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Thin-layer drying of cassava chips in multipurpose convective tray dryer: Energy and exergy analyses

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Abstract Energy and exergy data of the drying of thin-layer cassava (*Manihot esculenta*) chips in a multipurpose convective-type tray dryer at 50 °C were collected to evaluate the technical performance of the drying system. The energy and exergy parameters, i.e. energy utilization, energy utilization ratio, energy efficiency, exergy inflow and outflow, exergy loss, and exergetic efficiency were analyzed. The results indicate that the energy utilization, exergy inflow, exergy outflow, and exergy efficiency increased in the ranges of 9.53-24.66 kJ/s, 5.67-11.34 kJ/s, 2.21-8.04 kJ/s, and 38.90 %-70.86 %, respectively, with increasing drying time. The results also show that the energy utilization ratio, energy efficiency, and exergetic improvement potential tend to decrease in the ranges of 0.49-0.68, 47.48 %-62.62 %, and 0.96-2.33 kJ/s, respectively, with increasing drying time. Additionally, stable exergy losses were observed during the drying process, within the range of 3.30-4.27 kJ/s during drying. Further research and development that could be used to improve the performance of this drying process are also suggested.

1. Introduction

Indonesia is one of the top two producers of cassava (*Manihot esculenta*) in Asia, and at the same time is a significant importer of cassava [1]. Local Indonesian small and medium enterprises has successfully develop derivative product in their way that has growing attention for local market [2-4], e.g. modified cassava flour (MOCAF). MOCAF is flour produced from cassava that has modified, usually by fermentation using lactic acid bacteria such as *Saccharomyces cerevisiae*. Reports have been made regarding the potential of MOCAF for being a substitute for wheat flour [5] and being included in a composite for bakery products [6].

One critical step in the production of MOCAF is the drying process, in which the water contained in the cassava chips is minimized to an appropriate level prior size reduction process. Heat and mass transfer between the surface of the product and the air as medium is complicated process which made drying is not an easy task [7]. The drying process is commonly conducted by dryer due to efficient process. It is possible due to water contained inside product has greater vapor pressure and make water movement easier within the product. At the same time, higher temperature also considerably decreases the air relative humidity to enhance the air capability to carry water [8, 9].

Recently, Argo et al. [10] designed and tested a newly developed multipurpose convective tray dryer specifically designed for local MOCAF production. However, the dryer needed further testing regarding its energy-exergy related parameters. High latent heat required for water evaporation, as well as poor efficiency of energy used, caused high energy inputs for drying process is a must [9]. Since energy is a significant cost factor in MOCAF production, energy and exergy data can considerably contribute to lower production cost, also as tools for comprehensive dryer energy system evaluation.

Engineering system often use the first thermodynamics law to analyze the performance.

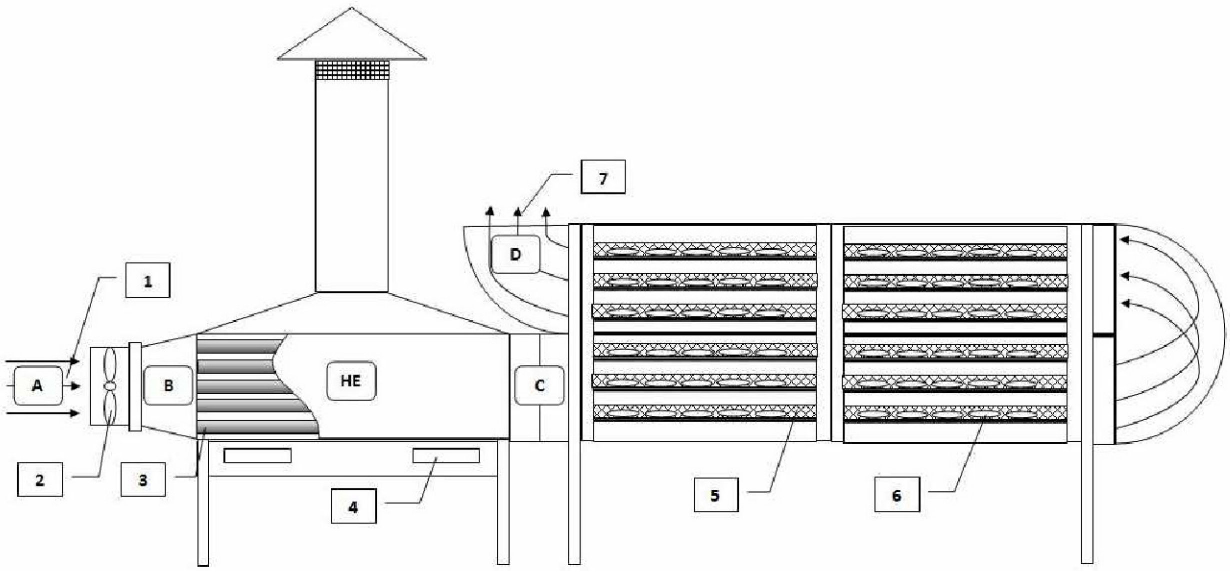

Fig. 1. Multipurpose convective tray dryer (1. Fresh air inlet, 2. Fan, 3. Horizontal tube-type heat exchanger (HE), 4. Gas burner, 5. Perforated tray, 6. Cassava chips, 7. Hot air outlet, A-D. Thermocouples points).

