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IMPLEMENTATION OF ARTIFICIAL INTELLIGENCE TECHNIQUES IN THERMAL COMFORT CONTROL FOR PASSIVE SOLAR BUILDINGS

A. I. DOUNIS,[1]† M. J. SANTAMOURIS[2] and C. C. LEFAS[1]
[1]Department of Electronics, Technical University of Crete and
[2]Physics Department, University of Athens, Ippokratous 33, 10680 Athens, Greece

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Abstract—Artificial Intelligence techniques are used to control thermal comfort levels in a passive solar building. The controller, as well as the necessary group of rules, are described and analysed. Fuzzy logic is used for the first time in passive building control.

Passive solar building Control AI Fuzzy logic

NOMENCLATURE

AI = Artificial Intelligence
AMB = Ambient
cz = Comfort zone
MAS = Maximum allowed value
MIN = Minimum allowed value
PMV = Predicted mean value
PMVd = PMV desirable
PMVr = PMV real
PPD = Predicted percentage of dissatisfied
RH = Relative humidity of indoor air
T_{air} = Temperature of indoor air
V = Velocity of indoor air

INTRODUCTION

The present paper considers the use of AI techniques for the control of the thermal comfort of passive solar buildings. A typical system is examined, consisting of a classical passive solar system and auxiliary energy sources (mainly auxiliary heaters). A passive solar system consists of a high inertia building with large windows facing south, outside shading devices and a ventilation facility for cooling. The aim of the control system is to minimize the difference between the desired and the actual thermal comfort. In this respect, the control system should maintain environmental conditions within the comfort zone.

In a classical optimal control system, this task is accomplished by estimating the system parameters in real time [1]. This, however, results in heavy computational loads and software that needs extensive modifications to be implemented in different buildings. On the other hand, a theoretically "optimal control" is not always feasible, and suboptimal solutions have to be followed in practice. The simpler type controller which has been used for the control of a space is a bang-bang controller with dead band. A thermostat has been used for these systems. A simple thermostat is inadequate because it controls the flow rates in a building on the basis of enclosure temperature alone [2]. Thus, it cannot respond to weather predictions, special physical discomfort conditions, or the relative costs of solar and auxiliary energy use. Also, its choice of flow rates is limited to OFF or ON conditions only. To overcome this limitation, recent control systems make use of more advanced techniques such as adaptive modelling, adaptive control, weather predictions with local weather models and optimizing algorithms to establish optimal strategies for integrated

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†To whom all correspondence should be addressed at: Sp. Davari 18, Koropi 19400, Greece.

control of window devices, such as blinds, vent windows, etc., and the conventional heating systems [3–12].

An alternative to the use of adaptive control strategies is to use an intelligent controller for the control of the building. Such an approach will yield only a suboptimal operation of the system, but can be easily implemented and modified for application in different buildings. The main advantage of AI techniques, operating on a set of logic inference rules, the knowledge base, i.e. implementing simple AI techniques, is that it can offer different levels of knowledge to implement the process control strategy. These different levels of knowledge are organized hierarchically, and an appropriate strategy is used for problem-solving [13]. In this paper, an intelligent controller is described which is based on rules without requiring the mathematical model of the system [14]. This is the main difference of intelligent controllers from adaptive controllers. AI techniques give the ability of extension of the intelligent controller so it can control multizone buildings.

Space temperature control within an acceptable zone does not imply comfort for the inhabitants. Other variables must be simultaneously controlled for comfortable conditions. This is the main reason behind the necessity to control the PMV index rather than the temperature alone. Human behaviour dependent factors are included in the PMV index, like clothing and activity, which makes it necessary to assume a certain model of human behaviour.

Every variable in the PMV index has a range of acceptable values, rather than a simple set point. Also the limits of this range are, in practice, vague. Consequently, a suitable controller should adjust the environmental conditions within the acceptable region and be flexible enough to change its priorities according to the type of demand from the acceptable region (comfort zone). A suitable controller can be built by utilizing fuzzy logic [15]. Fuzzy logic control is extremely well suited for this task which inherently has several vague conditions, as the desired set point of variables.

