Jurnal Kejuruteraan 34(1) 2022: 117-129
https://doi.org/10.17576/jkukm-2022-34(1)-11

Design and Analysis of Energy and Exergy Performance of an LPG-Powered Fish Drying Machine

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Received 4 May 2021, Received in revised form 29 June 2021
Accepted 29 July 2021, Available online 30 January 2022

ABSTRACT

A detailed design and analysis of the energy and exergy performance of a Liquefied Petroleum Gas (LPG)-powered fish drying machine are presented in this paper. The system designed is a modification to the conventional fish dryer which uses charcoal, electric or solar energy as sources of heat. The major problems of the conventional machines are; dangers of global warming from the burning of charcoals. The emission of smoke during operation causes environmental pollution which could have adverse effects on our respiratory systems. Moreover, it is difficult to attain uniform heat distribution using charcoal as a source of heat; erratic power supply in developing countries using electricity and inadequate sunshine using solar energy are all major problems of the conventional dryer. The gas-powered fish dryer is a fish processing device, which uses natural gas as the source of heat energy to reduce the moisture content of the fish. In this work, thermal analysis was carried out on the system after the design. The conduction and convection energy equations were applied to the system main component as well as the fish sample within the system. Numerical computational software (Scilab 6.0.0) was used in solving and analyzing the discretized form of the derived transient differential equations. Appropriate initial and boundary conditions were as well applied during the implementation of fully explicit forward and central difference numerical solutions for solving the differential equations. After solving and arriving at the temporal temperature profile of the dryer and the fish samples, other dependable parameters (energy consumed, exergy consumed, expended gas energy and exergy, energy and exergy efficiencies, etc.) were computed and plotted against time. After the result evaluation and testing, the designed machine proved successful and was found to have peak drying energy and exergy efficiencies of 90 % and 10% respectively.

Keywords: gas powered, galvanized mesh, oil pan, insulation, and chimney.

INTRODUCTION

Drying is one of the post-handling techniques used in food processing which involves moisture removal to prevent post-harvest losses and also, loss of food after harvest which could lead to food insecurity. Fish, a source of animal protein that also contains many vitamins and minerals that are widely available due to the cheapness of the product and availability of essential nutrients (Babiker et al., 2016) to many has been threatened by poor post-harvest techniques employed to preserve them. In other words, food security is not only dependent on large scale production but also, on preservative methods used. Therefore, Fish drying helps to improve the quality and extend the shelf life of the fish according to Daniela Borda, Anca I. Nicolau & Peter Raspor (2018) and Adeyeye, S.A.O. (2019).

The problem of post-harvest refining and packing have continuously prevented the micro and medium-scale farmers, produce merchants and food producers from successful fish business (Olaniyan & Adeoye, 2014). According to FSSAI (2017), the highest point of total viable count (TVC) in a dried fish product is 5 log (cfu/g). The counts of TVC were within the limit of acceptability indicating that the product was of good quality except for unsalted and sun-dried Pangasius, in which the total viable count of a fish during sun-drying was recorded at 5.02 log (cfu/g), indicating the product has a chance of early spoilage. However, the creation of different types and sizes of dryers have grown over the years, both for domestic and industrial usage. A typical profitable dryer usually consists of a heating system, air vents for adequate air circulation and an oven tray for laying the food items. A dehydrator that removes moisture from the fish needs a heating component and outlets which works simultaneously in making sure that the moisture contents are removed from the food. This procedure remains for hours until the food is dried up to significantly reduce water content, typically not up to 15 %, and according to Martin, Emily, Flick & Davis (2000), the moisture content of a fish is about 68 to 83 %. Flowra & Dil (2013) showed a moisture reduction of about 25 % will prevent bacteria from surviving. At this point, the microorganisms cease to grow and can be kept for several months under good condition, according to Sabina & Hossain (2011).

An active solar dryer designed and developed by Ikejiofor & Okonkwo (2010) with a solar collector, drying chamber, air outlet, suction fan and heat storage unit showed better results after testing of drying period between 8-11 hours compared to open sun drying method of 42-50 hours. A multipurpose dryer of 75 % drying efficiency for agricultural products was developed by Ilechie et al. (2010). Another design created by Olaniyan & Adesoji (2014) which uses charcoal as its heating source with external components such as heat exchanger and combustion chamber showed satisfactory drying results. Mujau & Gaius (2015) designed and constructed a domestic solar fish dryer from locally sourced materials that absorbed energy from the sun through radiation which is then used for drying. Another dryer that uses a kerosene stove to supply heat was developed by Omodara & Ade (2008), which has a heat exchanging material consisting of tubes with two being used as the inlet of fresh air whereas the two others work as an outlet for the smoke. This design helps to channel the smoke away from the drying chamber preventing smoke contamination.

But the existence of charcoal, solar and electric dryers have been found to be inefficient and most times, time-consuming. Taking into consideration the drawbacks of solar dryers, which source of power is solar, harnessing and storing this energy from the sun may be difficult and unattainable due to its production and maintenance cost. Furthermore, skeletal power supplies in developing countries and the high cost of procuring and powering a generation set could affect the use of electric dryers. The food-water content is typically very high, say; 80 % to 95 % for varieties of fruits and vegetables and 50 % to 75 % for different types of meats. Getting rid of moistness from food restricts different bacteria from increasing and destroying the food. Furthermore, the removal of moisture from food drastically decreases the heaviness of the food and as result, extends shelf life.

The majority of the foods are dried at temperatures of 54 °C, even though meat (animal flesh) which are subjected to irregular drying should be dehydrated at a higher temperature of 68 °C, or heated to those temperature points, to avoid pathogens that could be in the meat from spoiling the meat. Application of constant temperature and enough airflow is crucial in having successful food drying. Meanwhile, irregular heating or very high temperature can result in poor drying, higher loss of food mass and internal moisture content, which leave the food vulnerable to spoilage.

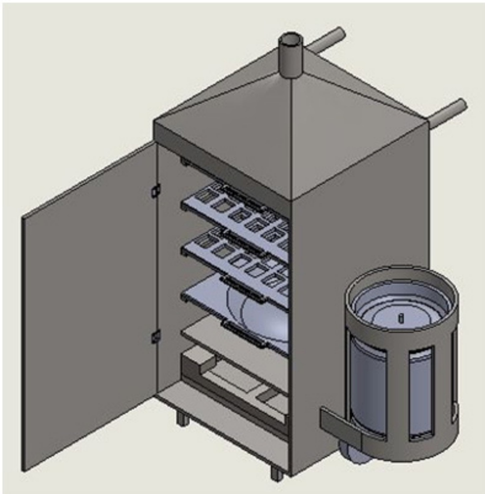
Therefore, the investigative study on the use of clean energy (Liquefied Petroleum Gas) in fish drying is hereby presented in this paper with the design and construction of the gas-powered fish dryer. The study also shows that society will benefit in the following ways:

1. More knowledge and awareness on the best fish drying method
2. Increase drying standards with controlled heating availability
3. Reduced cost and time-wasting compared to open space drying methods
4. Reduced soot and smoke formation with zero effect on ground and water pollution

