energy requirements of the module components and the total energy are given. The water balance and estimated plant evaporation are presented. An analysis of the effect of design alternatives of component sizing and energy use is discussed.

INTRODUCTION

The SOLGEM model is a numerical engineering model which solves the flow and energy balance equations for the air flowing through a growing environment, assuming quasi-steady state conditions within the system. SOLGEM provides a dynamic simulation of the controlled environment system in that the temperature and flow conditions of the growing environment are estimated on an hourly basis in response to the weather data and the plant growth parameters. The flow energy balance considers the incident solar flux; incoming air temperature, humidity, and flow rate; heat exchange with the roof and floor; and heat and moisture exchange with the plants.

A plant transpiration subroutine has been developed

to simulate the heat and moisture transfer between the plants and the air. This routine provides a realistic model of transpiration and leaf temperature in terms of incident solar flux, air temperature, air-flow velocity, roof and floor temperature, and humidity. Important plant characteristics such as stomatal opening, convective and radiative heat exchange, and canopy development are all included in the model.

The purpose of the SOLGEM dynamic simulation model is to provide an engineering estimate of the performance of a controlled-environment growing system. The required input to the model is a complete physical description of the system, i.e., size of all components, performance characteristics of the energy subsystems, and the weather data. For a given system design and a specific location, the hourly air temperature, humidity, and solar intensity experienced by the plants are determined. The results indicate whether or not the growing environment maintained by the system was satisfactory for optimum plant growth.

The simulation model also determines the quantities of mass and energy flowing between components. The sizing of components can be accomplished by monitoring the component output and noting excesses or deficiencies. In most cases, the performance of the overall system will be affected by varying

the size until the desired system performance is achieved.

The model can also be used to conduct parameter sensitivity studies. By varying the value of a specific input and repeating the simulation run with all other parameters fixed, it is possible to determine the sensitivity of the system performance to changes in this parameter. Sensitivity studies can be used to determine the most important design variables, and to indicate the benefits possible by making changes in system design.

APPROACH TO ANALYSIS OF PLANT GROWTH MODULE

Plant Growth Module

The SOLGEM model has been used to conduct an engineering analysis of a simplified version of a plant growth module. A sketch of the module is presented in Figure 1. The module simulated consisted of a growing space 1m wide, 1m tall, and 5m long. A bank of grow lights provided radiation. The air was circulated by a single fan which passed air over a cooling coil before cycling it back to the growing space. The cooling coil removed the thermal energy added by the grow lights, and condensed and removed the moisture transpired by the plants.

Modeling Plant Heat Transfer

In an enclosed growing environment the plants are a major factor in determining the energy balance of the system. The plants absorb the incident radiant energy and convert it to thermal energy, and to latent heat in the form of water vapor. (A small percentage of the energy is converted to chemical energy by the plants. This energy is negligibly small and consequently has not been included in the analysis.)

