

Design and Development of Family Size Solar Dryer Capable of Single Day Aqua and Horticulture Products Drying: Thermal Modeling and Experimental Validation

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ABSTRACT

Mass migration of able labour force from remote and rural areas to big cities is mainly driven by food insecurity, energy unavailability and reduction in economic opportunities. These have created demographic imbalances in larger cities, leading to social tensions and slums. Developing appropriate and cost-effective low-technology intensive solar drying technique has immense potential to initiate sustainable developmental activities in rural areas, where migration has decisively reduced options of development at various levels. In this paper, a family size Cabinet Solar Dryer (CSD) capable of drying aqua-products as well as horticulture products is presented. The model is developed theoretically and validated experimentally to meet various objectives of sustainable development in rural areas of India. It can be used in any other developing countries as well. The results indicate that the dryer designed and proposed is versatile in nature, easy in technology absorption, and localized in manufacturing. The dried products can be preserved for over six months with almost all essential and vital food values intact and without any application of pesticides and preservatives. They can be transported easily to economic hubs at room temperature, without any requirement of specialized services. Further, it does not require involvement of able labour force and can be easily handled by women and children casually.

Keywords: *Solar drying, Thermal modeling, Horticulture and aqua products, Food security.*

Nomenclature

A_c	area of tray (m^2)=area of glass cover(m^2)
C	specific heat ($J/kg\ ^\circ C$), coefficient
C_d	specific heat of humid air ($J/kg\ ^\circ C$)
F	fraction of solar radiation
g	acceleration due to gravity (m/s^2)
Gr	Grashof number
h_c	convective heat transfer coeff. ($W/m^2\ ^\circ C$)
ΔH	difference in pressure head (m)
$I(t)$	solar intensity on horizontal surface (W/m^2)
K	thermal conductivity ($J/m^2\ ^\circ C$)
K_v	thermal conductivity of humid air ($J/m^2\ ^\circ C$)
M	mass (kg)
M_{ev}	moisture evaporated (kg)
$P(T)$	partial vapour pressure at temp. T (N/m^2)
ΔP	difference in partial pressure (N/m^2)
R	coeff. of linear expression of partial pressure
t	time (s)

T	temperature ($^{\circ}\text{C}$)
T_a	temperature ($^{\circ}\text{C}$)
T_d	temperature just above fish/fruit surface ($^{\circ}\text{C}$)
T_f	fish/fruit temperature ($^{\circ}\text{C}$)
U	over all heat loss ($\text{W/m}^2\text{ }^{\circ}\text{C}$)
v	wind /air velocity (m/s)
γ	relative humidity of air (dec.)
ε	emissivity
σ	Stefan–Boltzman constant
λ	latent heat of vaporization (J/kg)
μ	dynamic viscosity of air (kg/m)
ρ	density of air (kg/m^3)
τ	transmissivity
μ_v	dynamic viscosity of humid air (kg/m)
ρ_v	density of humid air (kg/m^3)

1. INTRODUCTION

Global Climate changes are directly linked to harsh climatic conditions such as floods and droughts. In remote areas, these conditions have invariably caused mass migration of population in search of livelihood. Though, decades of efforts in the field of aquaculture and arid area horticulture in particular, have provided technically much needed relief as an alternative means of livelihood, it has never been practically realized so due to various constraints. For example, aquaculture has never been adopted in remote areas sensitive to climatic variations. Whether it is flood (overflowing ponds/low price) or harsh summer (drying of ponds), they are considered as extremely susceptible to vagaries of nature. Besides, risk factor involved in transportation and preservation with traditional knowledge have made them least sought after modern economic activities. Horticulture products too have faced similar problems and are confined mostly to local consumption level despite there high potential as food security, economic and employment generating activity.