However, several deficiencies of energy analysis have been reported. Akpinar and Kocyigit [11] stated that the concept is not responsive to the assumed process direction, e.g. if heat is assumed to be transferred spontaneously in the direction of increasing temperature, the energy analysis does not take it into account. In addition, energy analysis does not provide information regarding any thermodynamic process disability to change heat, with complete efficiency, into mechanical work [12]. Aviara et al. [9] also stated that different qualities of energy is not distinguishable by energy analysis, as well as any information is also not provided regarding on why mixture cannot spontaneously separate themselves [9].

Exergy analysis is needed to overcome these problems. If compared to the energy data, exergy data give more useful and practical information regarding system performance. In addition, standard energy analysis sometimes gives different or less accurate result of actual process than exergy analysis [11]. According to Dincer [8], exergy is described as the amount of work that can be obtained from a stream of matter, heat or work as it comes to equilibrium with an ambiance environment. It is a quantification of the potential of a stream to cause change, a result of not being totally steady relative to the ambiance environment. For specific purposes, e.g. study, design, and improvement of the systems; exergy analysis is simultaneously uses the principles of mass and energy conservation with the second law of thermodynamics. The method is a more helpful instrument in order to evaluate the efficient use of energy resource [13].

Previous researchers have found an excellent method for the energy and exergy analyses of the drying process [8, 12, 14]. Other authors have also made numerous reports regarding energy and exergy analyses of the drying of various agro-based and food stuffs using various systems of drying. For example, pistachios in a solar dryer [7, 15], red pepper slices in a convective dryer [16], potato [17] and eggplant [18] in a cyclone dryer, a timber dryer assisted with a heat pump [19], coroba slices in an air dryer [20], potato slices in a semi-industrial continuous band dryer [21], mulberry, mint leaves, jackfruit leather, red seaweed, ghost chili pepper, and ginger in a solar dryer [22-27], cassava starch in a tray dryer [9], and potato cubes in a fluidized bed dryer [28]. Aghbashlo et al. [29] also reviewed numerous reports on the application of the exergy analysis of various drying processes and facilities of agricultural-based products.

Certain performance factors on energy and exergy data of MOCAF production, i.e. thin-layer cassava chips drying using multipurpose convective tray dryer designed by Argo et al. [10], appears to be needed for further development of the dryer. The main objective of this project is to collect and evaluate technical performance, i.e. energy and exergy data of cassava chips drying using multipurpose convective tray dryer.

2. Materials and methods

2.1 Material preparation

The identical procedure for cassava chips preparation was adopted from previous study by Argo et al. [10]. The original average moisture content of the chips was 73.28±1.4 % (wb), with standard gravimetric measurement by AOAC [30]. The chips were divided into four equal portions of 3 kg each for each drying compartment, which amounts to 12 kg of total drying load.

2.2 Dryer description

The dryer used for cassava chips drying was the same dryer previously used by Argo et al. [10]. The multipurpose convective dryer consist of four drying compartments. Each drying compartment has three perforated trays placed one on top of another (Fig. 1). During operation mode, fresh air is sucked at 2.5 m/s of air velocity by electric fan, heated by heat exchanger, and forced into drying compartments. The heated air passes through 1st to 4th drying compartments consecutively, and out of the system through an outlet. The dryer was equipped with a thermo-controller device (Omron, Japan) that regulates the air temperature entering the drying compartments. Temperature of the drying air entering the drying compartments was maintained to within ±2 °C of the temperature set point.

In the operation mode, the ambient air is sucked by fan through the horizontal tube-type heat exchanger. The heat exchanger is heated by two gas burners powered by liquefied petroleum gas (LPG). The ambient air is heated up to the set point temperature and then enters the first to fourth drying compartments, sequentially. Inside the drying compartments, the hot air obtains water from the cassava chips and exit through the outlet. As an impact of continuous contact between hot air and chips, the reduction of water contained in the cassava chips is obtained. Continuous water removal leads to mass reduction as well as moisture content of the cassava chips in the drying compartments. For the energy and exergy data, four K-type thermocouples were placed at four points, namely the dryer inlet (A), heat exchanger inlet (B), heat exchanger outlet (C), and dryer outlet (D) (Fig. 1).

2.3 Drying experiments

The drying tests were conducted at 70 %-75 % and 28.67± 0.37 °C of relative air humidity and average dry bulb temperature, respectively. Temperature of the drying air entering the drying compartment was set at 50 °C. For an experimental run at the desired drying temperature, the empty dryer was allowed to run for 60 min to obtain stable desired air temperature prior the experiment. The drying process was conducted until the cassava chips reached their moisture equilibrium, i.e., 345 min [10]. The drying duration considering the detailed drying characteristics of cassava chips in the same dryer by previous report. The drying air temperatures at the point of the thermocouples were recorded during the experiment.