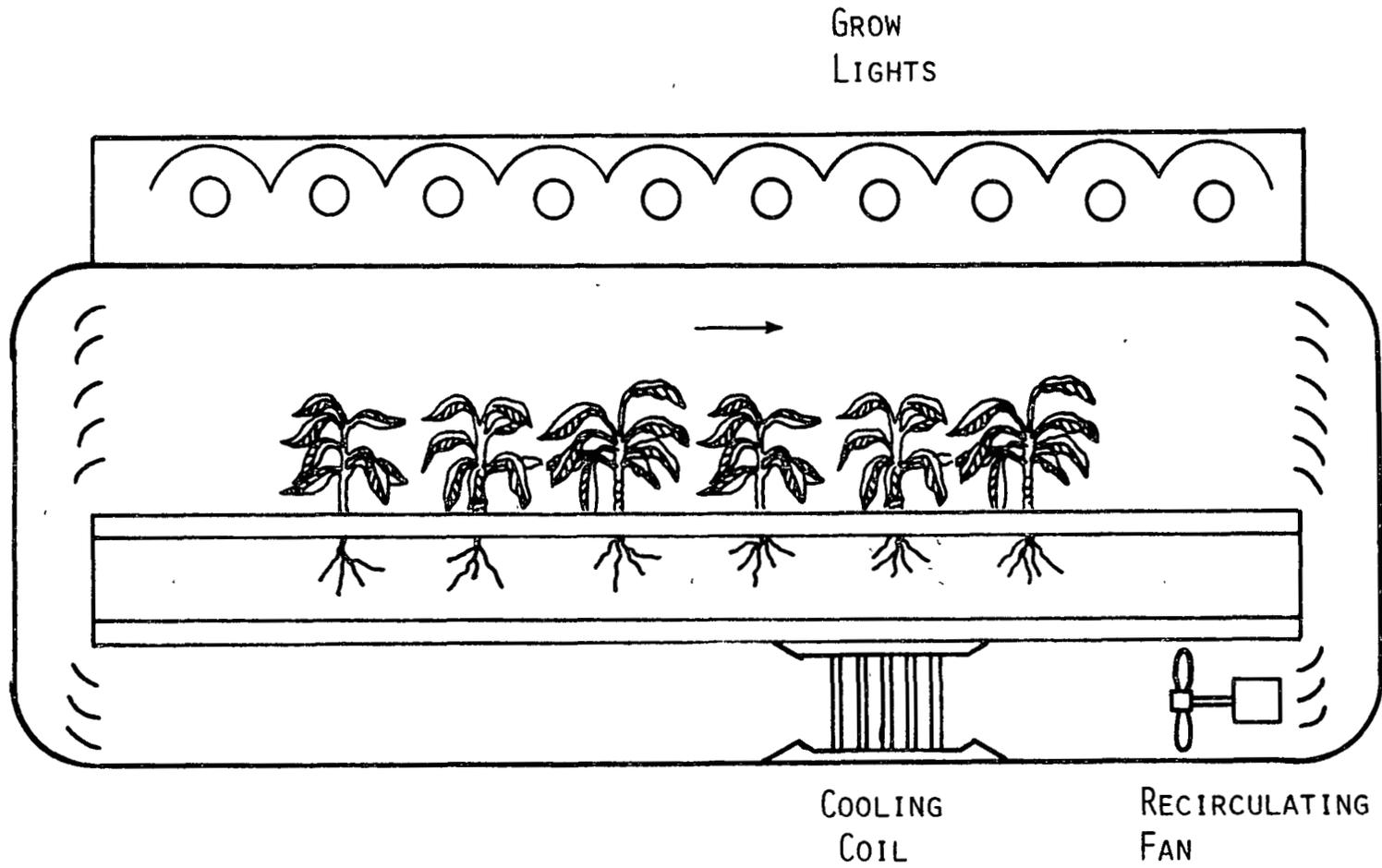


FIGURE 1. SKETCH OF PLANT GROWTH MODULE

The transpiration and leaf temperature model of Gates^{1,2} was used to calculate the energy balance of the plants.

The Gates model considers three energy transfer mechanisms:

- o Convection
- o Radiation
- o Transpiration

The convection of energy between the leaf and the air stream is governed by the temperature difference between the leaf and the air, and by the air flow velocity. The convection coefficients depend on the leaf geometry and are given by Gates.

The radiative exchange between the leaf and its surrounding is determined by considering five radiation sources as shown in Figure 2. The primary radiant energy input is QSOL, which in this case is the radiation supplied by the grow lights. Radiative exchange with the roof and the floor is included, as is the reflected radiation from the floor. Radiation from surrounding leaves is also considered in the energy balance.

Transpiration by the leaves is actually a mass transfer mechanism and is a significant term in the plant energy balance. The amount of energy that is absorbed by transpiration can range from 1/3 to 1/2 of the incoming radiation. The Gates transpiration model depends on leaf temperature,

