Exergy Analysis of Solar Cabinet Dryer and Evaluate the Performance Enhancement of Solar Cabinet Dryer by Addition of Solar Reflectors

Abdullah Aziz*‡ Saeed Ur Rehman**, Dr. Shafiq Ur Rehman**

**Mechanical Engineering Department, University of Canterbury, 20 Kirkwood Ave, Upper Riccarton, Christchurch.

*Engineering Sciences, Pakistan Naval Engineering College, National University of Science & Technology, Sector H-12, Islamabad.

(abdullah.aziz@pg.canterbury.ac.nz, saeed.rehman88@gmail.com, shafique@pnec.nust.edu.pk)

‡Corresponding Author; Abdullah Aziz, Mechanical Engineering Department, University of Canterbury, 20 Kirkwood Ave, Upper Riccarton, Christchurch. Tel: +64 27 435 2081, abdullah.aziz@pg.canterbury.ac.nz

Received: 22.06.2016 Accepted: 29.07.2016

Abstract- Solar dryer dehumidifies the moisture for food preservation using solar radiation. In this paper, performance evaluation of cabinet dryer by using energy and exergy analysis tool has been presented. Experimental work on proposed design of cabinet dryer has been carried out at Abraka, Nigeria. Analysis has been performed by solving the model equation of solar radiation of Abraka, Nigeria and mathematical model of solar cabinet dryer using Engineering Equation Solver. A solution of mathematical model will give the available useful energy and exergy of solar cabinet dryer. The performance of the system is evaluated by calculating energy utilized in the drying process using experimental data. The analysis highlights the energy losses, irreversibility, exergy losses and exergy destruction at different stages. Performance comparison of cabinet dryer with and without a reflector is also discussed. It has been concluded that cabinet drier without a reflector is able to convert 39% of solar energy as the available useful energy of dryer and convert about 13% of useful energy to exergy of the dryer system. While dryer with a reflector converts 42% of solar energy into available useful energy and converts about 17% of available energy to exergy of the dryer. Comparison of both dryers shows that dryer without reflector has twice the exergy as compared to the dryer with a reflector.

Key Words: Energy, Exergy, Solar dryer, cabinet dryer

1. Introduction

Drying is one of the oldest methods used for preservation of food. In history, it has been recorded that people used to dry meat and fish in the sun for preservation purpose. Drying is still significant in the modern age for the preservation of food as well as in its vast use of solar dehydrators. Food can be stored for longer periods without deterioration by reducing its moisture content [1]. Micro-organisms cause food spoilage, and the decay is unable to grow in the absence of sufficient water [2]. Sun drying is widely used in many tropical countries because of its low cost and simple mechanism [3]. But sun drying products usually do not meet international quality standards. Different methodologies and models are being developed to bring such dryers to a global regularization. Dincer et al. have proposed a methodology to improve exergy and energy of a solar equipment through different public and private locations and building [4]. This methodology was adapted by Rosen et al. in their exergy analysis [5] and by Bala et al. directly in their solar dryer [6].

Both analysis showed fair results but not good enough to be determined as an international standard. To get the international quality dry product by utilizing solar energy, a need for suitable solar dryer technology was felt. Different types of natural and force convection, direct, indirect, mix mode, box type and tunnel dryers were constructed and tested in different tropical countries [7]. The aim being the evaluation of feasibility in using the solar energy for the drying process. Energy and exergy analysis is the key tool to perform such study.

The solar dryer has been an important topic of research since the late 70s and many researchers have worked on performance analysis of these dryers. Both the energy and exergy analysis of dryers remained a key research area. Bolaji has constructed three different types of driers (Direct, Indirect, and Mix mode). Exergy analysis was performed on the basis of the experimental data [8]. Results show that average Exergy efficiency obtained of mix mode, indirect mode, and direct mode drier were 55%, 54%, and 33% respectively, concluding that the mix mode dryer has maximum exergy efficiency. Singh and Kumar have worked to find out the convective heat transfer coefficient for the three common types of solar driers direct, indirect and mix mode driers and installed different sensors for measurement of temperature at inlet, outlet, absorption plate and cover glass where an electrical heater is used to heat up absorption plate [9]. Results show that mix mode dryer have a higher value of convective heat transfer coefficient than indirect mode and direct mode has the least value. He also installed external source to force the flow in mix mode and indirect mode dryers. Results show that with an increase in air flow rate the convective heat transfer has also increased.