Arid and Semi arid areas in Bihar are not only prone to draught condition but also to flash floods from Nepal. These floods often cut-off low lying districts of Bihar from main land by surface and rail. Unavailability of Food and absence of employment in agriculture dependent high population density districts of Bihar during floods and droughts can ignite human catastrophe among marginalized farmers and labourers. Preservation technology is almost non-existent due to bad power situation, affordability and absence of technical expertise among local populace. Solar fish dryer has immense potential as low-cost and low-maintenance preservation technology in remote areas. During pre flood season, it can be used for fish drying by taking advantage of low price, and subsequently marketing in off-season at higher price. If these designs could be modified to include drying of horticulture products, its utility would increase several folds. Horticulture products especially from arid areas and semi-arid areas are rich in vitamins and essential minerals. These seasonal horticulture products have huge markets all over world but these are mostly consumed locally due to very short lifetime, expensive preservation technology and specialized transportation facility. A large part gets rotten before they reach bigger market. These can be dried in CSD in a hygienic manner and further value can be added by product development. Since water content is almost removed, weight of the product reduces by 50% to 80% and doesn't need specialized transportation facility besides increased time frame to store it under normal condition. Considering the importance of solar drying, a series of experiments were

undertaken to develop family size versatile CSD for drying aqua-products as well as horticulture products simultaneously. The system, Cabinet Solar Dryer under natural convection, is theoretically examined and modelled to incorporate changes for need based modification and evaluation. The model can predict the hourly fish/fruit temperature, dryer temperature and rate of moisture evaporation.

Locally available materials and cost-effectiveness has been given precedence while designing the experimental set-up. The passive solar dryer design proposed is capable of achieving 90° Celsius during peak summer and even dries products like fish (Rohu and Katla), Prawn, Bel, Aonwla, Jamun, Litchi, etc. in a single day (6-14 hrs). Temperature preservation and regulation mechanism is based upon high heat capacity local rocks (stones), which is available in plenty in these areas. Products were kept for six months to test their durability and preservation capacity. The whole drying process requires no chemicals and preservatives.

The system proposed is simple to operate and convenient for almost illiterate masses in this area. It can maintain 45-70° C range for more than fourteen hours, almost five hours after the sunset. By reducing or increasing the weight of the stones, temperature and number of hours can be traded off. The developed CSD can be lifeline of sustainable developmental activities in remote and rural areas. The results obtained indicate that the design proposed can be used in dual mode of operation - for fish as well as horticulture product drying, taking advantage of differing timings of the raw materials and season. It can be used for low temperature range (12 to 14 hours a day) and higher temperature range (4 to 6 hours a day).

2. WORKING PRINCIPLE OF CABINET SOLAR DRYER

The working principle of Cabinet Solar Dryer (CSD) is shown in fig. 1. The incident solar radiation is partially reflected by the glass cover (4% to 8%). Transmitted portion of the incident radiation is again partially reflected by fish/fruit surface. Remaining major part is absorbed by the drying material and blackened stone chips called, High Heat Capacity Material, kept in the bottom of the dryer. Due to high heat capacity, their temperature rises very slowly and they radiate in long wavelength range, which is opaque to the glass cover. These Long wavelength radiation increases the cabinet air temperature more as compared to that of drying material surface. Difference in the air temperature above the fish/fruit surface creates heat and mass transfer, i.e., transfer of water content from inside the drying material, which gets evaporated. High Heat Capacity Material (HHCM) absorbs more thermal energy for each degree rise of temperature and thereby used for regulation of temperature. Since, higher temperature of internal environment gives rise to higher thermal loss, HHCM reduces thermal loss. Lower temperature is preferred mode of drying due to its ability to preserve food value. Besides, it also allows drying process to continue during off-sunshine hours for longer period by slow release of thermal energy. The bottom and side walls are insulated by thermo-insulator material kept between double layers of galvanised sheet (body). The moisture is removed by the air entering into the chamber from lower side and escapes through higher side at the top as shown in the fig1. This process of moisture removal by ventilation is stopped by closing the vents after five hours or when the solar radiation starts decreasing. Most of the moisture content is removed by that period. Rest can remain inside the CSD till drying process is complete. Top glass is covered with insulation when thermal loss to external environment from the CSD exceeds thermal gain from solar radiation i.e. after 15hours.