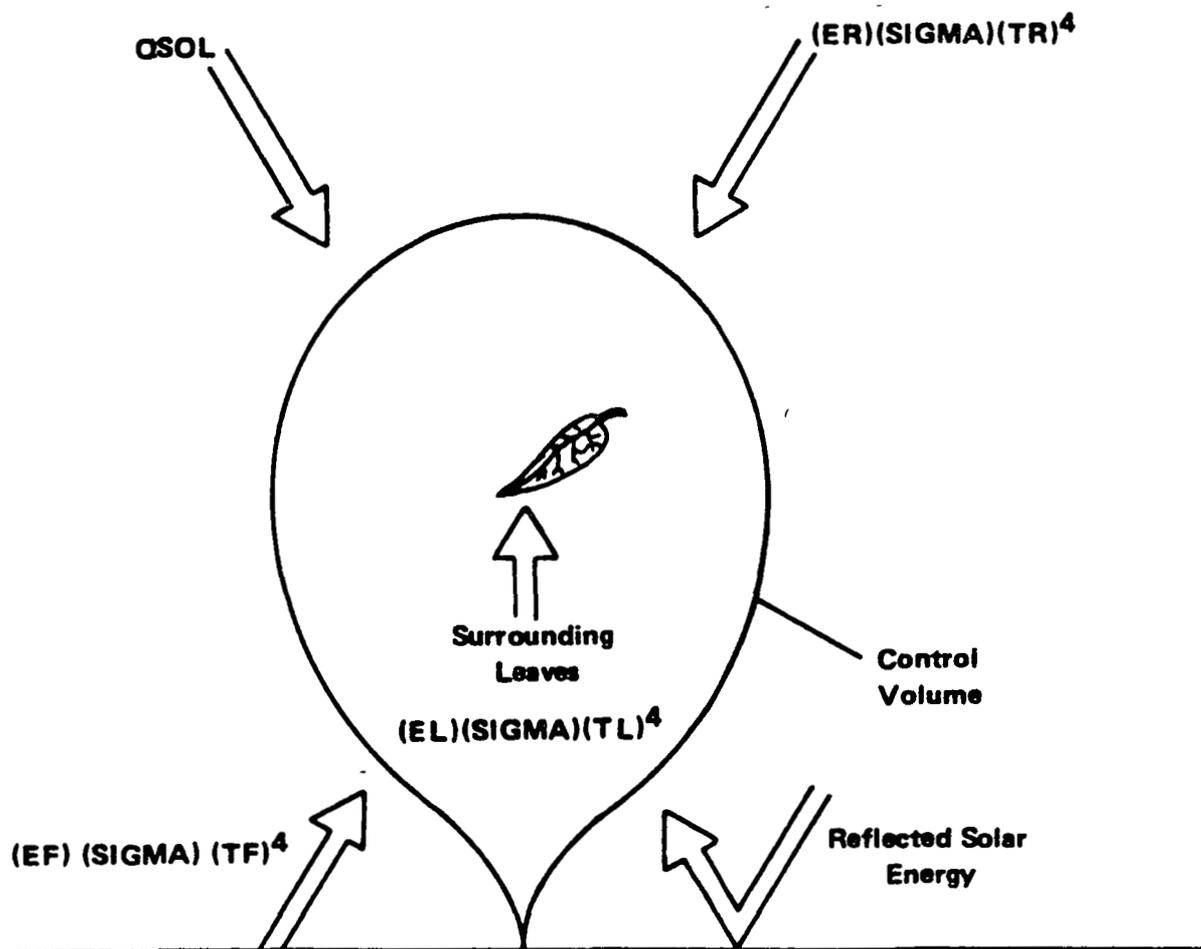


FIGURE 2. RADIATIVE HEAT TRANSFER TERMS INCLUDED IN THE LEAF ENERGY BALANCE

air temperature and humidity, air flow velocity, and a leaf stomatal resistance term.

The stomatal resistance is an attempt to simulate the opening and closing of the plant stomate, shown in Figure 3. The stomatal resistance was selected so the predicted water transpiration rate of a mature plant canopy matched the known performance of a greenhouse. The nighttime stomatal resistance of 500 sec/cm was recommended which virtually eliminated transpiration at night. The daytime value of 5 sec/cm was found to result in a transpiration rate sufficient to absorb 1/2 of the incoming solar radiation by a mature plant canopy during full sun conditions.

Description of Component Models

Cooling Coil. The cooling coil consists of a liquid-to-air heat exchanger using chilled water as the liquid cooling medium. The amount of air passing through the heat exchanger was varied by bypassing a portion of the recirculation air around the heat exchanger. The two air streams were then mixed together before reentering the growing zone.

This simple system is capable of providing dehumidification and removal of thermal energy in one process. By varying the chilled water temperature and the fraction of the recirculation air that is bypassed, it is possible to achieve

