PERFORMANCE STUDIES OF WASTE HEAT ASSISTED SOLAR DRYING AND DISTILLATION SYSTEMS

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by

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Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the

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DEDICATED

TO

MY BELOVED PARENTS

DECLARATION

I hereby declare that the work presented here in the thesis entitled "**Performance Studies of Waste Heat Assisted Solar Drying and Distillation Systems**" has been carried out by me towards the partial fulfilment of the requirement for the award of the degree of Doctor of Philosophy at the Department of Energy Science and Engineering, Indian Institute of Technology Delhi. The content of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma by me.

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CERTIFICATE

This is to certify that the thesis entitled **"Performance Studies of Waste Heat Assisted Solar Drying and Distillation Systems"** being submitted by **Mr. Sandeep Kumar Singh** in fulfilment of the requirements for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work performed by him under our joint guidance and supervision at **Department of Energy Science and Engineering, Indian Institute of Technology Delhi**.

Further, the results obtained herein have not been submitted in part or in full to any other University or Institute for the award of any degree to the best of our knowledge.

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(Sandeep Kumar Singh)

ABSTRACT

With the increase of conventional energy cost, it is becoming increasingly practical to incorporate renewable (solar) energy sources into distillation and drying processes. However, due to its intermittent and diluted nature, solar energy makes it impossible to operate the systems continuously. For several decades, researchers have been making continuous efforts to find other alternative or collaborative energy sources or thermal energy to run the distillation plant at the industrial level or the solar still at the domestic level. Though the source of energy at the domestic level is biomass combustion devices, they have large potential from a practical standpoint because, practically, it can be implemented in every home using simple, straightforward techniques. Similarly, in the drying industry today, using biomass as fuel is essentially synonymous with extending the drying period during cloudy or rainy days (backup heater) and even throughout the day and at night. This study presents the development of a solar biomass combined drying and distillation system during off-sunshine hours without altering the actual phenomenon.

An extensive literature survey highlights different ways of extracting the heat from the cookstove, and most of them recommend thermoelectric generators, which are not suitable to fulfil the energy requirements of the drying and distillation systems. Therefore, the concept of supplying preheating water by using waste heat from cookstove has been proposed in this study to enhance the performance of the drying and distillation systems while working as a single system. A two-dimensional axisymmetric computational fluid dynamics (CFD) model of the conventional cookstove having a water jacket has been created in ANSYS Fluent to analyse the fluid flow, temperature distribution, and heat gain by the water from the external surface of the cookstove and validated with the experimental investigations.

During the experimental study, it was found that the modified cookstove model was more

significant than the conventional cookstove. The energy and exergy efficiency vary at different mass flow rates of water in the water jacket. Further, the impact of using extracted waste heat in the improved solar dryer system has been investigated, and it was found that waste heat assisted hybrid solar dryers took less time as compared to conventional solar dryer and open sun drying for drying the agricultural product (ginger). Furthermore, the use of preheated water in the basin enhanced the productivity of the waste heat-assisted solar still significantly, over the conventional still, and reducing the cost of producing distillate. The results of the present work have been compared with those of previous researchers and found to agree. The above studies are expected to be useful for the design, development, and application of their commercialization in the market.

सारांश

पारंपरिक ऊर्जा लागत में वृद्धि के साथ, नवीकरणीय (सौर) ऊर्जा स्रोतों को आसवन और सुखाने की प्रक्रियाओं में शामिल करना तेजी से व्यावहारिक हो रहा है। हालांकि, इसकी आंतरायिक और धुंधला प्रकृति के कारण, सौर ऊर्जा सिस्टम को लगातार संचालित करना असंभव बना देती है। कई दशकों से, शोधकर्ता औद्योगिक स्तर पर आसवन संयंत्र या घरेलू स्तर पर अभी भी सौर को चलाने के लिए अन्य वैकल्पिक या सहयोगी ऊर्जा स्रोतों या थर्मल ऊर्जा को खोजने के लिए निरंतर प्रयास कर रहे हैं। हालांकि घरेलू स्तर पर ऊर्जा का स्रोत बायोमास दहन उपकरण है, उनके पास व्यावहारिक दृष्टिकोण से बड़ी क्षमता है क्योंकि, व्यावहारिक रूप से, इसे सरल, सीधी तकनीकों का उपयोग करके हर घर में लागू किया जा सकता है। इसी तरह, सुखाने उद्योग में आज, ईंधन के रूप में बायोमास का उपयोग करना अनिवार्य रूप से बादल या बरसात के दिनों (बैकअप हीटर) के दौरान और यहां तक कि पूरे दिन और रात में सुखाने की अवधि बढ़ाने का पर्याय है। यह अध्ययन वास्तविक कार्य को बदले बिना ऑफ-सनशाइन घंटों के दौरान सौर बायोमास संयुक्त सुखाने और आसवन प्रणाली के विकास को प्रस्तुत करता है।