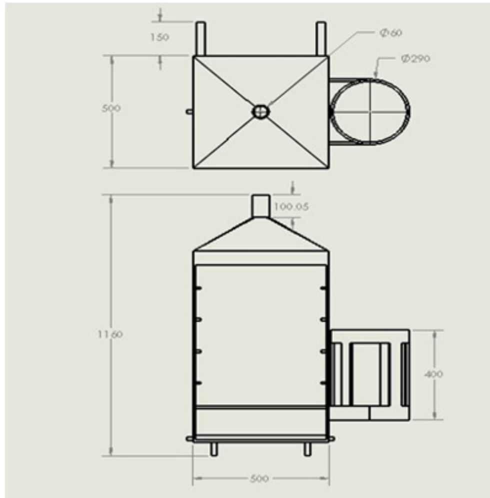
METHODOLOGY

SYSTEM PERFORMANCE

Figure 1 shows the dryer components which are grouped into four major parts, the cylinder, the burner, the drying chamber and the oil pan. The drying chamber consists of the trays or metal meshes on which the food to be dried is placed. These meshes are in layers which imply that the fishes or food placed on the different layers will receive different amounts of heat. The cylinder is an enclosed metal casing that stores and supplies the gas when needed with a valve attached to it for controlled flow. A hose is connected from the cylinder to the back of the drying chamber in which there is an attachment for the hose to the inlet. The burner is a metallic hollow pipe in which orifices are found for the ignition of the gas when the valve is opened. The burner is detachable for maintenance purposes and replacement. The oil pan is a conical shaped container in which the oil from the fish or food material being dried flows into for other possible domestic uses.



1 (a) Pictorial view of the G gas-powered fish dryer



1 (b) Front and top view of fish dryer

FIGURE 1.

MATERIAL SELECTION

The selection of materials is one crucial factor that must be taken into cognizance when carrying out an engineering project. Some important factors considered in selecting the material used for the design of the proposed fish dryer were based on physical, mechanical and economic considerations.

TABLE 1. Properties of Steel (Khurmi, R.S and J.K Gupta (2005)

S/N	Properties	Values
1	Modulus of elasticity	210000
2	Ultimate Tensile Strength	18822MPa
3	Percentage Elongation	40 %
4	Brinell Hardness	388
5	Poisson’s Ratio	0.3
6	Density (1000 kg/m³)	7.85
7	Melting Point	1410°C
8	Specific Heat (J/kg-k)	2081
9	Yield Strength	758MPa
10	Thermal conductivity ($Jm^{-1}\,s^{-1}\,°C^{-1}$)	45

Table 1 shows the properties of steel that was adopted for this design. The low carbon steel (mild steel) of 2mm thickness was used throughout. The choice of mild steel was as a result of its following properties: great conductor of electricity, which makes it easy for welding processes. It is an alloy with carbon content varying from 0.1% to 1.8%, which is a good conductor of heat.

WORKING DIAGRAMS (ALL DIMENSIONS IN MM)

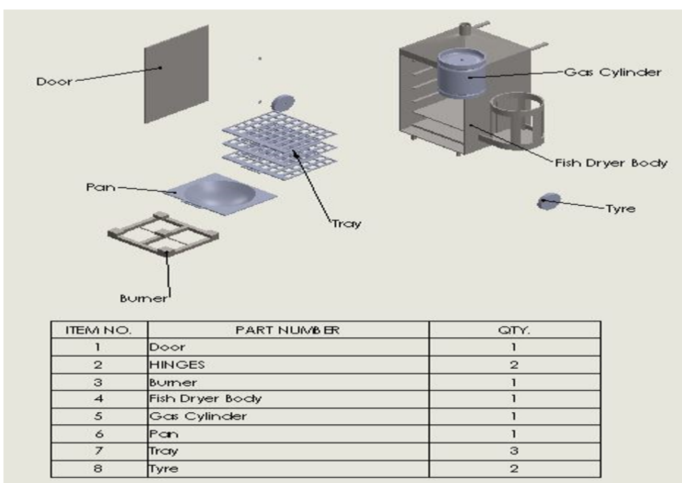


FIGURE 2. Exploded view showing components

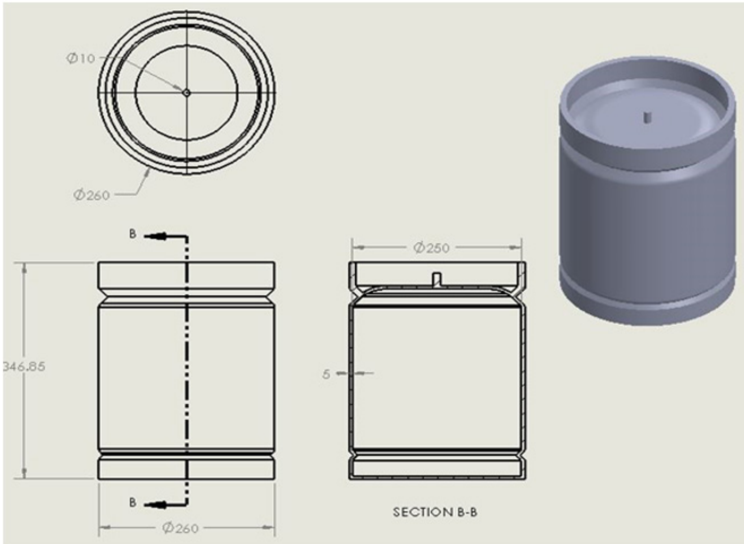


FIGURE 3. 2D and 3D diagram of the gas cylinder

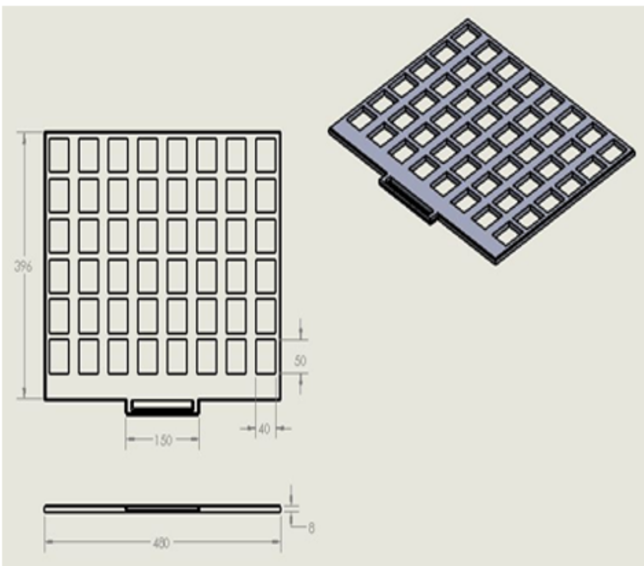


FIGURE 4(a). Diagram of the tray

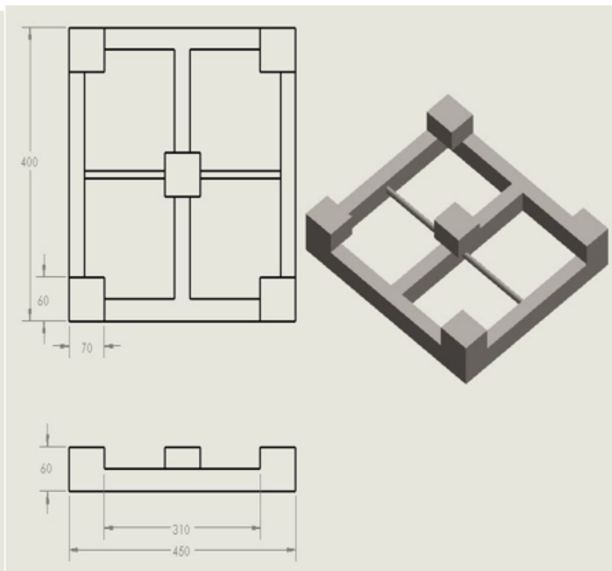


FIGURE 4(b). Diagram of the burner.