3. EXPERIMENTAL SETUP AND PROCEDURE

Experiments were performed in the months of June, July, August, September and October (2004) and of February, March and April (2005) for Cabinet Solar Dryer (CSD) fig. 2. A four-channel digital temperature indicator (range 125°C, least count 0.1°C) with copper constantan thermocouples was used for measurement of fish/fruit temperatures and air temperatures at different points inside the dryer. An electronic balance of 1 kg capacity with a least count of 0.01g was used for gravimetric analysis. Observations were recorded at an interval of half an hour. The whole unit was kept in open sun on clear days at a place with negligible wind velocity. The experiment was repeated five times for obtaining more accurate results. Nevertheless, the best results were obtained in summer months.

4. THERMAL ANALYSIS OF CSD

Thermal analysis of the CSD and drying process is developed on the basis of theoretical models of crop drying processes proposed by a few researchers. For example, numerical models considering diffusion as the primary transport mechanism [1,2], natural convection heat transfer model with density of air as a function of temperature and absolute humidity [3,4], coupled heat and mass transfer model within a single kernel of grain [5] simultaneous heat and mass transfer model [6], are some of the earlier works worth mentioning. The heat transfer coefficient is found to vary from 43 to 59 W/m²/K [7,8], which is much easier to dry as compared to aqua-products and horticulture products. The later is sensitive to high temperature and also drying rate.

The theoretical model proposed here is based upon formulating and solving energy balance equations for various components of the system. To simplify the computation process, following assumptions have been used;

- (i) the heat capacities of glass, fish/fruit tray, drying chamber wall and air have been neglected,
- (ii) volume shrinkage is negligible during drying process,
- (iii) heat flow is negligible,
- (iv) no condensation of water vapour inside the glass cover,
- (v) there is no stratification along the depth of fish/fruit due to this layer, and
- (vi) solar dryer is south oriented.

Energy balance equations

Energy balance equation of CSD chamber is based upon the coefficient of diffusion and differences in partial pressure due to the temperature difference of the CSD chamber air and ambient air. The energy balance equation for fruit/fish surface and the CSD chamber can be separately set-up following [9, 10]. Energy balance equation for Fish/fruit surface and for CSD can be written as;

$$F_c \alpha_c \sum I(t) A_c \tau_c = M_c C_c \frac{dT_d}{dt} + h_c (T_f - T_d) A_c + 0.016 h_c [P(T_f) - \gamma_d P(T_d)] A_c \quad (1)$$

$$(1 - F_c)(1 - \alpha_g) \sum I(t) A_c \tau_c + h_c (T_f - T_d) A_c + 0.016 h_c [P(T_f) - \gamma_d P(T_d)] A_c = C_d A_v \sqrt{2g \Delta H \Delta P} + \sum U_t A_c (T_d - T_a) \quad (2)$$

Where,

$$\Delta H = \frac{\Delta P}{\rho_r g}, \quad \Delta P = P(T_d) - \gamma_a P(T_a) \quad (3)$$