Babagana designed and constructed a mix mode vegetable solar dryer with forced and natural convection modes [10]. On the basis of analysis, he concluded that by using an external source to flow the air drying time can be reduced by approximately 40% to 50%. Sami et al. presented energy and exergy analysis of an indirect solar cabinet dryer based on mathematical modeling results [11]. It was concluded that exergy of the dryer is a function of temperature of the dryer. Dryer temperature also depends on the surface area of collector, length of collector and air flow rate. Gatea presented the design, construction and performance evaluation of force convection indirect mode solar dryer with V-grooved collector plate [12]. Experiments were performed with three tilt angles 30º, 45º and 60º of solar collector. Author concluded that performance of drying system was highly dependent on solar radiation, tilt angle, and ambient temperature. Higher energy was gained at a tilt angle of 45º as compare to 30º and 60º. Total loss factor increases with increase in solar radiation. Similar to work of Toshniwal and Karale [13], Basumatary et al. presented a paper on the design, construction and calibration of low-cost mix mode solar cabinet dryer [14]. Results showed that during 7 hours of drying operation, dryer removed 48.7% to 33% of moisture while open air drying removed 15.38% of moisture. Drying rate in mix mode cabinet dryer is approximately 2 to 3 times higher than open air drying.

Emelue et al. [15] presented an experimental work on the proposed design. An experimental study was performed in Abraka, Delta State of Nigeria located at coordinates of 5’ 47” North and 6’ 6” East. This data was used to construct two cabinet dryers and installing them side by side, one with adjustable reflectors as shown in Figure 1 and second without reflectors as shown in Figure 2. Authors have installed these two dryer, side by side, all loaded with same type and weight of the food sample.

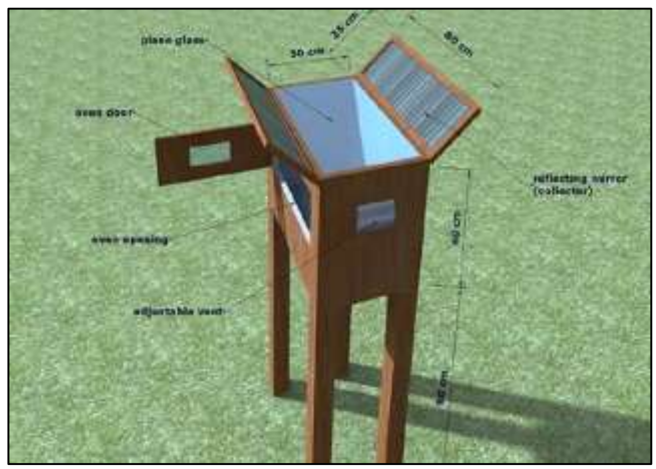

Fig. 1. Cabinet dryer with reflector

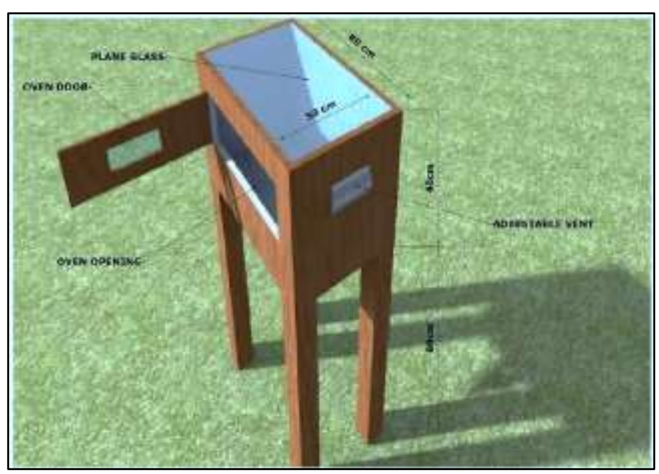

Fig. 2. Cabinet dryer without reflector

Temperature and weight values of samples, after every 1.5 hours, were recorded for both setups. Authors have compared the performance of drier$_1$ (with reflector), drier$_2$ (without reflector) in terms of temperature profile and weight reduction percentage.

2. Energy and Exergy Model

Exergy analysis is one of the most powerful tools that widely used in the design, simulation and performance evaluation of any energy systems. The energy gained by dryer is expressed as equation (1):

$$Q_u = \alpha\tau IA - U_{loss}(T - T_o) \quad (1)$$

Where Q_u useful energy of dryer (Watt), A is area of transparent cover (m^2), T is temperature of dryer (K), T_o is ambient temperature (K), U_{loss} is overall heat loss coefficient (W/K), α is solar absorption, τ is transmittance, I is incident solar radiation (W/m^2) [8].