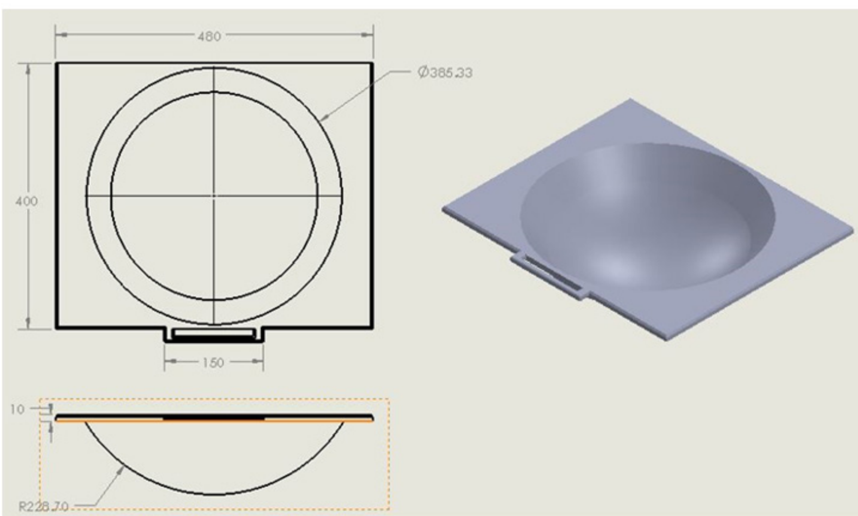


FIGURE 5. Diagram of the oil pan

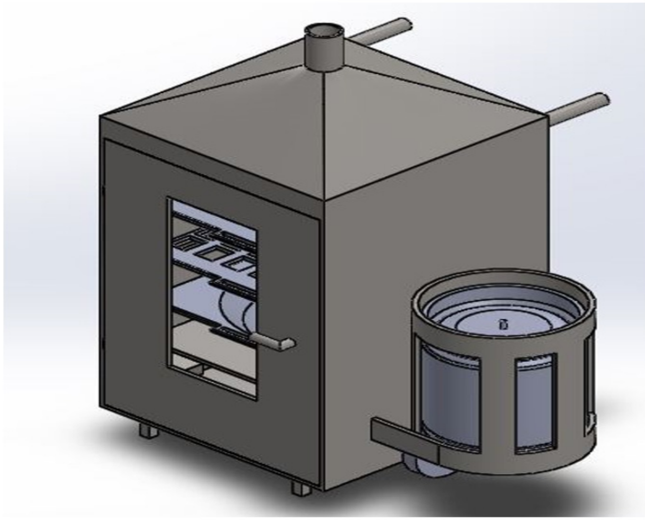


FIGURE 6. Complete diagram of the designed fish dryer (closed)

MODEL FORMULATION

The control volume of the elemental tray of the dryer was used for the development of the mathematical model for the drying temperature regime in the dryer as shown in Figure 7.

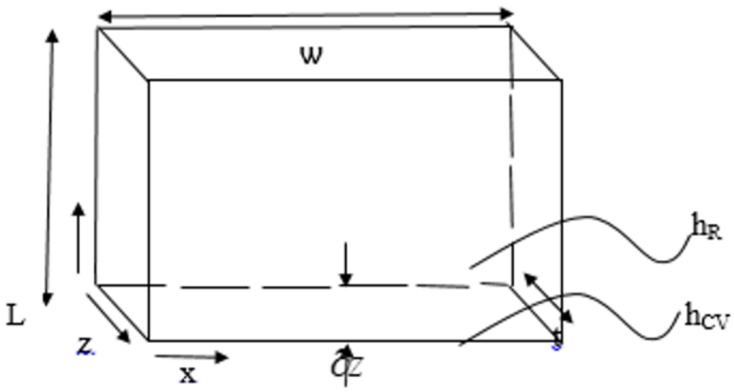


FIGURE 7. Control volume description of the tray

The temperature variation is modelled as 1-D case problem along the Z-direction donated as dz given as thickness of the tray, t. There were surface heat losses in form of convection and radiation with their respective heat transfer coefficients hcv and hR which were consequently captured in the control volume. The bulk surface heat losses were taken to be LT in the control volume energy equation as Equation 1.

From control volume energy equation:

$$\rho C\frac{\partial T}{\partial t} = U + k\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right] - L_T + \varphi \text{.........................(1)}$$

Stephen et al. (2020).

No Temperature variation in x and y direction. The temperature variation in x and y directions were assumed to be negligible. Temperature variation is only in vertical direction (z-direction).

$$\frac{\partial T}{\partial t} = \frac{U}{\rho C} + \frac{k}{\rho C}\left[\frac{\partial^2 T}{\partial z^2}\right] - L_T + \varphi \text{...(2)}$$

No internal heat generation U = 0

φ = total surface heat loss by convention and radiation

$\frac{k}{\rho C} = \alpha$ heat supply rate from the gas cylinder (W).

= thermal diffusivity (m2/s)

K = thermal conductivity of the tray material (W/mK)

ρ = Density (kg/ m3)

$$\frac{\partial T}{\partial t} = \alpha\frac{\partial^2 T}{\partial z^2} - \varphi\frac{L_T}{\rho C} + \frac{\varphi}{\rho C} \text{.................................(3)}$$

$L_T = U_{L,CV}\ A(T_{SL}-T_a) + U_{L,R}\ A(T_{SL}-T_a) + U_{p,cv}\ (T_{su}-T_a)\ A + U_{P,R}\ A(T_{SU}-T_a)$

C = Specific heat capacity of the tray material

A = Heat transfer area

T_{SL} = Lower surface heat transfer of the tray

T_{SU} = Upper surface heat transfer of the tray

T_a = Temperature reference

$U_{P,CV}$ = Upper surface convection heat transfer coefficient

$U_{L,CV}$ = Lower surface convection heat transfer coefficient

$U_{P,R}$ = Upper surface radiation heat transfer coefficient

$U_{L,R}$ = Lower surface radiation heat transfer coefficient

Discretizing Equation (3) with fully explicit forward difference discretization scheme with k and i as temperature and surface notation gives:

$$\frac{T_i^{k+1}-T_i^k}{\Delta t} = \alpha\left(\frac{T_{i+1}^k - 2T_i^k + T_{i-1}^k}{(\Delta z)^2}\right) + \frac{\varphi}{\rho C} - \frac{L_T}{\rho C} \quad \text{......(4)}$$

$$T_i^{k+1} = T_i^k + \frac{\alpha\Delta t}{(\Delta z)^2}\left(T_{i+1}^k - 2T_i^k + T_{i-1}^k\right) + \frac{\varphi\Delta t}{\rho C} - \frac{L_T\Delta t}{\rho C} \quad \text{......(5)}$$