A further goal of the control strategy is to achieve maximum energy savings by reducing the operation of the auxiliary heater and cooler, exploiting the capabilities of a passive solar building design.

THERMAL COMFORT

According to Fanger's theory, the thermal comfort in a space is expressed by a thermal index, which is calculated by Fanger's equation [16]. This thermal sensation is ranged between the seven points of the psycho-physical ASHRAE scale (from -3 cold through 0 neutral to $+3$ hot) [17].

Variables that play a crucial role in thermal comfort are:

Person dependent variables such as: activity and thermal resistance of clothing.
Environment dependent variables such as: air temperature, mean radiant temperature, relative air speed and air humidity.

Thus, a well proven comfort index exists, but there are problems. There are psychological factors influencing the neutral temperature, resulting in the movement of the PPD curve away from zero. Also, people tend to acclimate in a certain space. In addition, there are factors not included in the PMV index. Air temperature, mean radiant temperature and air speed differ between rooms. They differ even between starting points within the same room. Consequently, the PMV index is not constant in space and in time, but this is not a serious problem in practice [18].

Finally, it must be noted that there are aspects of comfort which are non-thermal but may be interactive through psychological mechanisms with thermal comfort. A good example is a glare which causes optical discomfort. Another non-thermal comfort problem is noise from the operation of the openings for ventilation and noise generated within buildings where rooms are interconnected to provide through routes for natural ventilation.

INTELLIGENT CONTROL

The intelligent controller takes decisions with ON/OFF operations which adapt the real level of thermal comfort to the desirable level in real time. The control of thermal comfort is obtained by a group of rules which derive the appropriate control actions. In this system, the rules are set so that the action tends to approach the results:

$$\mathrm{PMV(real)} - \mathrm{PMV(desirable)} = 0.$$

The real PMV is calculated by Fanger's equation after the measurements of the temperature of the indoor air, of the relative humidity, of the velocity of the air and the mean radiant temperature.

In Fig. 1, the process represents the physical system. The condition interface consists of the conjunction of values of the measurements with the computation unit for the calculation of the PMV. The action interface is a modification to the control inputs.