एक व्यापक साहित्य सर्वेक्षण कुकस्टोव से अपशिष्ट गर्मी निकालने के विभिन्न तरीकों पर प्रकाश डालता है, और उनमें से ज्यादातर थर्मोइलेक्ट्रिक जनरेटर की सिफारिश करते हैं, जो सुखाने और आसवन प्रणालियों की ऊर्जा आवश्यकताओं को पूरा करने के लिए उपयुक्त नहीं हैं। इसलिए, एकल प्रणाली के रूप में काम करते समय सुखाने और आसवन प्रणालियों के प्रदर्शन को बढ़ाने के लिए कुकस्टोव से अपशिष्ट गर्मी का उपयोग करके पानी की आपूर्ति करने की अवधारणा को इस अध्ययन में प्रस्तावित किया गया है। जल-प्रवाह का विश्लेषण करने के लिए एएनएसवाईएस (ANSYS) फ्लुएंट में पानी की जैकेट वाले पारंपरिक कुकस्टोव के द्वि-आयामी अक्षीय कम्प्यूटेशनल द्रव गतिशीलता (सीएफडी) मॉडल का निर्माण किया गया है, तापमान वितरण, और कुकस्टोव की बाहरी सतह से पानी के तापमान में वृद्धि और प्रयोगात्मक जांच के साथ मान्य किया गया है।

प्रयोगात्मक अध्ययन के दौरान, यह पाया गया कि संशोधित कुकस्टोव मॉडल पारंपरिक कुकस्टोव की तुलना में अधिक उत्तीर्ण था। एनर्जी और एक्सर्जी दक्षता, पानी के विभिन्न जन प्रवाह दरों पर भिन्न होती है। आगे, उन्नत सौर ड्रायर प्रणाली में अपशिष्ट गर्मी के उपयोग के प्रभाव की जांच की गई है, और यह पाया गया कि कृषि उत्पाद (अदरक) को सुखाने के लिए पारंपरिक सौर ड्रायर और खुले सूर्य की सुखाने की तुलना में अपशिष्ट गर्मी की

सहायता से हाइब्रिड सौर ड्रायर को कम समय लगा। इसके अलावा, बेसिन में पहले से गर्म पानी के उपयोग ने अपशिष्ट गर्मी की सहायता से पारंपरिक आसवन की तुलना में हाइब्रिड सौर आसवन उत्पादकता को भी काफी बढ़ाया, और उत्पादन की लागत को कम किया। वर्तमान कार्य के परिणामों को पिछले शोधकर्ताओं के परिणामों के साथ तुलना की गई है और सहमत पाया गया है। उपरोक्त अध्ययन बाजार में उनके व्यावसायीकरण के डिजाइन, विकास और अनुप्रयोग के लिए उपयोगी होने की उम्मीद है।

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NOMENCLATURE

A_{sb}	Area of still basin (m^2)
A_g	Area of glass cover (m^2)
K	Thermal conductivity (W/m˚C)
C_{pl}	Calorific value of petrol (kJ/kg)
C_{fuel}	Calorific value of petrol (kJ/kg)
C_{pellet}	Calorific value of pellets (kJ/kg)
C_p	Specific heat of water (kJ/kg˚C)
C_{pb}	Specific heat of basin water (kJ/kg˚C)
$C_{p.pot}$	Specific heat of the pot (aluminium vessel) (kJ/kg˚C)
d_f	Number of degrees of freedom of regression model
E	Amount of energy needed for the drying process (kJ)
E_{in}	Energy produced by the fuelwood and the igniting fuel (kJ)
E_o	Energy required to boil the water (kJ)
Ex_{in}	Exergy input (kJ)
Ex_o	Exergy output (kJ)
h_{fg}	Latent heat of evaporation for water (kJ/kg)
$h_{c,b-g}$	Convective heat transfer coefficient between water and glass (W/m^2 ˚C)
$h_{c, g-a}$	Convective heat transfer coefficient from glass to ambient ($W\ m^2$ ˚C)
$h_{r, b-g}$	Radiative heat transfer coefficient from water to glass (W/m^2 ˚C)
$h_{e, b-g}$	Evaporative heat transfer coefficient between water and glass (W/m^2˚C)
$h_{r, g-a}$	Radiative heat transfer coefficient from glass to ambient ($W/\ m^2$ ˚C)
I(t)	Total solar radiation (W/m^2)
M_c	Product's moisture content (kg)
M_f	Product's mass after drying (kg)
M_i	Product's mass before drying (kg)
$M_{i,exp}$	ith experimental equilibrium moisture content
$M_{i,pre}$	ith predicted equilibrium moisture content
M_m	Quantity of moisture that must be removed (kg)
M_t	Mass of the product at any time (kg)
M_w	Mass of the dried product by wet percentage basis (kg)