$\frac{\alpha\Delta t}{(\Delta y)^2} = F_o$ ----- mesh Fourier number

$\frac{\varphi\Delta t}{\rho C} = \psi$ - - - --- Thermal losses factor (temperature equivalent of loss)

Equation (5) then becomes:

$$T_i^{k+1} = T_i^k + F_o\left(T_{i+1}^k - 2T_i^k + T_{i-1}^k\right) + \psi - \theta \quad \text{......(6)}$$

$$T_i^{k+1} = T_i^k\left(1-2F_o\right) + F_o\left(T_{i+1}^k + T_{i-1}^k\right) + \psi - \theta \quad \text{......(7)}$$

Initial and Boundary Conditions

$$\left.\begin{aligned} &\text{i) } T|_{t=0} = T_a = T_i \qquad \text{iii) } T|_{Z=L} = T_{U.S} \\ &\text{ii) } T|_{Z=0} = T_{L.S} \end{aligned}\right\} \quad \text{......(8)}$$

Equation (7) can be solved numerically with ***Scilab 6.0.0*** software to evaluate the transient temperature regime of the tray.

For that of the fish as similar geometry as that of the tray is assumed, similar equation is used with the removal of the gas thermal factor ψ.

The initial condition is thus

$$T_f\big|_t = T_i^k$$

Where T_i^k is the temperature of the tray at any time k and node i.

Mean specific heat capacity of catfish, $C_{p,f}$ is 3.6 kJ/kgK.

Mean density of catfish is $920 kg/m^3$. The thermal conductivity k, is a function of the temporal temperature in the dryer given by:

$$k_f = 0.0401 + 0.0059T_i^k + 0.3805M_{dr} \quad \text{......(9)}$$

$$U_{P,CV} = \frac{N_u\lambda_{air}}{L} \quad \text{......(10)}$$

Where $N_u = 0.68 + \frac{\left(0.67R_a^{1/4}\right)}{\left(1+\left(\frac{0.492}{P_r}\right)^{9/16}\right)}$ ......(11)

The Raleigh number, R_a is $R_a = G_rP_r$

Where Grashoff number and Prandtl number respectively given as Gr and Pr are

$$P_r = \frac{\mu}{\alpha}$$

$$G_r = \frac{g\beta\Delta T l^3}{\mu^2}$$

Where mean temperature difference ΔT is evaluated as $\Delta T = T_f - T_a$

$$\beta = \frac{2}{T_f + T_a} = \frac{1}{T_{av}}$$

l = length of the tray

All properties are gotten at mean dryer temperature, T_m given by:

$$T_m = \frac{T_f + T_a}{2} \quad \text{......(12)}$$

$$U_{L,CV} = \frac{N_u\lambda_{air}}{L} \quad \text{......(13)}$$

$U_{L,CV} \equiv U_{P,CV}$ except that T_f is replaced with T_t in the equations

$$U_{P,R} = \frac{\left(T_t^2 + T_a^2\right)\left(T_t + T_a\right)}{\frac{1}{\in_d} + \frac{1}{\in_f} - 1} = U_{L,R} \quad \text{......(14)}$$

$$Md_rC_{pf}\left(T_f - T_a\right) = AU_R\left(T_t - T_a\right) + AU_{CV}\left(T_t - T_a\right)$$

$$M_{dr} = \frac{AU_R\left(T_f - T_a\right) + AU_{CV}\left(T_f - T_a\right)}{\left[C_{pf}\left(T_f - T_a\right)\right]} \quad \text{......(15)}$$

Where M_{dr} is the moisture content of the fish

If the initial mass of the fish is donated as M_o; then

$M_{rm} = M_o - M_{dr}$ ____remaining mass of the fish after drying

$Energas = MgCV_{f-gas} \times \Delta t$ _______ Gas expanded energy

$Enerfish = M_{dr} C_{pf} (T_t - T_f)$ __ fish drying consumed energy

$EnerEff = \frac{Enerfish}{Energas} \times \frac{100}{1}$ _______ Dryer energy efficiency

$Exergas = MgC_{VF-gas} \Delta t \left(1 - \frac{T_a}{T_t}\right)$ ____ Gas expanded exergy

$Exergfish = M_{dr} C_{pf} (T_t - T_f) \left(1 - \frac{T_a}{T_t}\right)$ ___ fish drying consumed exergy

$ExerEff = \frac{Exerfish}{Exergas} \times \frac{100}{1}$ _______ Dryer exergy efficiency

RESULTS AND DISCUSSION

The model equations were solved with ***Scilab 6.0.0*** software. The dryer properties as outlined in the table were used during the computation. The temporal temperature of the dryer tray where the fishes were dried was computed as well as that of the fish. The gas used in the process was modelled to be leaving the cylinder with a low flow rate of 8.0 g/s (on a scale multiple of 100 of the real case).

THE TRAY TEMPORAL TEMPERATURE

Initially, the dryer together with all the trays was at a temperature of 300K (27^{o}C). It can be observed from Figure 8 that the bottom tray maintained the highest temperature regime since the position of the gas dispensing channel is within the bottom tray. The top tray always has the least temperature regime as heat is gradually lost with the dryer during the transfer to the top tray.