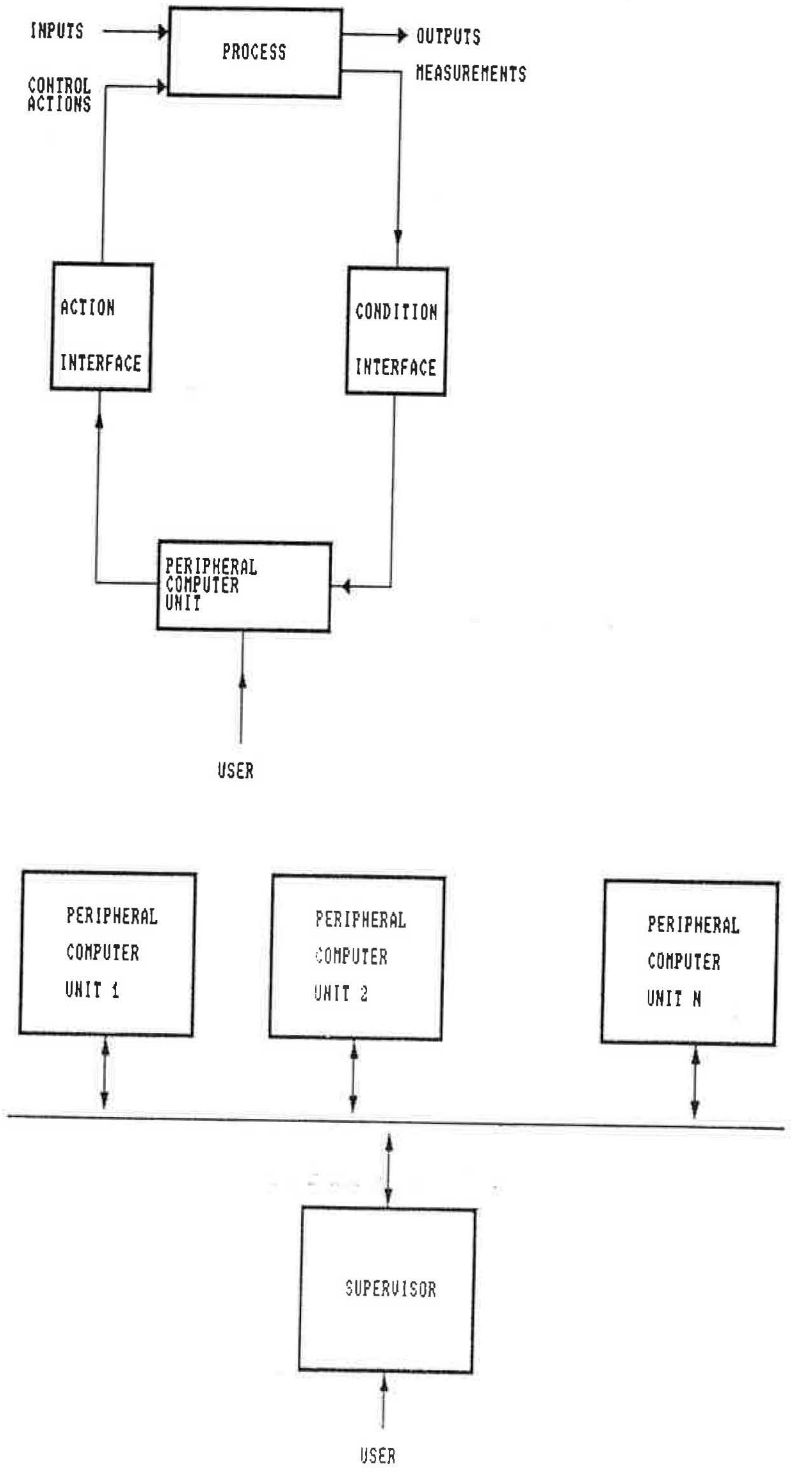

Fig. 1. Design details of the intelligent controller.

The software windows aid the user to communicate with the system. The information given by the user is: the desirable PMV and the user's activity levels and clothing. With these elements, the controller tries to minimize the difference between the real and desirable index. In accordance with the tolerance limits set by the ISO [19], the controller tries to regulate the PMV within a ± 0.5 deviation zone. It is considered that ventilation is achieved by natural means as well as using fans. About 0.5 air changes per hour of ventilation is required for health reasons. Mechanical ventilation equipment is controlled by ON/OFF operations. Control of natural ventilation levels is achieved by adjusting vent window openings. In the case where ceiling fans are used for summer cooling, the extended comfort zone defined in Ref. [20] should be used.

Dehumidification or humidification of the indoor air can also be achieved by ventilation. Ventilative dilution is a simple and cheap source of dehumidification [18]. According to moisture control standards [21], relative humidity should be held lower than 70%. However, for optimal health conditions, the interior relative humidity should be held below 60% [22].

Shading devices can be used for control of direct solar gains, control of day lighting and prevent inconvenient glare. The controller adjusts the position of the shading device in order to keep the indoor temperature in the comfort zone, or to keep the illumination at a comfortable level. The shading device also adjusts positon only as a function of the sun and the amount of solar radiation, for instance to avoid glare [23]. However, in the case where the user prefers to view the outside environment, the controller can satisfy this requirement.

