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Development of convective heat transfer correlations for common designs of solar dryer

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ABSTRACT

The knowledge of convective heat transfer coefficient h_{cpf} (absorber plate to flowing air) is necessary to predict or evaluate thermal performance of any solar dryer. In order to determine h_{cpf}, laboratory models of direct (cabinet), indirect and mixed mode solar dryer are designed and constructed to perform no-load steady state experiments for natural and forced air circulation. The dryers are operated under indoor simulation conditions for absorbed thermal energy and air flow rate for the range of 300–800 W/m^2 and 1–3 m/s, respectively. Separate methods depending on mode of heat utilisation are proposed for determination of h_{cpf} for different dryers. Correlations of h_{cpf} in terms of dimensionless numbers are developed for each dryer operating under natural and forced convection. Levenberg–Marquardt algorithm is used to develop temperature dependent correlations. A close agreement between experimental and predicted h_{cpf} values obtained from proposed correlations for natural convection dryers demonstrates their reliability. However, for forced convection dryers, there is a need to use temperature dependent *Nu–Re* correlation for more accurate results. The low uncertainty ranging from 0.3% to 0.8% in the determination of h_{cpf} confirms the accuracy of experimental data obtained for various dryer designs operated under different conditions.

1. Introduction

In India there is a significant amount of post-harvest losses of fruits and vegetables estimated at about 35%, the monetary value of which is approximately 10^4 million dollars annually [1]. The reason may be attributed to improper handling, poor preservation strategies and insufficient storage facilities. It therefore becomes imperative to minimize these food wastes to a largest extent possible and make them available in the off-season at remunerative prices. For the preservation of these agricultural products, the convective hot air drying using fossil fuels/grid-electricity is the most common technique employed in commercial dryers around the globe. However, due to unreliable or too expensive for the farmer to utilise them, more emphasis is being paid to solar energy as an alternative source for such applications [2]. In addition, it has tremendous potential especially in several regions of the world, where this source is abundantly available.

In past four decades, various types of solar dryers have been designed, developed and tested with the aim of achieving faster drying of food product at minimum cost. Ekechukwu and Norton [3] presented a comprehensive review on design, construction and operation of different types of solar dryers. However, all these dryers can be broadly grouped into three major types as direct, indirect and mixed mode, depending on the arrangement of system components and mode of solar heat utilisation [4]. The operation of these dryers is primarily based on the principle of natural or forced air circulation mode. In many rural regions of developing countries, the farmers have been preferably adopting natural convection over forced mode operated dryer, since it is inexpensive to construct and easy to operate without the need of grid connected electricity and supplies of other non-renewable sources of energy. In addition, natural convection cabinet dryer of direct type has been popular among farmers especially in India because of its ability for drying 10–15 kg fruits and vegetables at household level [5,6]. Selection of solar dryer for a particular food product is primarily governed by quality requirements and economic factors.

The common practice in predicting performance of solar energy system is to solve a set of several inter-related steady state heat balance equations representing various components [7]. The convective heat transfer coefficient, h_{cpf} (absorber plate to flowing air) is an important parameter that is required for mathematical modelling, computer simulation and performance prediction [8]. Understanding heat transfer between plate and fluid will not only help in improving the performance of system but also serves as performance index for comparison of various designs. Higher value of h_{cpf} is always desirable as it assists in faster drying of food product. Muneer et al. [9] discussed various aspects of heat transfer in different geometries of the physical system and types of air flow and presented related empirical correlations for convective heat