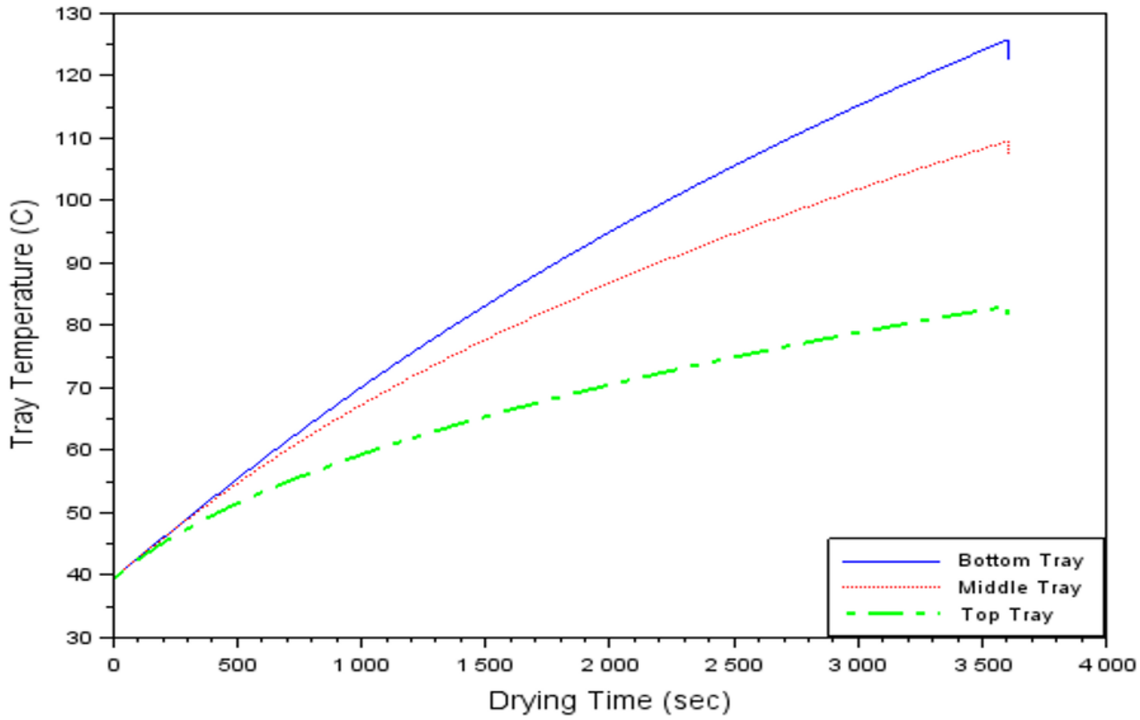


FIGURE 8. Tray temporal temperature variation.

THE FISH TEMPORAL TEMPERATURE

Similarly, the heat was transferred to the fishes on the tray resulting in a similar fish temperature regime though on a lower value. It can be seen from Figure 9 that the fish was initially always at a slightly lower temperature than that of the tray. It had a more gradual temperature increment compared to that of the tray. Meanwhile, the same trend was maintained as fishes on the bottom tray witnessed higher temperatures. After an hour, (i.e. 3600 seconds), the peak sensible drying temperature of the fish was attained after which the temperature started dropping.

When the gas mass flow rate was increased to 16mg/s, the temperature of both the tray and fish recorded was very high as can be seen in Figure 10, which combined the fish and tray temperature in K but the temperature recorded was unacceptably high for fish drying.

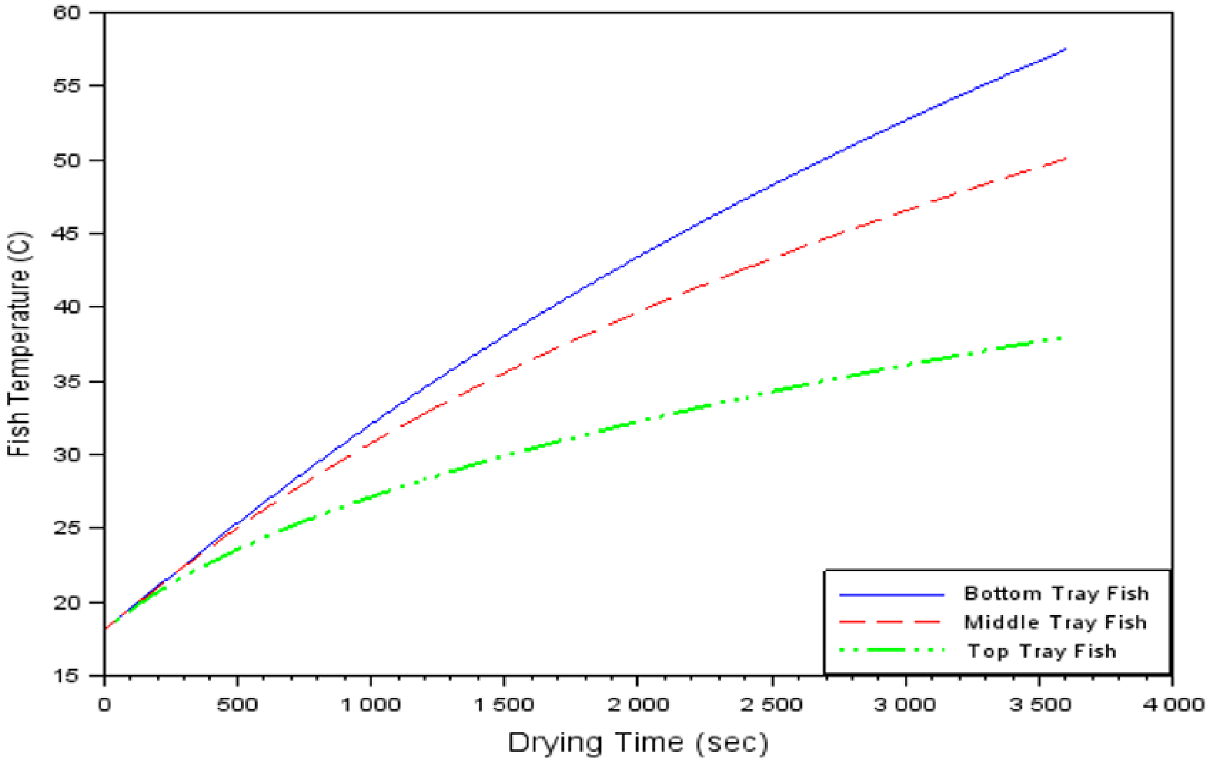


FIGURE 10. Tray and fish temporal temperature variation.