All the useful energy of dryer is not available as exergy of dryer. Only some part of useful energy is converted to Exergy of dryer can be obtained by using equation (2):

$$Exergy = Q.(1 - \frac{T_{sink}}{T_{source}}) \quad (2)$$

Where Q is heat transfer, T_{sink} is ambient temperature and T_{source} is the temperature at which heat is released [16].

Exergy efficiency or 2nd Law efficiency is define as the ratio of actual energy utilized by the system and maximum energy system can be utilized or exergy of system [16]. It can be expressed as equation (3):

$$\eta_{2nd\ law} = \frac{Energy\ Utilized}{Exergy\ of\ system} \quad (3)$$

In drying process energy utilized is the product of mass of water evaporated and amount of energy required to evaporate 1 kg of water. It can be expressed as equation (4):

$$Energy\ Utilized = m_w\ h_{vap} \quad (4)$$

Where Energy Utilized is energy consumed by during drying process, m_w from material and h_{vap} is latent heat of vaporization [2].

3. Energy and Exergy Analysis

To perform energy and exergy analysis of cabinet dryer, we begin with the solar radiation model from Abraka, Nigeria. Peak Solar radiation was observed near 1230 hours. Before peak hours, solar radiation has an increasing trend and after peak hours it starts decreasing. Energy and exergy analysis of cabinet dryer has been performed by dividing the process into two stages. 1st stage covers the absorption process in which dryer has absorbed solar energy and converts it into useful energy for drying process. 2nd stage describes the drying process in which useful energy is being utilized for moisture removal from food stuff. Energy utilized has been calculated by using experimental data reported by Emuele.et.al [15].

a. Energy and exergy analysis of 1st stage (Absorption process)

Figure 3 shows the solar model of Abraka, Nigeria, which has been used to perform the analysis. Both the dryers were operated at same time to keep all the parameters same.

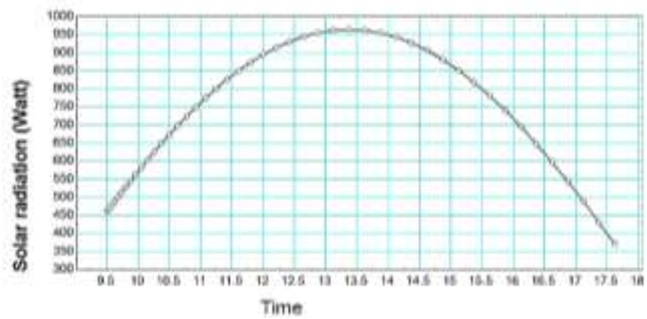

Fig. 3. Solar Radiation Model

Figure 4 shows the solar energy coming into the dryer. Dryer with reflector has more energy coming in as compare to the dryer without reflector due to installation of reflectors. It was measured that the total energy enter in the dryer with reflector is 1.46 times higher than the dryer without a reflector.

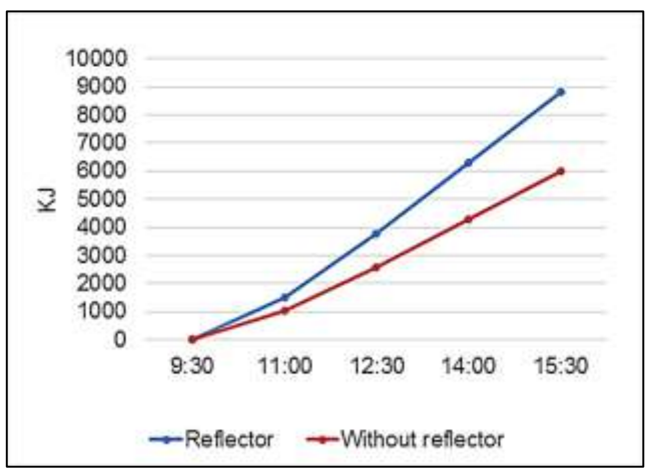

Fig. 4. Solar Energy of Absorption process

Figure 5 shows the available useful energy of dryer, which is available for drying process. Solar energy of dryer with reflector is higher than dryer without a reflector. Therefore, same trend has been noticed while analysis the available useful energy of dryer. Dryer with a reflector has 60 percent more energy available for drying process as compare to the dryer without a reflector.