If-then type of logic inference rules are used to follow diagram paths [Figs 2(a,b)]. Since various variables in the diagram have satisfactory value ranges, rather than satisfactory unique values, there is, inherently, a certain degree of "fuzziness" in the implementation of the logic rules. In practice, even the limits of the acceptable region are not crisp, but fuzzy, since small deviations from the acceptable region cannot be treated in the same way as large ones. This is best modelled as a fuzzy set of acceptable variable values. Consequently, a membership function (see Appendix) must be established for every variable, defining the degree of membership of each value is the (now fuzzy) set of acceptable values.

A suitable decision table is made by using fuzzy set theory on the logic diagram [Figs 2(a,b)]. This table, in turn, is used to build the inference engine and, consequently, the control protocol of the rules [24, 25].

THE CONTROLLER ELECTRONICS

Although the present paper describes the system for the control of one process only (i.e. one space), its hardware has to be designed to accommodate multiple zone processes. In this respect, a network of single board computers is used, supervised by a central station. To reduce costs, a custom design is used for every peripheral computer unit, whereas a standard, commercially available computer is used for the supervisor.

The network hardware is based on the RS-485 standard. This is done for two reasons: (a) the requirement is low cost and has wide availability; (b) the rate of the exchanged data is rather small so that a low speed network protocol can be used. The RS-485 can be easily implemented for network lengths of 2 km.

The peripheral computer unit design uses the industry standard 8052 single chip computer, operating in the single chip mode. A 12 bit A/D converter is used (MAX 172), equipped with a sample and hold circuit, a 32:1 analog multiplexer and the relevant signal conditioning circuits. The A/D converter is also provided with two flip-flops ensuring synchronization between the operation of the A/D converter and the single chip computer. This is necessary to avoid digital noise to corrupt the analog input and measurements.

Digital I/O is accomplished through the digital I/O port. Since the 8752 in its single chip mode does not provide handshake signals, these are simulated by a small software routine. Although this is clearly a slow process, it creates no problems, since the driven actuators are themselves very slow. Addressable latches (HCT 259) are used to demultiplex the signals to the digital I/O port, providing a total of 48 output signals. Its signal is capable of driving an optically isolated solid-state switch (a.c. or d.c., Grayhill were used in our original design). Each digital output line can also be used as a digital input, providing some degree of output checking capability.