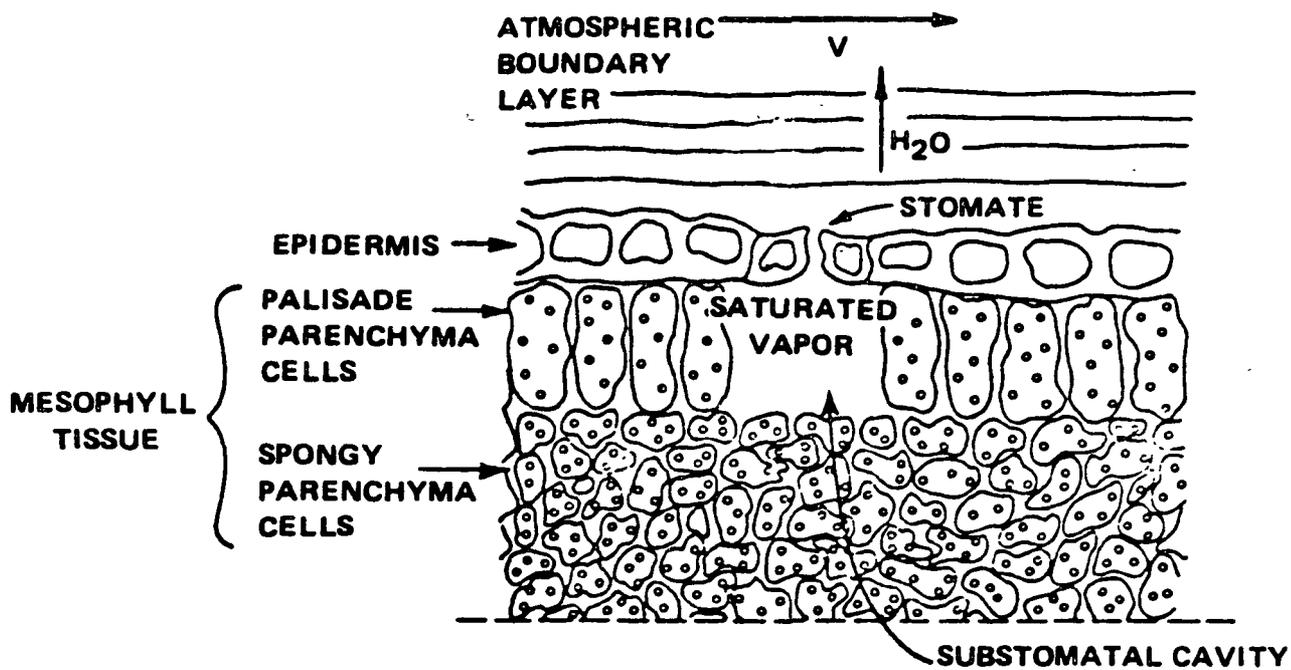


FIGURE 3. LEAF CROSS SECTION

desirable levels of temperature and humidity in the growing zone for all realistic conditions of radiation input and plant transpiration. A detailed discussion of this process follows in a later section.

Grow Lights. The grow lights provide radiant energy input to the plant canopy. In addition to triggering the growth process, which is not included in the SOLGEM model, the radiant energy affects the leaf temperature and the amount of water vapor transpired by the plants.

For the purposes of this simulation, the grow lights were assumed to be 80% efficient, meaning that 80% of the energy input to the grow lights was emitted as radiation, and 20% was given off as thermal energy. The radiant energy was transmitted to the plants, then to the air by convection and transpiration. The thermal energy was transmitted directly to the air by convection from the lights.

Circulation Fan. The electric energy supplied to a fan motor is transferred to the air stream in three distinct forms: kinetic, potential, and thermal. Kinetic energy is imparted to the air by the fan blades creating a moving air stream. Potential energy is imparted to the air by the fan blades in the form of the pressure rise across the fan. Thermal energy is imparted to the air stream in several

ways. Viscous frictional heating of the air stream occurs because of the interactions between the air and the fan surfaces. Conduction to the air stream of the thermal energy generated by mechanical friction and electrical resistance also occurs.

For a particular air flow rate, the kinetic energy is proportional to the velocity squared. The air velocity through the fan can be reduced significantly by using larger diameter fans. The required flow rate and pressure rise can be achieved by selecting the appropriate fan speed. Thus by using large-diameter, variable-speed fans the kinetic energy can be minimized.

Potential energy considerations lead to the need to minimize the product of flow rate and pressure rise. The flow rate requirements are fixed by the thermal energy input of the grow lights. However, the pressure rise is a function of the system design. Thus a low pressure rise system is desirable.

The temperature rise of the air through the fan system results from frictional effects and inefficient hardware. Thus fans and motors having the highest efficiency should be selected for the plant growth module.

Given a particular plant growth module design(i.e., the pressure drop is a function of the air flow rate), the fan energy must be minimized by minimizing the air flow requirements, and by choosing the appropriate number and size of fans.

Temperature and Humidity Control Strategy

The air passing through the growing zone absorbs the heat generated by the grow lights and increases in temperature. The air also absorbs the moisture transpired by the plants. All the thermal energy and moisture absorbed by the air must be removed as the air passes through the recirculation ducts.

Air Flow Velocity. The air flow velocity can be increased by increasing the recirculation fan speed. As the air flow velocity increases the temperature rise across the growing zone decreases. Thus the air flow velocity can be used to control the allowable temperature variation across the growing zone.

Chiller Control. Two chiller control variables are required in order to condition the recirculation air. By varying the chilled water temperature and the fraction of air bypassing the chiller, the temperature and humidity

of the recirculation air can be controlled. Lowering the chilled water temperature and increasing the bypass increases the amount of water removed relative to the amount of sensible heat. Raising the chilled water temperature while reducing the bypass will result in more sensible heat reduction and less water removed.

RESULTS OF ANALYSIS

An analysis of the plant growth module was conducted for an illumination level of $1000 \mu\text{mol}/\text{sec}/\text{m}^2$. The temperature of the air exiting the growth zone was fixed between 25 C and 26 C. The relative humidity was held between 60 and 70 percent.