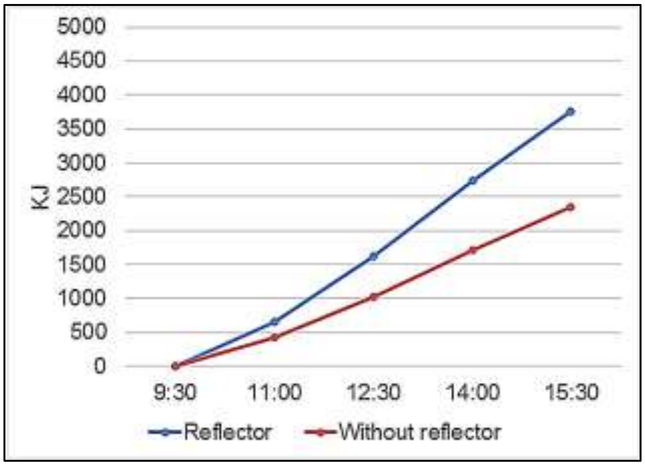

Fig. 5. Useful energy of dryer

If we analyze the energy efficiency of both dryers as shown in Figure 6, it can be noticed that both the dryer follow the similar trend but dryer with a reflector has more energy efficiency due to high energy input for dryer with reflector while keeping remaining parameters same for both dryers. In absorption process there are two main energy losses, energy loss from top glass cover and energy loss from side walls and base. Both are dependable on the temperature difference inside and outside of the dryer. The energy loss is lesser due to the difference in initial temperatures. Therefore, better efficiency can been observed at the peak solar radiation time of 1400 hours. The efficiency experience a drop, as more energy is being lost through wall and top cover with the increase in temperature inside the dryer.

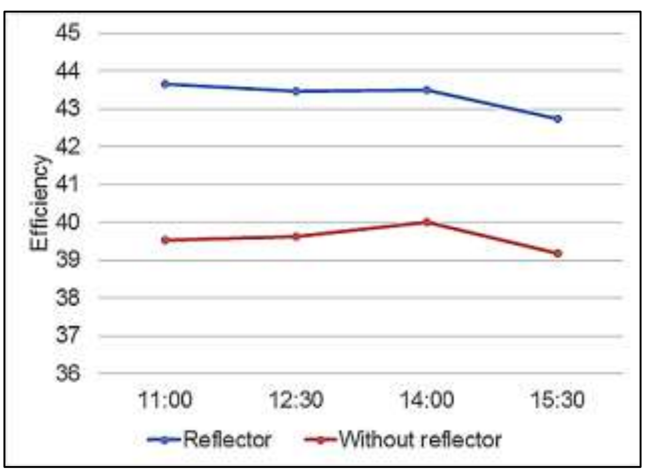

Fig. 6. Energy Efficiency of absorption process

The exergy of a system is highly dependent on the temperature of sink and source. In the case of a solar dryer, the source is dryer itself and the sink is the surrounding ambiance. Ambient temperature is same for both dryers but cabinet temperature for dryer with reflector is higher than dryer without reflector. This has a significant impact on the exergy of the dryers, hence the exergy of the dryer with reflector has increased almost twice than that of dryer without reflector. A comparison of exergy conversion efficiency of both dryers is shown in Figure 8. Dryer with reflector converts more available energy to exergy of dryer as compare to the dryer without reflector. Exergy conversion efficiency of dryer with reflector is 17% and dryer without reflector has 13%. Both the dryer follows the similar trend. Initially temperature difference between inside and outside of dryer is small therefore less exergy conversion efficiency was observed. It increases with the increase in temperature difference over the passage of time.