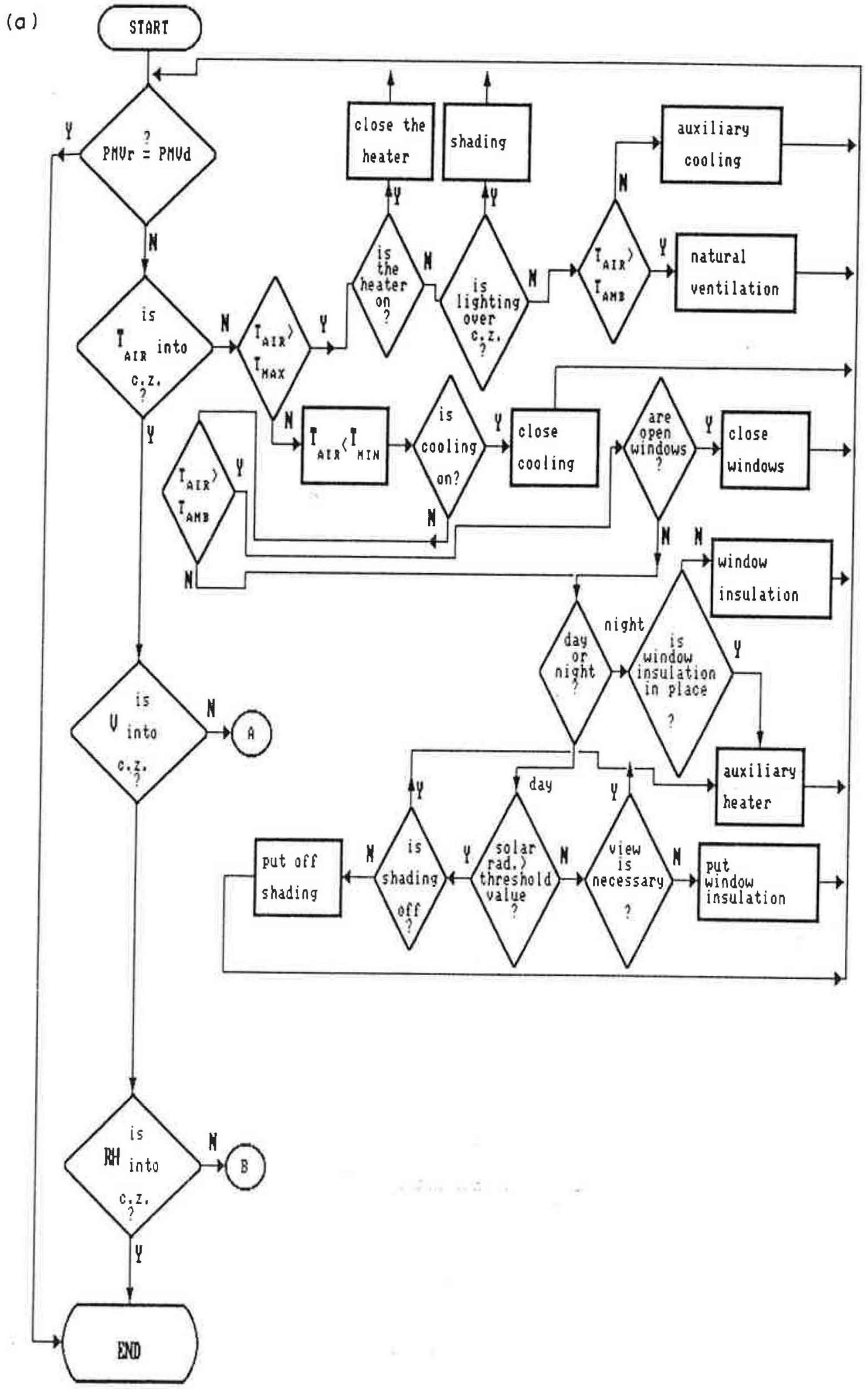

Fig. 2(a). *(Caption overleaf).*

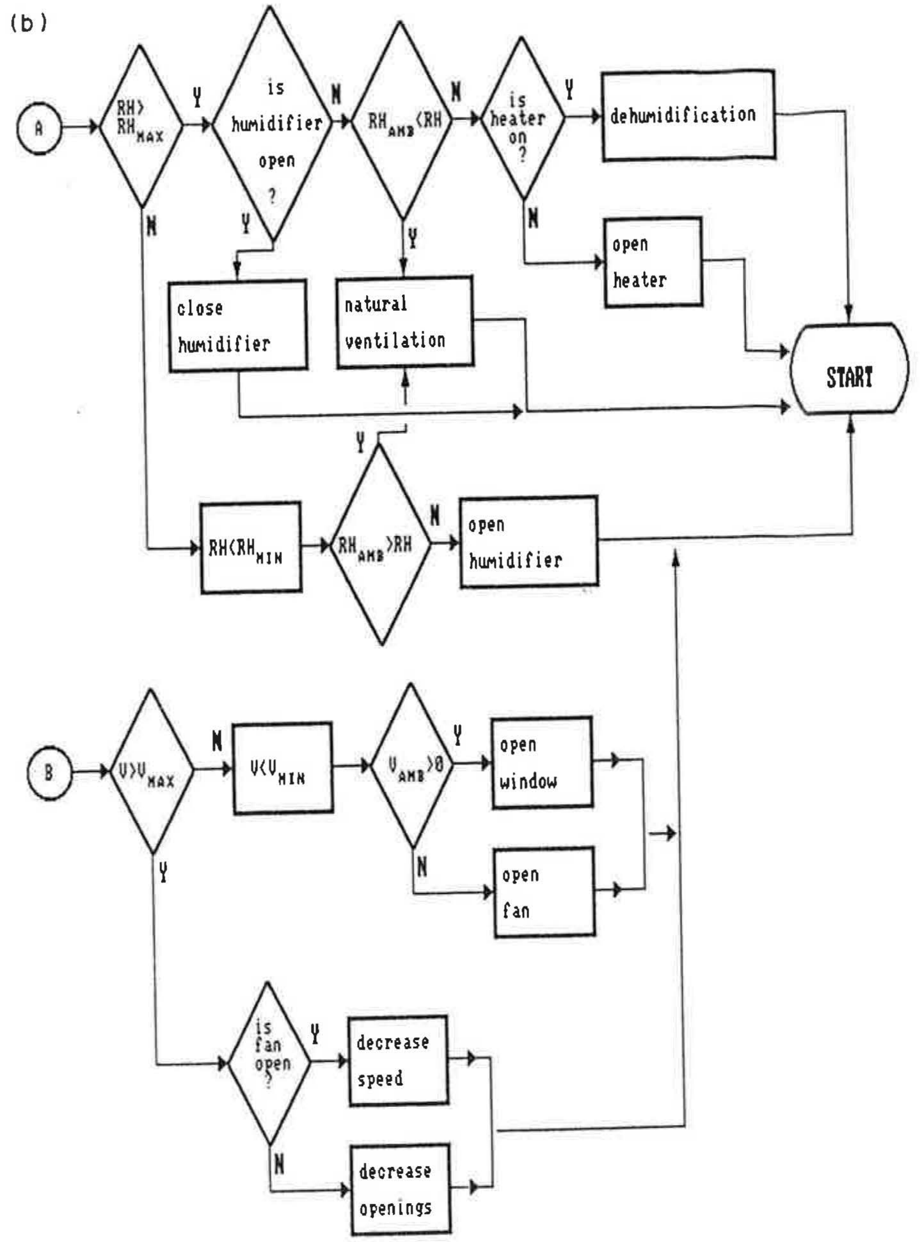

Fig. 2b

Fig. 2. Flowchart of the controller.

Finally, the peripheral computation unit is equipped with its own power supply unit. This unit contains a battery back-up circuit so that measurements are taken in a power down situation, although commands cannot be given.

CONCLUSIONS

The present paper presents a way of implementing AI techniques for the control of passive solar buildings. The techniques presented here may well be implemented in other similar systems, like greenhouses, and are easily extended in fairly complex thermal systems, such as centrally heated villages, hybrid solar buildings, etc. The presented AI control presents serious advantages over classical controllers, which are very cumbersome in any control application of buildings requiring something beyond energy management optimization.

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APPENDIX

Some Relevant Aspects of the Fuzzy Sets Theory

A fuzzy subset A of a universe of discourse U is characterized by a membership function $\mu_A(u)$, which assigns to each element $u \in U$ a number $\mu_A(u)$ in the interval 0–1, which represents the grade of membership in A. Three basic operators used are defined as follows:

(a) The union of the fuzzy subsets A and B of the universe of discourse U is denoted by $A + B$ or $A \cup B$, with a membership function defined by

$$\mu_{A+B}(u) = \max[\mu_A(u); \mu_B(u)].$$

The union corresponds to the connective 'OR'.

(b) The intersection of the fuzzy subsets A and B is denoted by $A \cap B$, with a membership function defined by

$$\mu_{A \cap B}(u) = \min[\mu_A(u); \mu_B].$$

The intersection corresponds to the connective 'AND'.

(c) The complement of a fuzzy subset A is denoted by $\neg A$, with a membership function denoted by

$$\mu_{\neg A}(u) = 1 - \mu_A(u).$$

Complementation corresponds to negation 'NOT'.