$m_{e,b\text{-}g}$	Mass of water evaporated from basin to glass (kg)
m_f	Mass flow rate of water (kg/sec)
m_{fhwj}	Final mass of hot water received from the without jacket (kg)
m_{pellet}	Mass of pellets consumed (kg)
m_{pot}	Mass of vessel along with lid (kg)
m_w	Mass of water in the vessel (kg)
m_{hwj}	Mass of hot water received from the jacket (kg)
n	Total number of pots used (always n >1)
N	Number of observations
Nu	Nusselt number
P_w	Partial saturated vapor pressure at a basin water temperature (N/m^2)
P_g	Partial saturated vapor pressures at glass cover temperature (N/m^2)
p	Partial pressure (N/m^2)
$Q_{c,g-a}$	Convective heat loss from cover to ambient (W/m^2)
$Q_{c,w-g}$	Convective heat transfer between water and glass (W/m^2)
$Q_{e.w-g}$	Heat transfer by evaporation from water to glass cover (W/m^2)
$\dot{Q}_{r,w-g}$	Heat transfer by radiation from water to glass cover (W/ m^2)
$Q_{r,w-a}$	Radiative heat loss from glass cover to ambient (W/m^2)
Q_b	Heat supplied by the biomass (W/m^2)
Q_b	Heat supplied to the heat exchanger (W/m^2)
Ra	Rayleigh number
R_i	Coefficient of determination
t	Time (hr, sec)
t_g	Glass cover thickness (mm)
T_1	First vessel final temperature of water (˚C)
T_2	Second vessel final temperature of water (˚C)
T_3	Last vessel final temperature of water (˚C)
T_a	Ambient/room temperature (˚C)
T_g	Glass cover temperature (˚C)
T_{fw}	Final temperature of water (˚C)
T_{flame}	Flame temperature (˚C)
T_{iwj}	Initial temperature of water entering the jacket (˚C)

T_{fhwj}	Temperature of hot water received from the water jacket (˚C)
T_{fuel}	Temperature of burning fuel (˚C)
T_{pf}	Final temperature of the pot (˚C)
T_{pi}	Pot initial temperature (˚C)
T_{sky}	Sky Temperature (˚C)
T_{sb}	Temperature of steel basin (˚C)
T_w	Basin water temperature (˚C)
T_{wf}	Water final temperature without water jacket (˚C)
T_{wi}	Water initial temperature (˚C)
$u_1, u_2, u_3, \ldots, u_n$	Uncertainties in $z_1, z_2, z_3, \ldots, z_n$
v	Air velocity (m/s)
x	Volume of oil used (ml)
X	Mass content of water per kilogram of dry material
$z_1, z_2, z_3, \ldots, z_n$	Independent variables

Greek symbols

ρ	Density (kg/cm^3)
ρ_f	Density of fuel (kg/cm^3)
τ	Transmissivity
η	Cookstove efficiency (%)
α	Absorptivity
α'_g	Absorbtivity by the cover
β	Coefficient of thermal expansion of the fluid
α'_{sb}	Absorbtivity of basin
υ	Kinematic viscosity (m^2/s)
κ	Thermal conductivity (W/m-K)
σ	Stefan–Boltzmann constant (W/m^{2}K^4)
θ	Inclination angle (degree, ◦)
ε_g	Emissivity of glass cover
ε_w	Emissivity of basin liner
ε_{eff}	Effective emissivity between water surface and glass cover
ψ	Exergy efficiency (%)

Abbreviations

A,B & C	Constant in the model
AMI	Advanced motic image
BIS	Bureau of Indian Standard
CF	Cah flow
CPC	Concentrated parabolic collector
CSS	Conventional solar still
DSSS	Double slope solar still
DC	Dish collector
EMC	Equilibrium moisture content
EMC^0	Monolayer moisture content
ERH	Equilibrium relative humidity
ETC	Evacuated tube collector
FD_IM	Forced draft initial model
FD_WHRS	Forced draft waste heat recovery system
FD_B	Forced draft base model
FPC	Flat plate collector
HPC	Heat pipe collector
HWST	Hot water storage tank
MED	Multi effect distillation
MEB	Multi-effect boiling
MRE	Mean relative error
MSF	Membrane stage flash
NCV	Net calorific value
OSD	Open air sun drying
PTC	Parabolic trough collector
RE	Renewable energy
SAC	Solar air collector
SEE	Standard error of estimation
SS	Single slope
SSP	Shallow solar pond
SSSS	Single slope solar still
TSS	Tubular solar still

VC	Vapour compression
WEF	Water energy food
WHO	World health organization
WHSS	Waste heat recovery system
WHSS	Waste heat assisted solar still