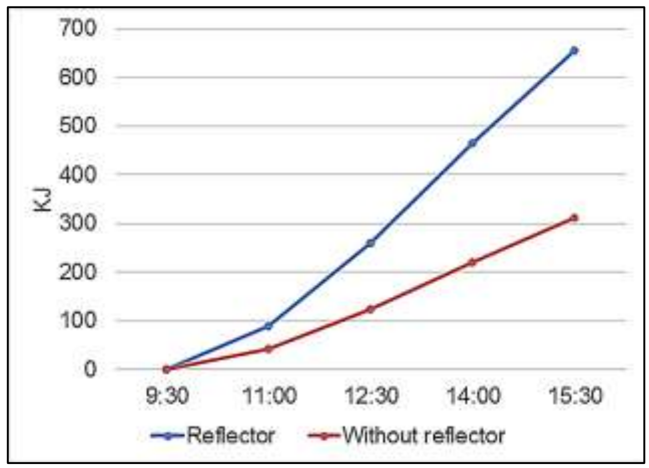

Fig. 7. Exergy of drying process

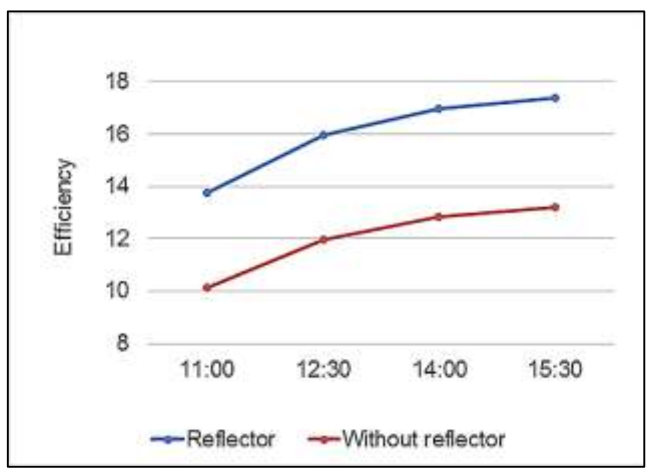

Fig. 8. Exergy conversion efficiency

It was observed that during energy and exergy analysis of absorption process, dryer with reflector has better performance than dryer without reflector. Dryer with reflector has higher solar energy input resulting in more available energy for drying process and higher exergy. Alike progression can be seen in terms of exergy conversion efficiencies.

b. Energy and exergy analysis of 2nd stage (drying process)

In drying process, the moisture of food sample has been removed by utilizing the useful energy available. Energy utilized has been calculated by using the data of moisture removed during experiment as reported by Emulue.et.al [15]. Same mass and type of food sample were loaded in both the dryers and placed in both dryers side by side to keep all the parameters identical. It has been observed that trend of energy utilized for both dryers is similar for all six days of the experiment. Figure 9 shows that dryer with reflector have utilized more energy in drying process as compare to dryer without reflector. As dryer with reflector have higher exergy available for drying as well as high cabinet temperature. Trend of energy utilized by both dryers is same. Driving force for drying is the difference in moisture level of saturated air and moisture level currently present in air. Moisture level present in food sample has a large impact on the drying rate. Drying rate is constant till the critical moisture level is achieved, afterwards it starts decreasing continuously. Initially drying rate is high for both dryers as the level of moisture present in the dryers is also high. With passage of time, rate of drying is reduced due to the reduction in moisture level of food sample. Figure 9 shows that dryer with reflector has utilized 16% more energy as utilized by dryer without a reflector.

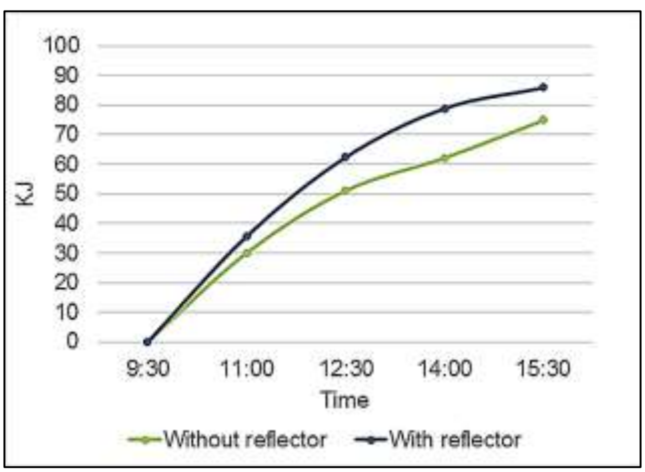

Fig. 9. Energy Utilized in drying process

By the comparison of energy efficiency for both dryer, it is observed that dryer without reflector is more efficiently utilized energy as seen in Figure 10. Although the dryer with reflector utilized more energy than energy utilized by dryer without reflector but energy available for drying process in dryer with reflector is 1.46 times the energy of dryer without reflector which lead to the lower energy efficiency of dryer with reflector. Trend of peak efficiency for both dryers is similar with respect to starting hours and reduction over time due to maximum moisture level present in the food sample initially, so the maximum energy was utilized in starting hours.