The air temperature rise through the 5 m plant growth module is shown in Figure 4. For the mature plants, the temperature rise is less than 1 C at an air flow rate of $60 \text{ m}^3/\text{min}$. This is equivalent to 1 m/sec flow velocity.

For seedlings the amount of water transpired is significantly less. Thus the temperature rise at a given air flow rate is greater than for mature plants.

Figure 5 presents the average leaf temperature as a function of air flow rate. The average leaf temperature appears to be slightly less sensitive to air flow rate than the air temperature. Thus increasing the air flow velocity is not as beneficial to reducing plant temperatures as would be indicated by calculating air temperature only.

The effect of cooling water temperature on the humidity

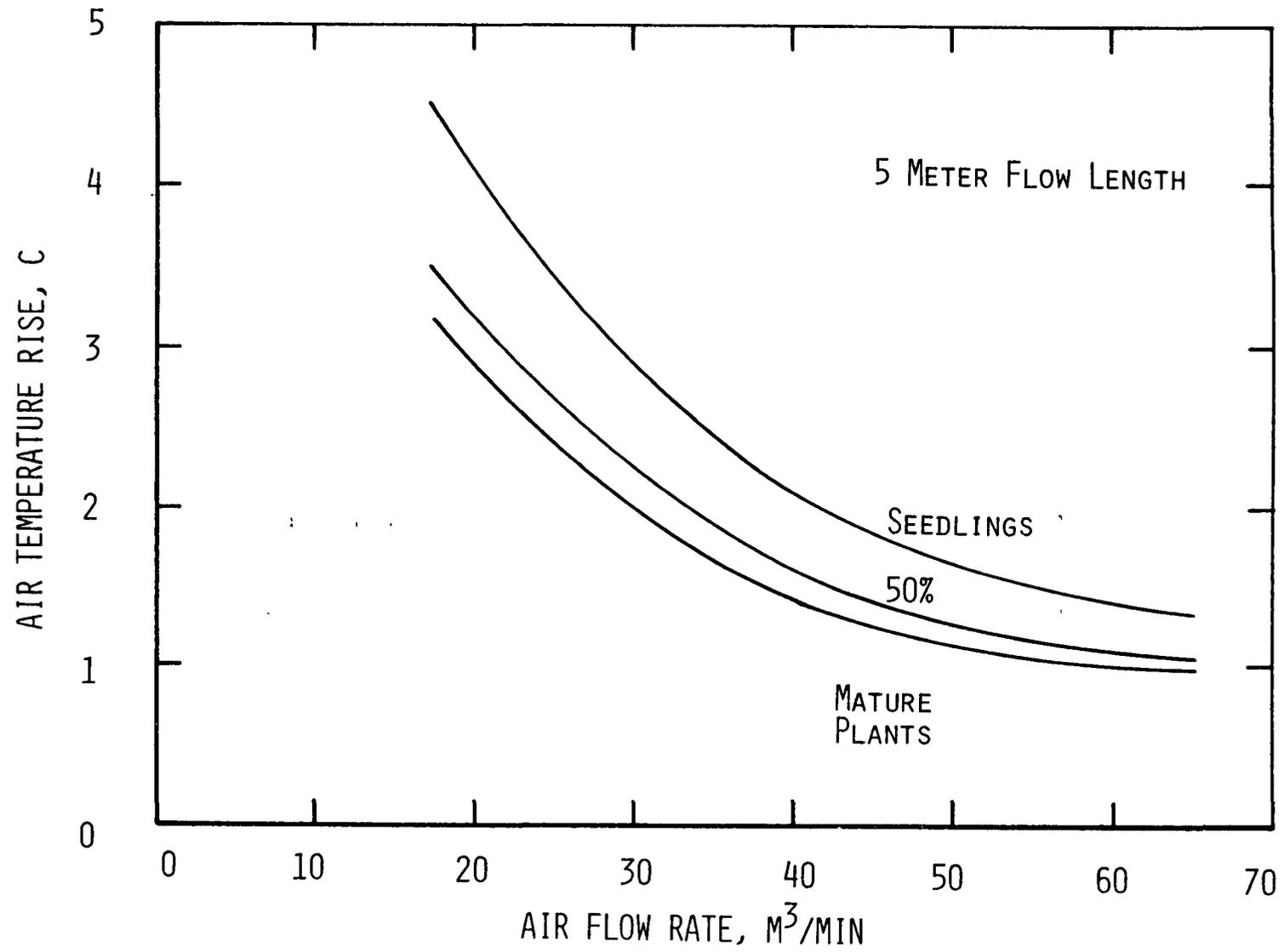


FIGURE 4. AIR TEMPERATURE RISE THROUGH PLANT GROWTH MODULE

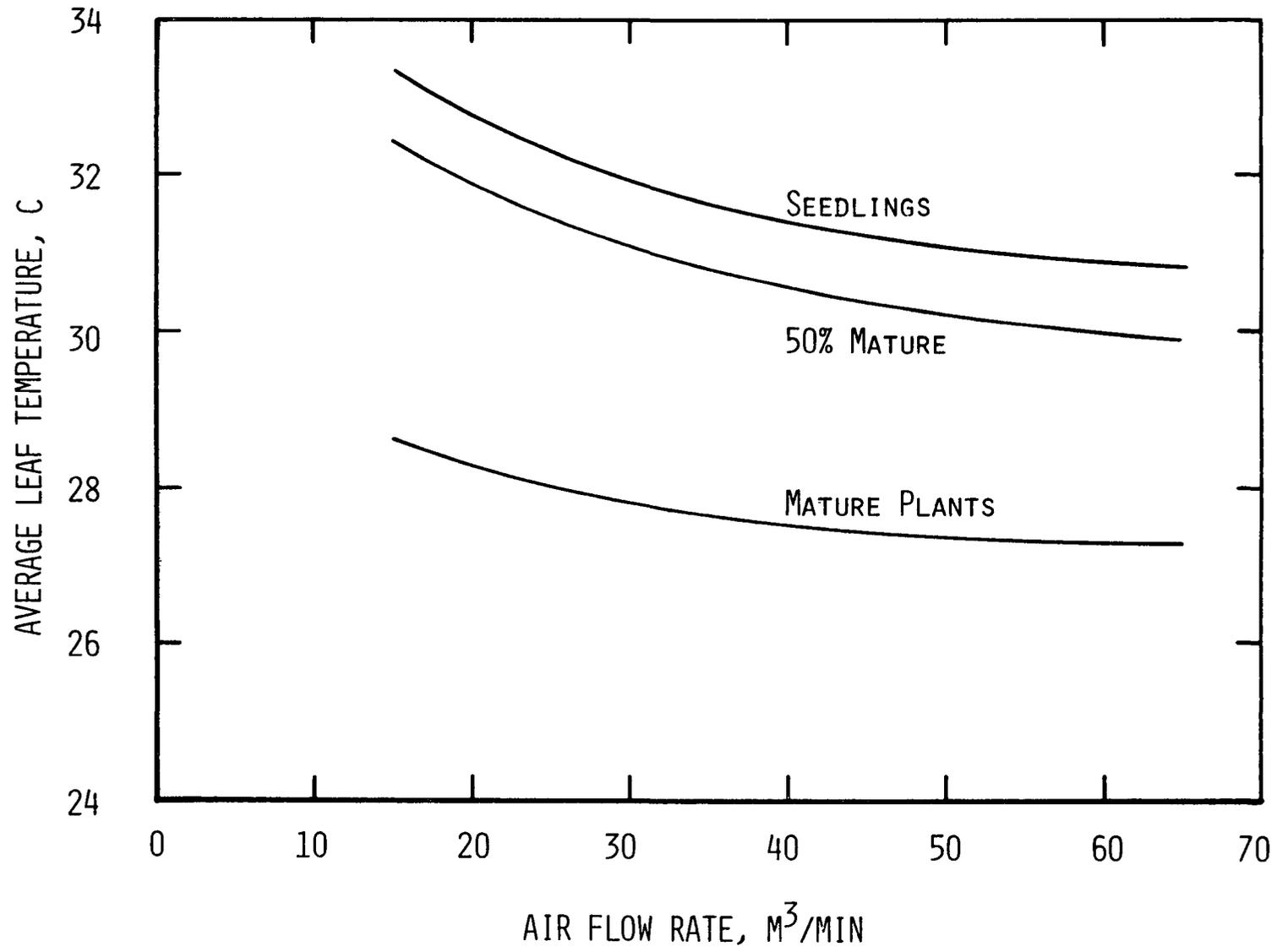


FIGURE 5. AVERAGE LEAF TEMPERATURE

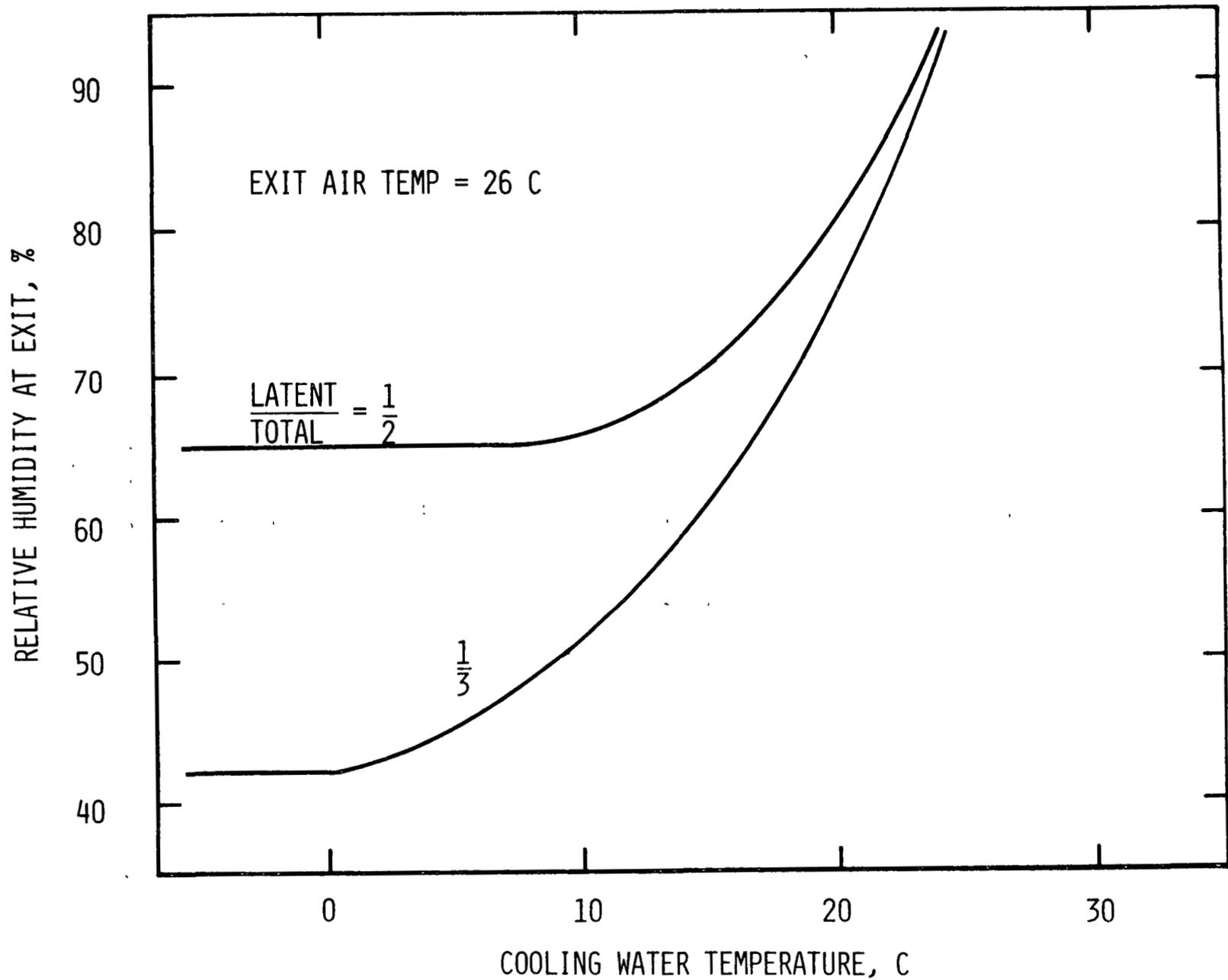


FIGURE 6. HUMIDITY LEVEL VERSUS COOLING WATER TEMPERATURE AND LATENT HEAT RATIO

level in the growing zone is presented in Figures 6 and 7. For practical levels of the latent heat ratio (the ratio of energy absorbed by transpiration to the total energy absorbed by the air stream), it is possible to achieve humidities down to 65 percent with a cooling coil. At lower transpiration rates characteristic of young plants, the humidity could be controlled with water near room temperature.

Figure 7 shows the effect of air temperature on cooling water temperature. For higher air temperatures in the growing zone, the allowable cooling water temperature is higher. Higher cooling water temperatures result in lower energy requirements for humidity control.

Energy Requirements. The energy requirements for the plant growth module are given in Table 1. Shown are the estimates for a 5 m and a 30 m module. Lighting is the major energy user, although the energy required for cooling is significant. The fan energy is relatively small for the 5 m module, but becomes sizable when scaled up to 30 m. The 30 m module is assumed to have the same cross section area in the air return ducts as the 5 m module and the same air flow velocity. The fan energy could be reduced by 2 or 3 by enlarging the air return ducts and cooling coil.