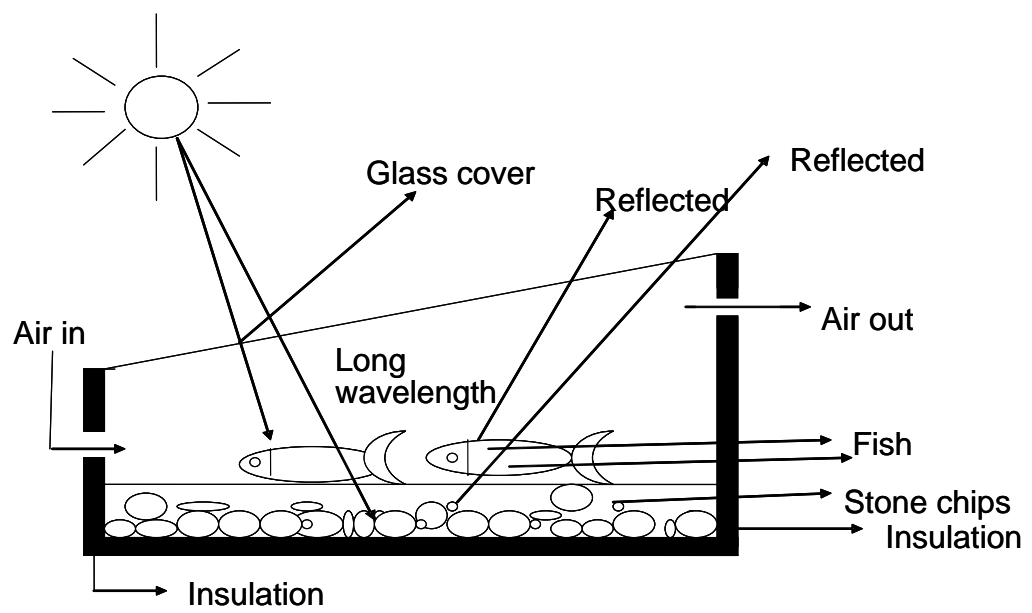


Fig. 1 Thermal processes involved in cabinet solar dryer.

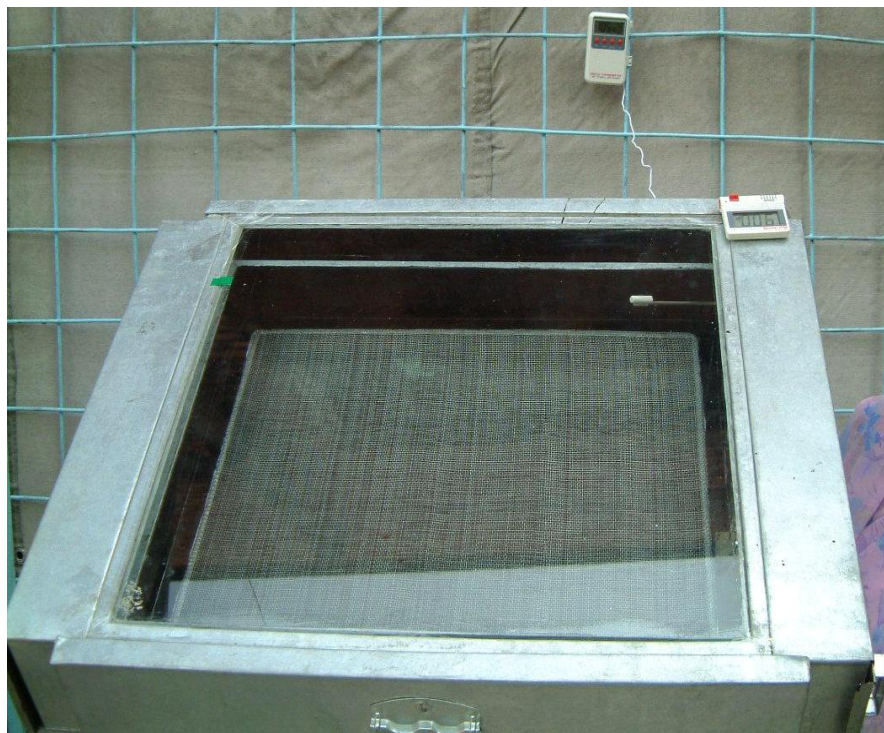


Fig. 2 Family size cabinet solar dryer.

Table 1a Hourly solar intensity and ambient temperature (April 16, 2005).

Hours	Solar Intensity (W/m ²)	Ambient Temperature (T _a)
7	10	22
8	155	23.5
9	235	26
10	380	28
11	605	31
12	675	31
13	725	33
14	580	35
15	480	36
16	275	35
17	100	33
18	20	33

Table 1b Constant used in numerical calculation.