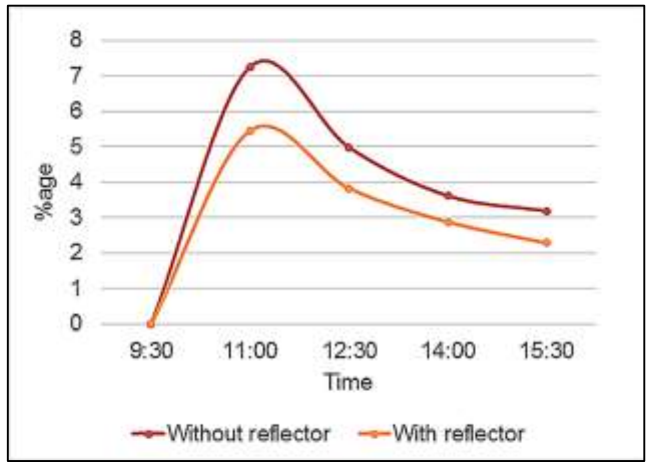

Fig. 10. Energy Efficiency of drying process

Similar to energy efficiency, exergy efficiency of dryer without reflector is higher as compare to exergy efficiency of dryer with a reflector. Although dryer with reflector utilized more energy but exergy of dryer with reflector is 160% of exergy of dryer without reflector. Both dryer shows similar trend of 2nd law efficiency due to maximum energy was utilized in initials hour as shown in Figure 11.

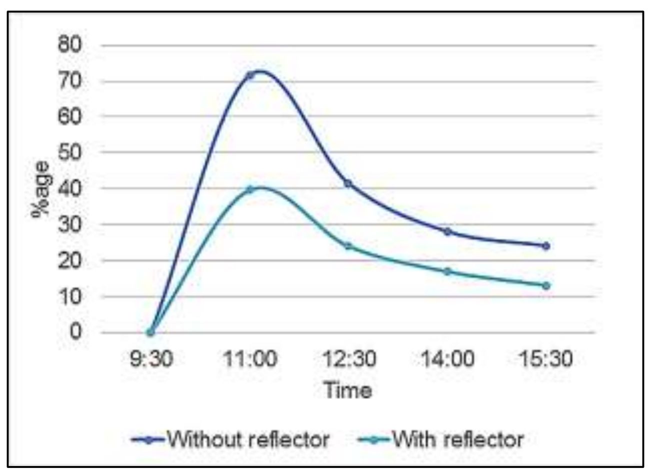

Fig. 11. 2nd law efficiency of drying process

It has already been discussed that drying rate is highly influenced by critical moisture level. When critical moisture has been achieved in the food sample, there will be a reduction in drying rate. So we can say that energy utilization trend is dependent on the mass of food sample. If the mass of loaded food sample is less than the capacity of dryer than critical moisture level will be obtained in initial hours, as observed in reported cases. Although maximum exergy available for drying has peak value near 1230 hours. Figure 12 shows the relation between the mass of loaded food sample and energy utilized in the drying process. It is observed that energy utilized has increased with increase in mass of food sample. So, we can get optimum efficiency by keeping the mass of food sample maximum as per the capacity of the dryer.

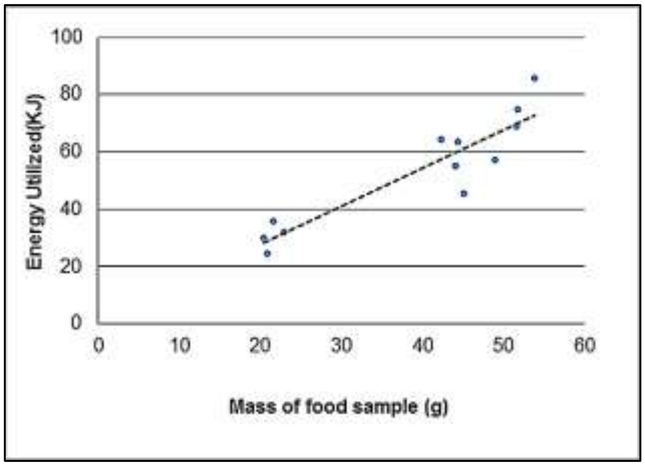

Fig. 12. Energy utilized v/s mass of food sample

The capacity of the dryer with reflector is 60% more than that of the dryer without reflector with an equal mass of food sample loaded in both dryers which resulted in higher energy and exergy efficiency of the dryer without reflector than dryer with a reflector. Assuming that optimum exergy efficiency of dryers are 70% then the optimum mass is approximately 200g and 100g for a dryer with reflector and dryer without reflector respectively. By comparing optimum mass and actual loaded mass of both dryers, we can observe that dryer with reflector was operated at 25% capacity and dryer without reflector was operated at 50% capacity. It is safe to say that both the dryers were operated at under load condition that's why during peak hours maximum exergy was not utilized. It is observed that if both the dryers will operate at same loading capacity the dryer with a reflector will have better performance than dryer without a reflector and optimum mass of food sample should be loaded to get maximum efficiency in drying process.