Water Usage. The total water transpired by the plant

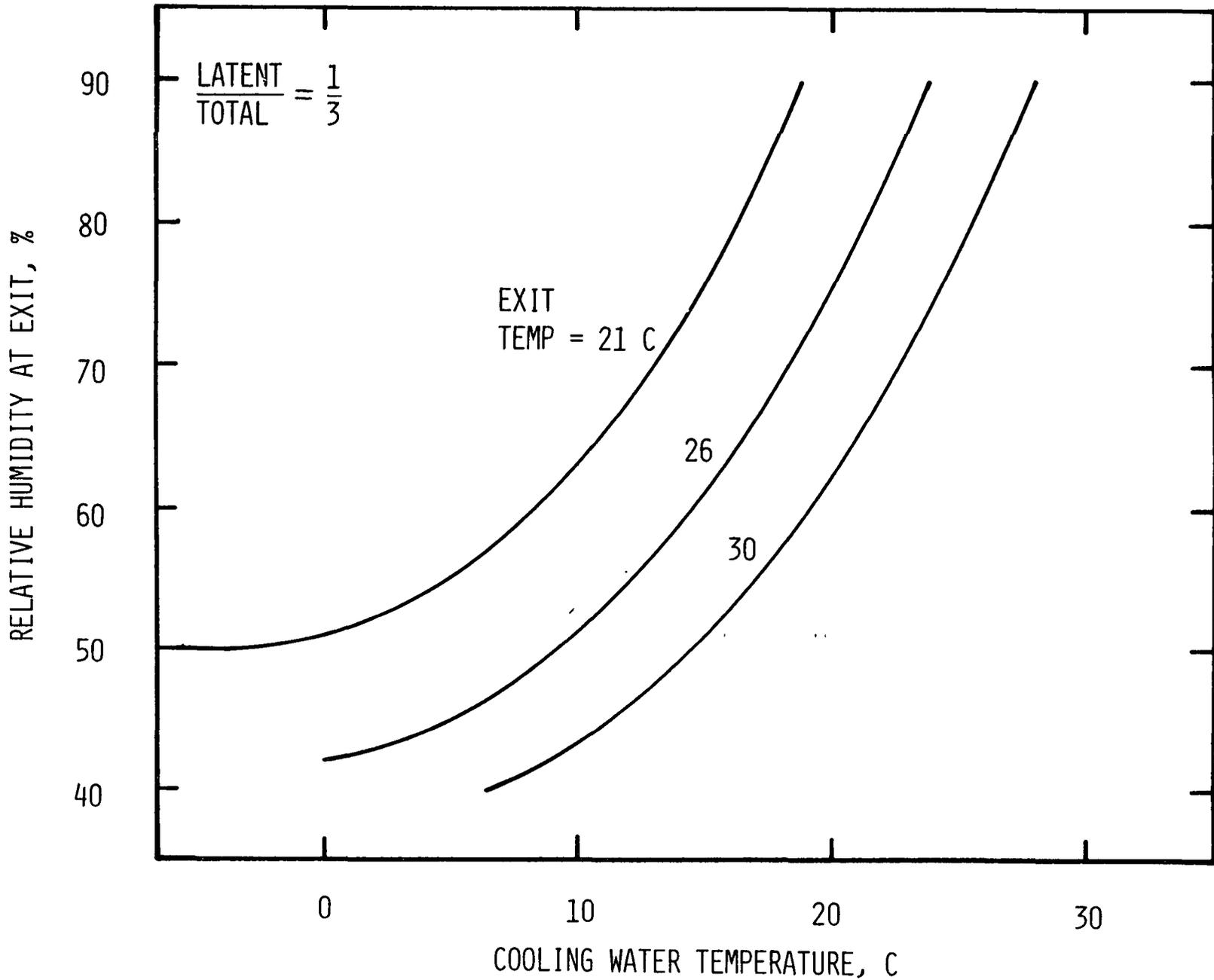


FIGURE 7. HUMIDITY LEVEL VERSUS COOLING WATER TEMPERATURE AND AIR TEMPERATURE

Table 1. Plant Growth Module Energy Requirements.

	Total Power, kw	Lighting %	Cooling %	Fan %
5 meter	2.5	69	27	4
30 meter	16.0	65	25	10

growth module filled with mature plants is estimated to be approximately 850 gm/hr. This level of transpiration, coupled with the light energy input, results in a latent heat ratio of 1/3.

CONCLUSIONS

The temperature and humidity of a closed-cycle plant growth module can be controlled with a circulating fan and a chilled water cooling coil. The fan speed controls the temperature rise of the air passing through the growing zone. The amount of thermal energy removed from the recirculating air can be controlled by the fraction of air passing through the cooling coil, the remainder being bypassed. The temperature of the circulating water controls the amount of moisture removed, thus controlling the humidity level in the growth zone.

Minimizing the energy requirements of the plant growth module will require minimizing the air flow rate, and reducing the pressure drop through the recirculation ducts. It will also require operating the cooling coil in the most energy efficient mode. If the chilled water is generated by a heat pump, the higher the chilled water temperature, the more efficiently the heat pump will operate. Thus it will be most efficient to operate the plant growth module at the highest acceptable temperature and humidity.

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