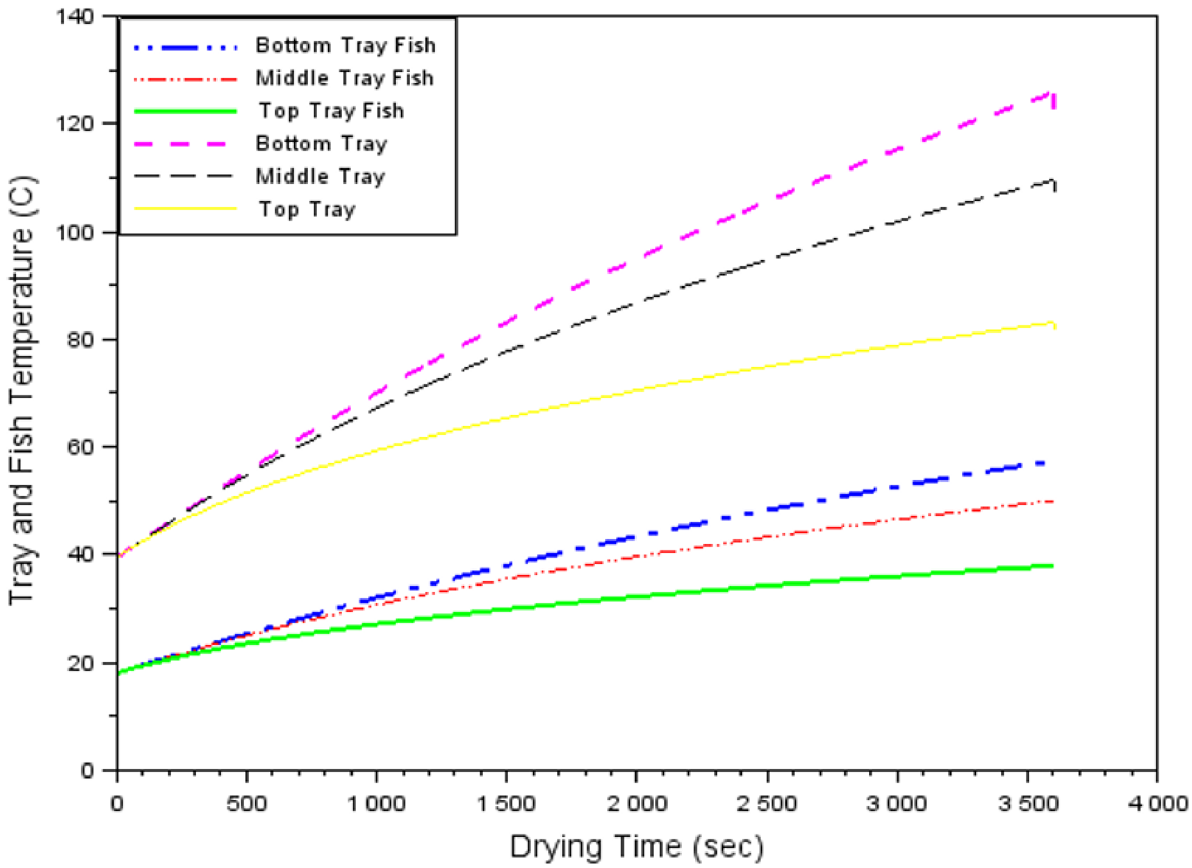


FIGURE 10. Tray and fish temporal temperature variation.

THE FISH DRYING MASS

The dropping of the sensible drying temperature can be attributed to the static drying rate (mass reduction) of the fish as observed in Figure 10. Figure 11 shows the variation of the mass of the fish dried with time. A particular sample of 550 g of fish was used to test-run the model and also experimentally for the model validation. It could be observed that the experimental data for the drying and that of the model were very close. The errors in % between the experimental and numerically computed values at the different times fall within 2 % to 4.5 %. The middle and the top trays were used because the bottom tray easily starts burning the sample on it when tested. The mass drying rate was initially very high and fast for the first 35 minutes, thereafter increasing gradually till its sensible peaked around 75 minutes. It could be observed that there was not much mass drying after 75 minutes (1 hour, 15 minutes). At this point, the fish could be brought out, even though it could also undergo further drying as a better preservative measure, in case of a long period of usage. Hence, the closeness between the experimental data and mathematical model justifies the reason to use this derived model for the computation of other parameters associated with the drying process (which include mass drying fraction, energy, exergy, energy efficiency, exergy efficiency, etc.).

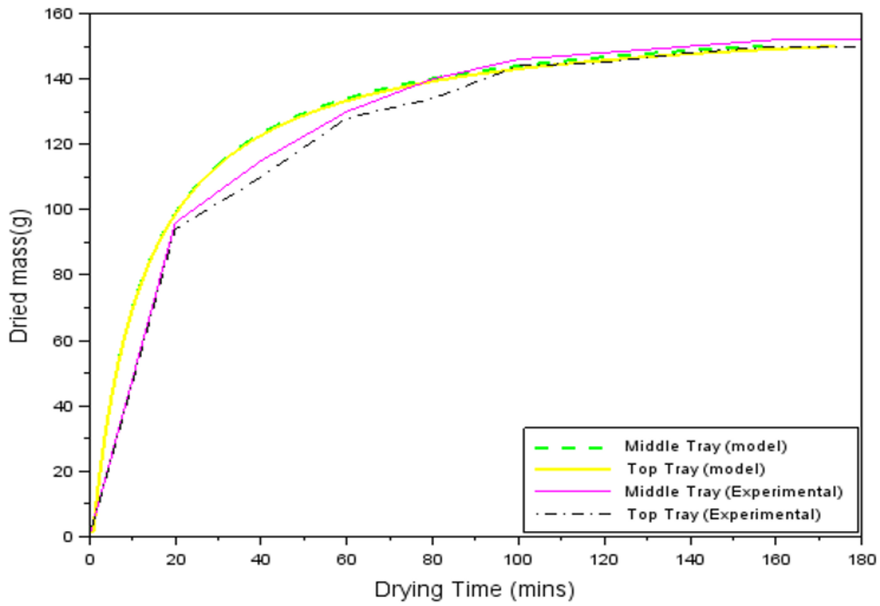


FIGURE 11. Dried mass of the fish variation with time.

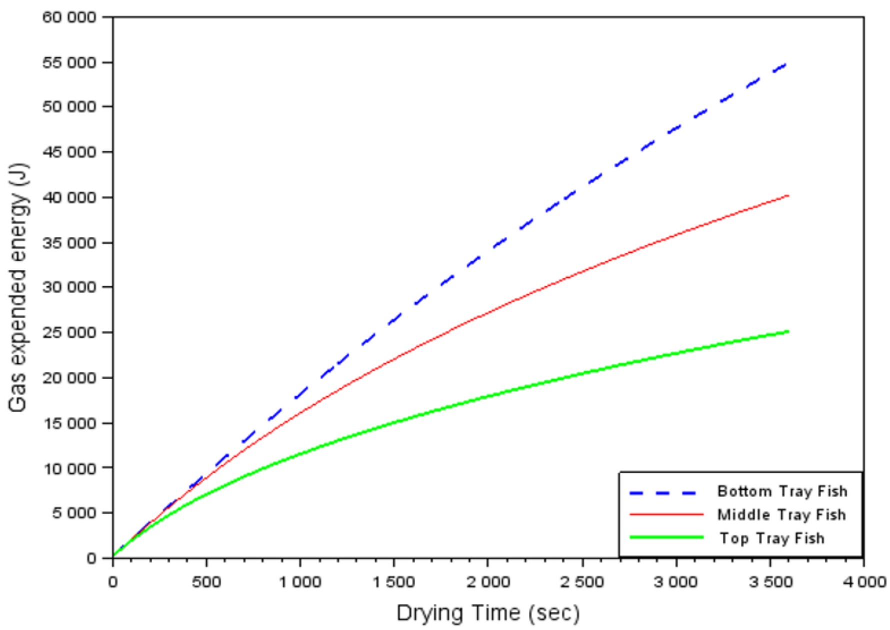


FIGURE 12(a). Gas drying period expended energy.