4. Conclusion

Energy and exergy analysis of solar cabinet dryer with reflector and cabinet dryer without reflector was performed. From results it has been concluded that dryer with a reflector has absorbed more energy because of reflectors. So the overall performance of dryer with reflector is better than dryer without reflector in the absorption process. It can be concluded that dryer with a solar reflector with same parameters and dimensions has 46% more energy available for drying, utilizes 16% more energy for drying, has 60% more drying capacity than dryer without a solar reflector. Maximum energy and exergy efficiency can be obtained by operating the dryers at full load capacity. The study will help improve the efficiency of future solar drying systems in order to utilize maximum energy.

5. References

[1] Center for Resource Solutions, "Why Clean Energy?," 2014. [Online]. Available: http://buycleanenergy.org/why.

[2] R. L. Earle, Unit Operation if Food Processing, Pergamon Press, 1983.

[3] M. A. Maehlum, "Solar Energy Pros and Cons," Energy Informative, 12 May 2014. [Online]. Available: http://energyinformative.org/solar-energy-pros-and-cons/.

[4] I. Dincer, M. M. Hussain and Al-Zaharnah, "Energy and exergy use in public and private sector of Saudi Arabia," *Energy Policy,* vol. 34, no. 141, pp. 1615-1624, 2004.

[5] M. A. Rosen and I. Dincer, "Exergy as the Confluence of Energy, Environment and Sustainable Development," *Exergy, An International Journal,* vol. 1, no. 1, pp. 3-13, 2001.

[6] B. K. Bala, M. A. Morshed and M. F. Rahman, "Solar Drying of Mushroom Using Solar Tunnel Dryer," in *International Solar Food Processing Conference*, 2009.

[7] B. K. Bala and S. Janjai, "Solar drying of fruits, vegetables, spices, medicinal plants and fish: Development and potentials," in *International Solar Food Processing Conference*, 2009.

[8] B. O. Bolaji, "Exergetic Analysis of Solar Energy Drying Systems," *Natural Resources,* vol. II, no. 2, pp. 92-97, 2011.

[9] S. Singh and S. Kumar, "Development of convective heat transfer correlations for common designs of solar dryer," *Energy Conversion and Management*, vol. 64, pp. 403-414, 2012.

[10] G. Babagana, K. Silas and B. G. Mustafa, "Design and construction of forced and natural convection solar vegetable dryer with heat storage," *ARPN Journal of Engineering and Applied Sciences*, vol. 7, no. 10, pp. 1213-1217, 2012.

[11] S. Sami, N. Etesami and A. Rahimi, "Energy and Exergy Analysis of an indirect solar cabinet dryer based on mathematical modeling results," *Energy*, vol. 36, no. 5, pp. 2847-2855, 2011.

[12] A. A. Gatea, "Design, construction and performance evaluation fo solar maize dryer," *Journal of Agricultural Biotechnology and sustainable development*, vol. 2, no. 3, pp. 39-46, 2009.

[13] U. Toshniwal and S. Karale, "A Review Paper on Solar Dryer," *International Journal of Engineering and Research and Applications*, vol. 3, no. 2, 2013.

[14] B. Basumatary, M. Roy, D. Basumatary, S. Narzary, U. Deuri, P. K. Nayak and N. Kunar, "Design, construction and calibration of low cost solar cabinet dryer," *International Journal of Environment Engineering and Management*, vol. 4, no. 4, 2013.

[15] H. U. Emelue, N. Omehe, P. O. Ghome and K. Amanze, "Design and construction of cabinet solar dryer," *British Journal of Applied Science & Technology*, pp. 270-284, 2015.

[16] Y. A. Cengerl and M. A. Boles, Thermodynamics: An Engineering Approach, McGraw-Hill Higher Education, 2006.