Rule Relation

To relate the fuzzy subsets A and B of disparate universes of discourse U and V, the fuzzy conditional statement is introduced, that is $A \rightarrow B$ or "if A then B". Here, A (the antecedent) and B (the conclusion) are fuzzy subsets rather than propositional variables. A relation R from A to B is a fuzzy subset of the Cartesian product $U \times V$, where $A \in U$ and $B \in V$. The membership function is defined by

$$\mu_R(u, v) = \mu_{A \to B}(u, v) = \min[\mu_A(u); \mu_B(v)].$$

Compositional Rule of Inference

If R is a fuzzy relation from U to V, and x is a fuzzy subset of U, then the fuzzy subset y of V that is induced by x is denoted by

$$y = x \circ R$$

and defined as follows: $\mu_y(v) = \max \min(\mu_x(u), \mu_R(u, v))$.

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DEVELOPMENT OF A TWO-DIRECTIONAL AIR FLOW PADDY DRYER COUPLED WITH AN INTEGRATED ARRAY OF SOLAR AIR HEATING MODULES

A. CHAKRAVERTY and S. K. DAS
Post Harvest Technology Centre, Indian Institute of Technology, Kharagpur-721 302, India

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Abstract—An integrated array of solar heating collector modules of 20 m² area has been designed and coupled with a two-directional air flow batch dryer of 0.5 tonne holding capacity. The integrated collector consists of 10 compartments with 13 common partitions among themselves to minimize heat losses from the edges and the area of each compartment is 2 m². It is organized in 2 rows and 5 columns. Results with 0.32 kg/s air flow rate showed that the outlet temperatures of the air in different months of the year varied between 50 and 60°C (where the rise in air temperature, ΔT varied between 18 and 26°C) as desired for raw paddy drying. An average efficiency of the combined air flow organization was slightly higher than that of the parallel air flow organization. The solar system took 3.5 h to dry 500 kg of raw paddy from 23.5 to about 14% (db) at 0.30 kg/s air flow rate with the production of the same head yield as in the case of sun drying. It took 12 h of sunshine when the same paddy was sun dried for 6 h continuously in each day for two consecutive days.

Solar grain drying Solar paddy dryer Solar energy Solar air heater

INTRODUCTION

Harvesting of paddy at a high moisture level, followed by controlled mechanical drying, significantly reduces field losses and increases the head yield. The traditional practice of crop drying on the cemented floor by direct sunshine involves the risk of weather damage, admixture of dust and losses owing to birds and rodents. On account of the increasing oil price and high operating costs of drying with oil fired or coal fired heating systems, the use of mechanical drying has not been popularized, except in coastal areas and in some modern rice mills under the Government or cooperative sectors in India. A flat-plate solar collector is suitable for heating air 15–20°C above ambient temperature [1], and hence, it can be useful for grain drying.

During the past few years, experiments on solar drying of a wide range of agricultural products have been carried out in different parts of the globe using different designs of solar collectors [2]. But no suitable commercial solar paddy dryer is available in the developing countries, particularly in India.

The present study has been undertaken with the following objectives:

(1) To develop an integrated array of flat-plate solar air heating modules for a paddy dryer of 0.5 tonne holding capacity and
(2) To study the performance of the above integrated solar paddy drying system.

MATERIALS AND METHODS

A batch dryer of 500 kg holding capacity has been designed for drying wet raw paddy from an initial moisture content of 25% (db) to a final moisture content of 15% (db). The yearly average daily sunshine hours, ambient temperature and relative humidity at Kharagpur (22.3°N, 87.2°E) were recorded to be 6.83 h, 26.3 °C and 70%, respectively [3]. Considering the effective period of operation of the solar dryer from October to May (excluding the months from June to September for frequent rainy days) at Kharagpur, India, the optimum collector tilt was estimated to be 30° with the horizontal surface using the method developed by different workers [4–6]. The yearly average daily solar insolation on the horizontal and on the 30° inclined collector surface