Parameters	Values
C _d	0.425
g	9.8
t	3600
M _f	3-5kg
R ₁	397.52
R ₂	-7926.90
v	0.5
α _g	0.85
λ	2.26 *10 ⁶
Ac	0.5m ²
ε	0.9
σ	5.67 *10 ⁻⁸
τ	0.9

Table 1c Convective heat transfer coefficient (h_c) for 2.5×10⁵<Gr<4.0×10⁵

Fish/Fruit	h _c .(W/m ² °C)
Fish (Labeo rohita)	30
Prawn	30
Litchi (Litchi chinesis)	26.1
Aonla (<i>Emblica officianalis</i>)	14.05
Wood Apple (<i>Aegle marmelos</i>)	8.45
Jamun (<i>Eugenia Jambolana</i>)	8.20

Thermal efficiency (CSD)

Thermal efficiency is defined as the ratio of heat energy utilized in moisture removal from the fish/fruit surface and the total heat energy input from solar radiation. The overall thermal efficiency of CSD is computed using following expression,

$$\eta_o = \frac{\lambda \sum_{t=1}^{24} \hat{M}_{ev}(t)}{3600 \sum_{t=1}^{24} I(t)} \quad (4)$$

Where, \hat{M}_{ev} is the hourly rate of moisture evaporated from fish/fruit can be calculated,

$$\hat{M}_{ev} = 0.016 \frac{h_c}{\lambda} [(R_1 T_{f+} R_2) - \gamma_d (R_1 T_d + R_2)] A_c t \quad (5)$$

The overall thermal efficiency of the CSD depends upon the moisture removal rate from the fish/fruit for a given solar radiation. Therefore the drying rate can also be predicted for different moisture content of drying material.

Heat utilization factor

Heat utilization factor is defined as;

$$H.U.F = \frac{\text{Heat Utilized}}{\text{Heat Supplied}} = \frac{T_d - T_f}{T_d - T_a} \quad (6)$$

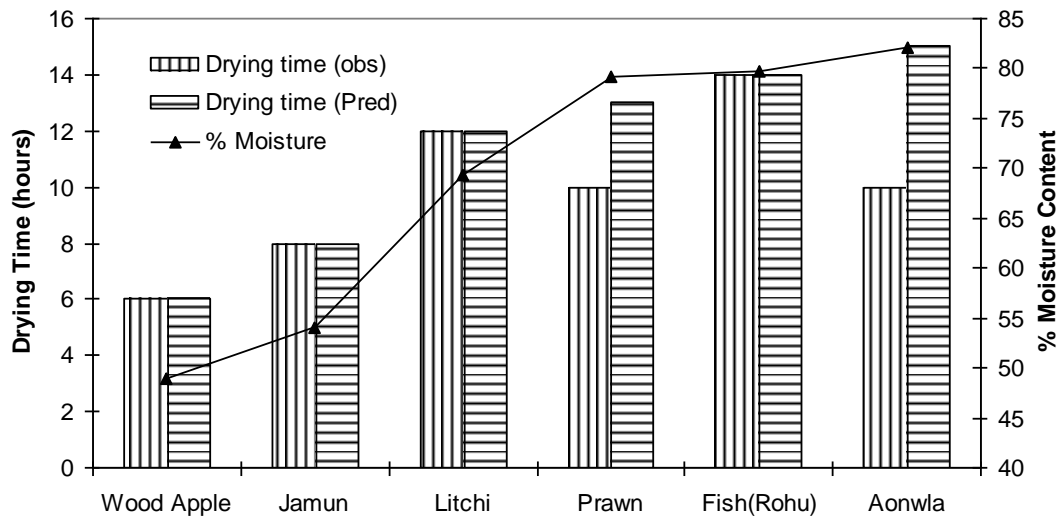


Fig. 3 Variation of moisture content by weight (%) and drying time, observed & predicted value for wood apple (*Aegle marmelos*), Jamun (*Eugenia Jambolana*), Litchi (*Litchi chinesis*), Prawn, Rohu (*Labeo rohita*) & Aonla (*Emblca officianalis*).