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Nomenclature

A_c	area of collector plate (m^2)
A_d	area of dryer plate (m^2)
D_h	hydraulic diameter (m)
h_{cpf}	convective heat transfer coefficient from plate to air of collector–dryer assembly ($W/m^2\,°C$)
$h_{c,cpf}$	convective heat transfer coefficient from plate to air of collector ($W/m^2\,°C$)
$h_{c,rpg}$	radiative heat transfer coefficient from plate to glass of collector ($W/m^2\,°C$)
$h_{d,cpf}$	convective heat transfer coefficient from plate to air of dryer chamber ($W/m^2\,°C$)
$h_{d,rpg}$	radiative heat transfer coefficient from plate to cover of dryer chamber ($W/m^2\,°C$)
h_{rpg}	radiative heat transfer coefficient from plate to glass of collector–dryer assembly ($W/m^2\,°C$)
k_a	conductivity of air (W/m °C)
L	characteristic length (m)
P	wetted perimeter (m)
Q	heat transfer rate (W)
S	absorbed thermal energy flux (W/m^2)
$\overline{T}_{am}$	average ambient air temperature (°C)
T_b	mean bulk temperature (K)
$\overline{T}_{cp}$	average temperature of collector plate (°C)
$\overline{T}_{cg}$	average temperature of collector glass cover (°C)
$\overline{T}_{cf}$	average temperature of collector hot air (°C)
$\overline{T}_{dp}$	average temperature of dryer chamber plate (°C)
$\overline{T}_{dg}$	average temperature of dryer chamber cover (°C)
$\overline{T}_{df}$	average temperature of dryer chamber hot air (°C)
$\overline{T}_f$	average temperature of hot air of collector–dryer assembly (°C)
$\overline{T}_g$	average temperature of glass cover of collector–dryer assembly (°C)
T_{mf}	mean plate-fluid temperature (K)
$\overline{T}_p$	average temperature of plate of collector–dryer assembly (°C)
T_w	wall temperature (K)
V_m	mean air flow rate (m/s)
U_b	bottom-loss coefficient of collector–dryer assembly ($W/m^2\,°C$)

Dimensionless numbers

Gr	Grashof number
Nu	Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
Re	Reynolds number

Greek symbols

σ	Stefan Boltzman's constant ($W/m^2\,K^4$)
β	volumetric thermal expansion coefficient (1/K)
ν	kinematic viscosity (m^2/s)
ε	emissivity

transfer coefficients in terms of dimensionless numbers. Hegazy [10] developed extensive mathematical models based on energy balance concept for various designs of photo-voltaic/thermal air collectors and studied their comparative performance. Forson et al. [11] carried out simulation studies for performance prediction of single pass double duct air heater. In both of these studies, it can be noticed that published heat transfer correlations have been employed for computer simulation investigations. Most recently, Pakdaman et al. [12] developed convective heat transfer correlation for natural convection air heater with rectangular finned absorber plate to evaluate the thermal performance. The application of published correlations developed for solar air heater and conventional system geometries may not be amenable for performance prediction of solar dryers and therefore lead to erroneous results. Goyal and Tiwari [13] presented the theoretical analysis for thermal performance of reverse flat absorber cabinet dryer assuming constant values of h_{cpf}. In addition, Jain and Tiwari [14] published experimental results of convective heat transfer from food product to hot air for several food crops using solar greenhouse dryer whereas effect of shrinkage on heat transfer coefficient during drying of potato cylinders is reported by Rahman and Kumar [15]. However, these studies carried out for load condition are highly influenced by food product moisture removal rate leading to heat transfer results with a wide variation for a given test condition.

The literature review indicates that many researchers, while predicting performance of solar dryers systems are constrained to utilise convective heat transfer correlations published for standard geometries of system and specific test conditions [16–18]. The reason for this attempt may be attributed to scarcity of relevant heat transfer correlation for specific dryer design and given test condition. The lack of research interest among the researchers may be due to complex geometry of dryer system comprising solar air heater integrated with drying chamber and air flow pattern. In addition, many established correlations have neglected the effect of air property variation due to temperature change, with an aim of providing a simpler formulation. It appears from the review of literature that the limited work on h_{cpf} determination and development of heat transfer correlations for any dryer design has been reported so far. In the present work, modest attempt is made to bridge the research gap by development of heat transfer correlations for the most common dryer designs in different operating conditions, thus enabling researchers to predict thermal performance of specific dryer with more reliable and accurate results. It is well recognised that testing of solar equipment under indoor controlled simulation is preferred to variable outdoor climatic conditions for obtaining more reliable steady state results. In addition, it provides a more meaningful and effective means of comparison among various designs of equipment. Further, the experiments with no-load provide consistent results as these are not influenced by type, composition and moisture content of food product [4]. Thus, in the present study, laboratory models of direct (cabinet), indirect and mixed mode solar dryers have been designed and constructed for indoor natural and forced convection experiments under no-load condition. The major objectives of present study are: (i) to carry out no-load steady state indoor experiments on three most common designs of solar dryer for different operating conditions (ii) to propose separate methodology for the determination of convective heat transfer coefficient, h_{cpf} for each dryer design (iii) to develop correlations for h_{cpf} in terms of dimensionless numbers for different solar dryers and validate their reliability through comparison with experimental results.

2. Experimental arrangement

2.1. Construction details of dryers

The cabinet, indirect and mixed mode laboratory models of solar dryer were fabricated for experimental investigation. The