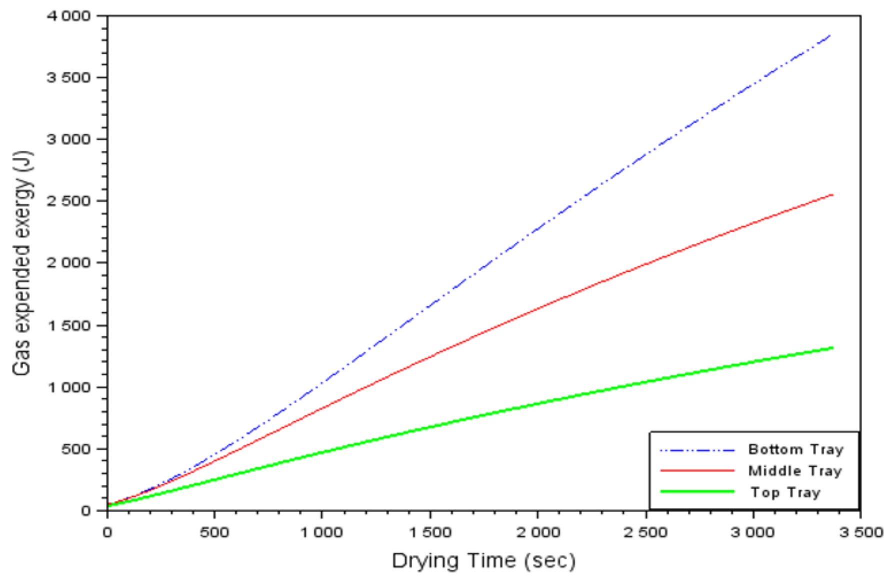


FIGURE 12(b). Gas drying period expended exergy.

GAS EXPENDED ENERGY AND EXERGY

It can be observed from Figures 12a and 12b that the energy and exergy used by the gas in the drying process followed the same trend. The bottom tray still maintained the maximum energy and exergy absorbed from the gas. This is demonstrated by the skyrocketed nature of the energy and exergy increment in Figure 11 as well as the highest temperature recorded in Figure 8, which could be the reason for the burning of the drying item (fish) within a short while. Fraction of these energy and exergy were consumed by the fishes in the dryer as shown in Figures 13a and 13b. It can as well be seen that the corresponding energy and exergy of the fish did not start from 0 like that of the tray, which implies that the tray had been heated to a relatively high temperature before the fishes were dropped into the dryer. For traycase, the amount of the used or consumed exergy is usually within 6% to 11% of the corresponding energy whereas it is usually within 0.85% to 3% for the fish case resulting from the higher entropy generation within the fish during drying. This was equally verified from the incremental change of the fish thermal conductivity with drying time. The fish thermal conductivity as a function of time is shown in Figure 14 to observe its change with time. For the drying period of 3600 seconds, the average thermal conductivity change had been observed to be 0.38 W/mK as seen in Figure 14.

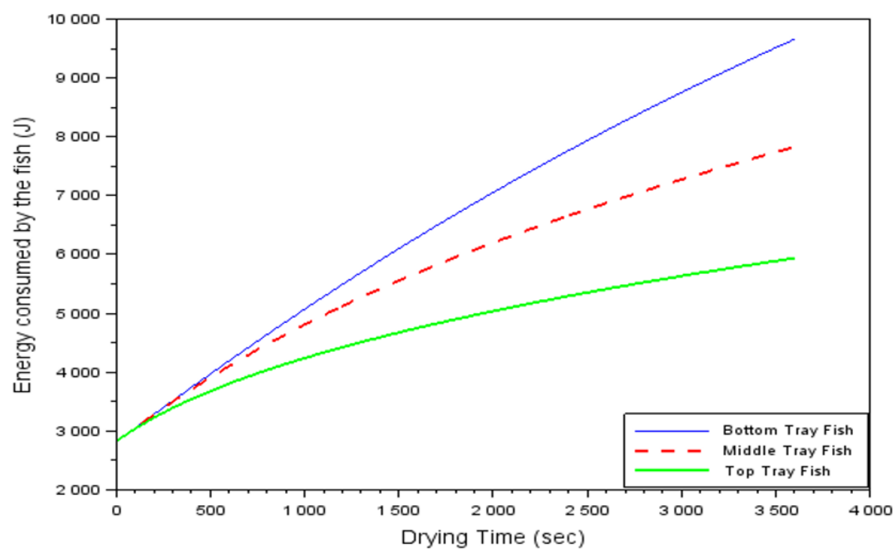


FIGURE 13(a). Fish consumed energy during the drying process.

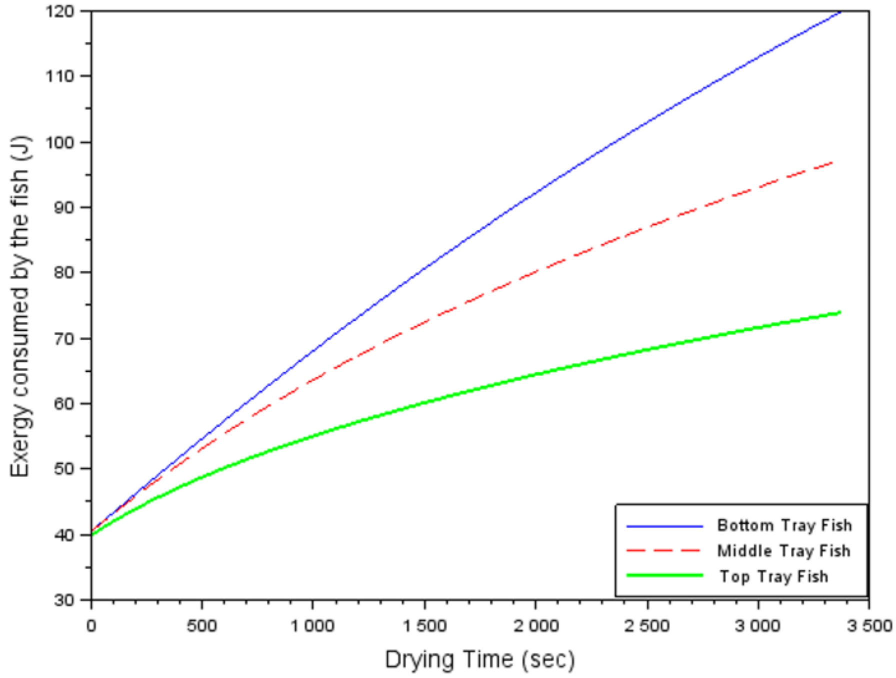


FIGURE 13(b). Fish consumed exergy during the drying process.

The energy and exergy of the dryer were plotted in Figures 15a and 15b. The energy variation profile was plotted as the left diagram of Figure 15 while the right diagram is the combined plot of both energy and exergy to show their relationship. From the left diagram of the figure, the top energy increase is 76% (i.e. from 17% to 76% for the bottom tray, 17.5% to 90% for the middle tray and 18% to 89% for the top tray) with the middle tray maintaining the maximum efficiency gain at the record time of roughly the 25th minute till the end. From Figure 15b, the net exergy change is 10.0% (i.e. from 0.4% to 10.4% for the bottom tray) with the same middle tray maintaining the maximum efficiency gain at roughly the 10th minute. Since the dryer exergy started increasing from approximately 0%, it justified the fact that the exergy of the dryer is the maximum possible useful energy of the dryer from the active state to the dead state.