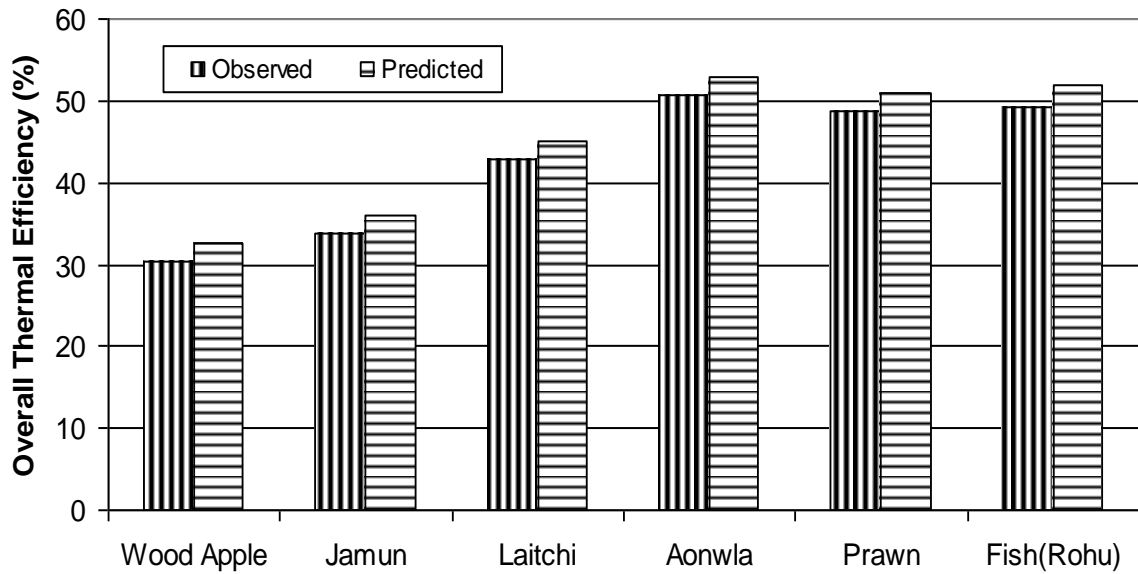


Fig. 4 Variation of over all thermal efficiency (%), observed and predicted value wood apple (*Aegle marmelos*), Jamun (*Eugeria Jambolana*), Litchi (*Litchi chinesis*), Prawn, Rohu (*Labeo rohita*), and Aonla (*Embllica officianalis*).

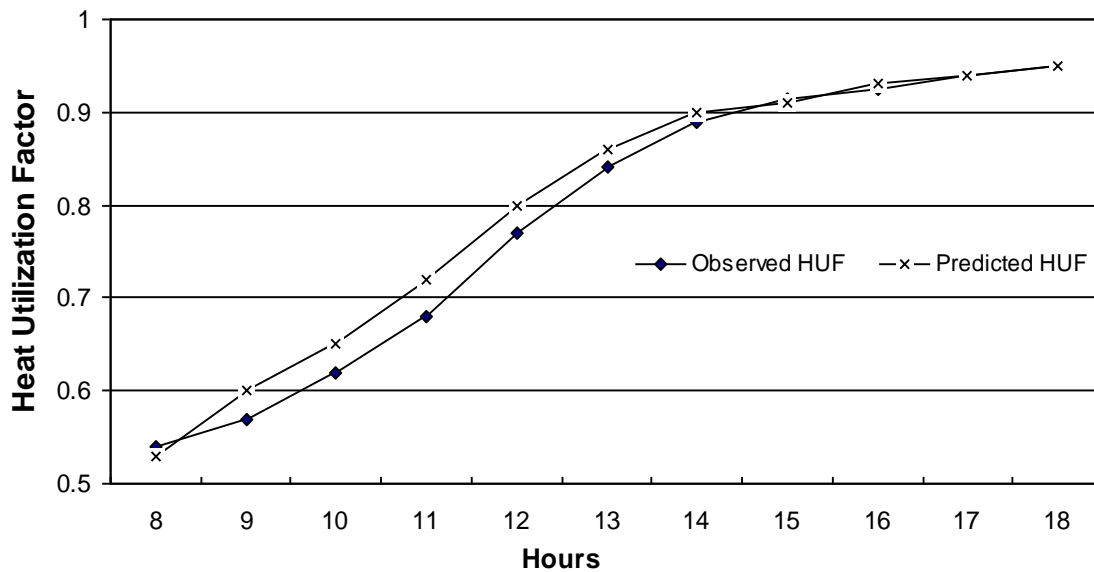


Fig. 5 Variation of Heat Utilization Factor (H.U.F.) for CSD.