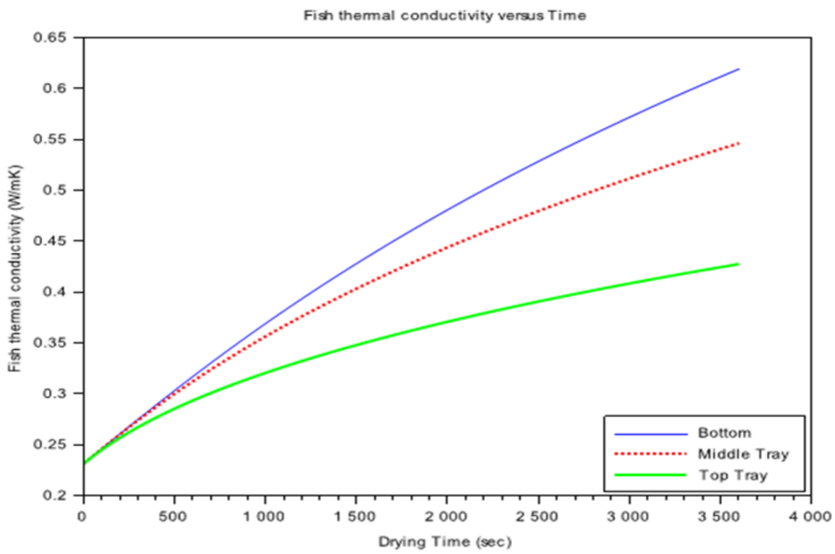


FIGURE 14. Fish thermal conductivity variation with time.

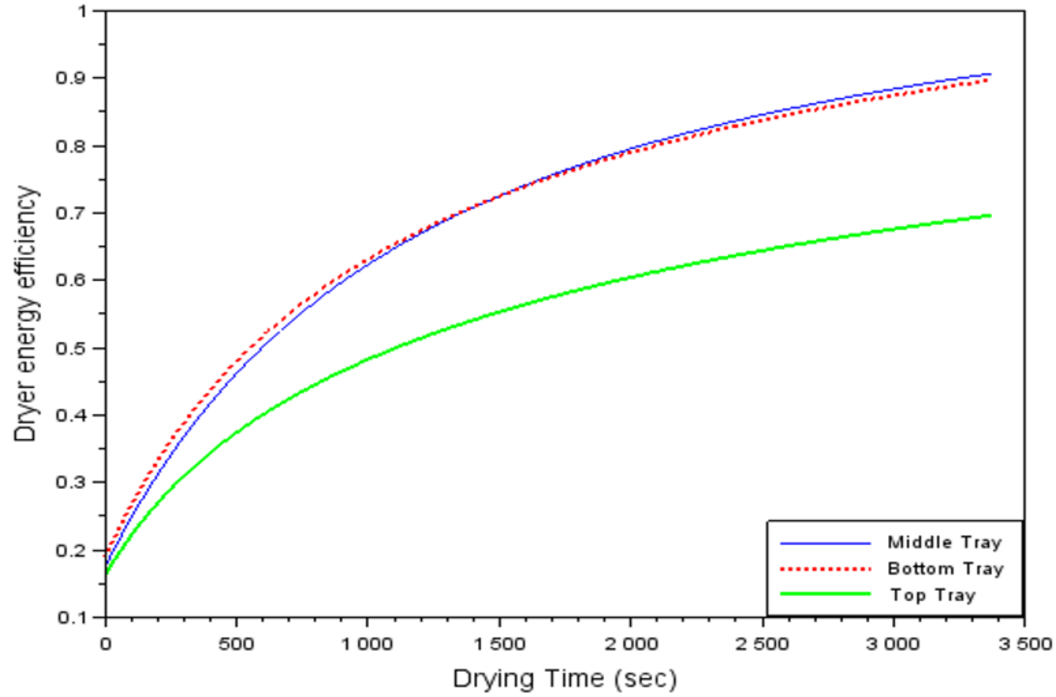


FIGURE 15(a). Energy efficiency of the dryer.

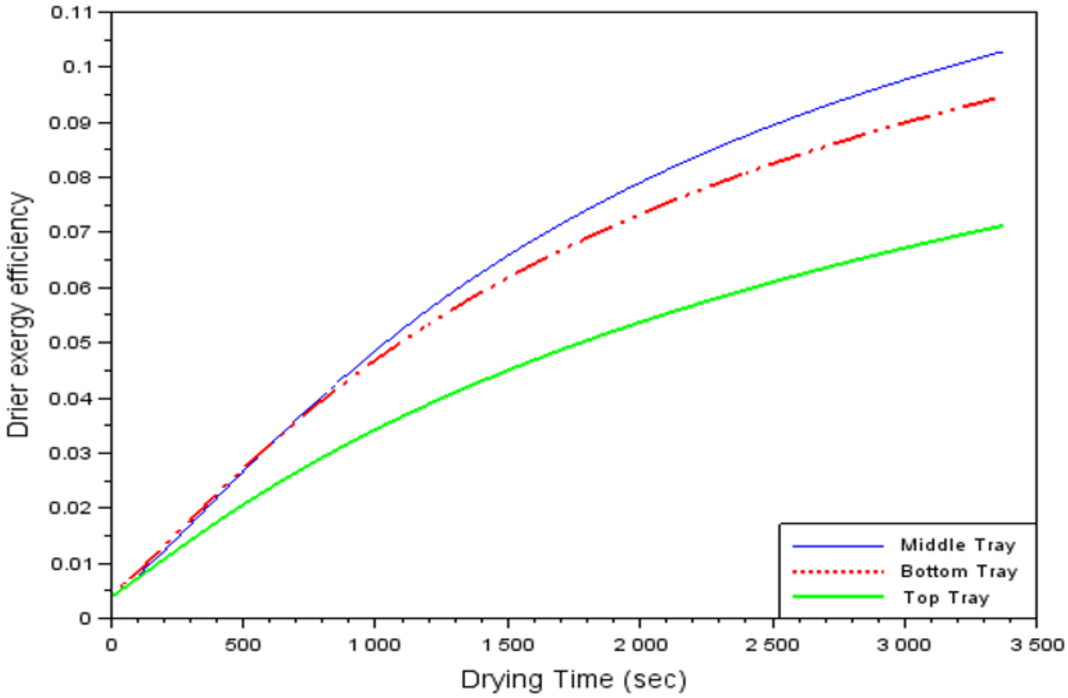


FIGURE 15(b). Exergy efficiency of the dryer.

CONCLUSION

From the results, it is clear that high levels of energy and exergy efficiency were recorded in the dryer, which was also a reflection of the recorded exergy of the system as well as the corresponding efficiency. This is as a result of the level of insulation in the dryer as much heat loss was minimized and the gas high combustion efficiency achieved. It can also be seen that the middle tray is the most efficient tray for drying, with little or no loss due to burning caused by excessive temperature. Through the proper regulation and control of the gas flow rate to the combustion nozzle, gradual drying was witnessed even though it took more time to achieve better drying. Again, the high second law (exergy) efficiency recorded in the system justified the fact that it would serve as a good agent for drying materials especially the high moisture content items like fish. With the high mean exergy efficiency of the system which is almost 10% of the mean system energy efficiency, it implies that the exergy destruction within the dryer is minimized, which makes the dryer highly reliable for input energy maximization.

ACKNOWLEDGEMENT

The authors are highly thankful to Alex Ekwueme Federal University and Federal Polytechnic for their excellent help and support to conduct this research.

DECLARATION OF COMPETING INTEREST

None.

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