5. RESULTS AND DISCUSSIONS

A series of experiments were conducted to investigate the solar drying process of wood apple (*Aegle marmelos*), Jamun (*Eugeria Jambolana*), Laichi (*Litchi chinesis*), Prawn, Catla (*Catla catla*), Rohu (*Labeo rohita*), and Aonla (*Embllica officianalis*). The experimental results obtained are compared with the theoretical results predicted by solving equations (1) and (2). Here results are presented for sixteenth day of April 2005. The numerical input

values of climatic parameters and various parameters are given in table 1a, 1b and 1c. While solving the differential equation, it is assumed that there is no shrinkage ratio between fresh fruit/fish and of its dried pieces.

It was observed that the physico-chemical parameters, size and water content of the materials used for drying experiments are quite different. Water content varies from 60% to 80% by weight. In case of Aonla, Prawn and fish, Catla (*Catla catla*) and Rohu (*Labeo rohita*), it is ~80% while, for wood apple, it was merely 60%. Size of the drying material was also found important as fish of weight more than one kg was found difficult to dry in a day. Alternatively, it is proposed to dry fish of bigger size after cutting into pieces. Similarly, fibrous materials like wood apple had different characteristics affecting drying time. Drying time varied from 6 hours for wood apple to 14 hours for Catla (*Catla catla*) and Rohu (*Labeo rohita*). Besides, food value preservation was an important consideration in the whole process. Though, food value is understood to be preserved for drying temperature below 100°C, higher temperature above 75°C was found to have impact on the taste in dried fish. Brittleness was also found. However, for fruits, it had no impact.

These are important consideration in controlling inside cabinet temperature by optimizing the weight of high heat capacity materials. To obtain a theoretical basis of HHCM weight optimization and drying time theoretical model developed is compared with observed results in terms of overall thermal efficiency (η_o) and heat utilization factor (H.U.F.). Figure 3 shows the drying time and percentage moisture content for the fish and horticulture produce. The observed results are averaged for a series of experiments and provide an overview of drying process. Except for Prawn and Aonla, theoretical results match with experimental results. In case of prawn, discrepancy in result can be explained by the small size of local variety, for which convective heat transfer coefficient values should be different as considered from standard values. The result also indicates steep rise in drying time with moisture content of the fruits.

It may be concluded, that water content of the material primarily governs the drying time in similar conditions. However, an exception was also found in case of Gaincha (*Macrogynathus aculeatus*). This fish has oily skin and its tissues prevented drying action. Even after twice drying time used as compared to Rohu, drying was not complete. Fig. 4 shows variation of overall thermal efficiency for drying of Prawn, fish and varieties of horticulture products. It is interesting to note that the drying efficiency is better for higher moisture content materials. Fig. 5 shows variation of another important parameter, heat utilization factor (H.U.F.). Results indicate fare degree of match between experimental and theoretical values obtained. For lower values of drying time, some discrepancies were found due to the approximations used in numerical solution of thermal equations.

The results obtained, theoretical and experimental are in good agreement. This indicates that mathematical model based upon the energy balance equation can be used further to predict drying time of new products. Besides it can be used to optimize the weight of the high heat capacity materials. Another advantage would be to modify the CSD for specialized drying, which is temperature sensitive. In this case, HHCM can be replaced by appropriate phase change materials in the required temperature range. Besides, the dried products were further investigated for leftover moisture content and it was invariably found less than 5% in all the cases. The dried products were stored at normal room temperature for six months and no deterioration in taste and quality was found.

The proposed family size cabinet solar dryer (CSD) can be used as a plank in sustainable developmental planning for remote areas and/or rural areas. It can be used for food security, and employment generation and economic activities. Besides, conventional energy saving and renewable energy are other known benefits.

Acknowledgement

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