2.4 Energy analysis

For the mathematical calculations of the energy analysis, the method previously used by Aviara et al. [9] was adopted. The present setup was considered as an open system with a stable flow process that was examined by applying conservation energy principles and the constant flow of mass. From this perspective, the energy balance is expressed as follow.

$$\dot{Q} - \dot{W} = \sum \dot{M}_{ao}\left[h_o + \frac{v_o^2}{2}\right] - \sum \dot{M}_{ai}\left[h_i + \frac{v_i^2}{2}\right] \quad (1)$$

Eq. (1) becomes Eq. (2) and Eq. (2) becomes Eq. (3) for two specific reasons, i.e. no involvement of mechanical work in the dryer during cassava chips drying process; and no involvement of resultant motion in the drying process, hence the momentum components ($v_o^2/2$ and $v_i^2/2$) are eliminated.

$$\dot{Q} = \sum \dot{M}_{ao}\left[h_o + \frac{v_o^2}{2}\right] - \sum \dot{M}_{ai}\left[h_i + \frac{v_i^2}{2}\right] \quad (2)$$

$$\dot{Q} = \sum \dot{M}_{ao} h_o - \sum \dot{M}_{ai} h_i \quad (3)$$

By assuming the equality of entering and leaving the mass flow rates of the drying systems ($M_{ao} \equiv M_{ai} \equiv M_a$), Eq. (3) can be written as follows.

$$\dot{Q} = \dot{M}_a\left(h_o - h_i\right) \quad (4)$$

Eq. (5) as follows was used to calculate the mass flow rate of drying air entering into drying compartments.

$$\dot{M}_a = \rho_a \dot{V}_a \quad (5)$$

The enthalpies and the specific heat of the drying air at the inlet and outlet temperatures were calculated by Eqs. (6) and (7), respectively.

$$h = Cp_{da} T_{da} + W h_{sat} \quad (6)$$

$$Cp_{da} = 1.0029 + 5.4 \times 10^{-5} T_{da} \quad (7)$$

The energy utilization during drying was determined by applying Eq. (4) and transforming it into Eq. (8) as follows.

$$EU = \dot{M}_a\left(h_i - h_o\right) \quad (8)$$

The energy utilization ratio and energy efficiency were determined using Eqs. (9) and (10), respectively. Energy efficiency was defined as the ratio of the energy expended to the energy supplied to the drying system.

$$EUR = \frac{\dot{M}_a\left(h_i - h_o\right)}{\dot{M}_a\left(h_i - h_\infty\right)} \quad (9)$$

$$\eta_{energy} = \frac{E_i - E_o}{E_o} = \frac{\dot{M}_a\left(h_i - h_o\right)}{\dot{M}_a h_i} \times 100\% \quad (10)$$

2.5 Exergy analysis

For the mathematical calculations of the exergy analysis, the method previously used by Aviara et al. [9] was adopted. The exergy balance is stated as follows for an open system. Eq. (11) consist of several components, namely, the internal energy component ($U - U_\infty$); entropic component ($S - S_\infty$); work component (P_∞ ($V - V_\infty$); momentum component ($V^2/2$); and gravity component (($Z - Z_\infty$)g).

$$Ex = \left[U - U_\infty\right] - T_\infty\left[S - S_\infty\right] + P_\infty\left(V - V_\infty\right) + \frac{v^2}{2} + \left(Z - Z_\infty\right)g + V\left(P - P_\infty\right) \quad (11)$$

Since there is no agitation or relative motion during drying process in convective tray dryer, the gravity and momentum components were neglected. Then, Eq. (11) reduces to Eq. (12) and yields Eq. (13).

$$Ex = \left[U - U_\infty\right] - T_\infty\left[S - S_\infty\right] + P_\infty\left(V - V_\infty\right) + V\left(P - P_\infty\right) \quad (12)$$

$$Ex = \left[U + PV\right] - \left[U_\infty + P_\infty V_\infty\right] - T_\infty\left(S - S_\infty\right) \quad (13)$$

For substitution of *U* + *PV* terms by enthalpy, Eq. (13) becomes as follow.

$$Ex = Cp_{da}\left[\left(T - T_\infty\right) - T_\infty \ln\frac{T}{T_\infty}\right] \quad (14)$$

Eq. (14) was used as the basic equation to determine the inflow and outflow of exergy at the inlet and outlet temperatures of the drying compartments. The exergy inflow minus the exergy outflow (Eq. (15)) was defined as exergy loss during drying.

$$\sum Ex_l = \sum Ex_i - \sum Ex_o \quad (15)$$

The exergy inflow and outflow to the drying compartments was calculated as follows, substituting Eq. (7) into Eq. (14).

$$Ex_i = 1.0029 + 5.4\times10^{-5}T_{dai}\left[\left(T_{dai} - T_\infty\right) - T_\infty \ln\frac{T_{dai}}{T_\infty}\right] \quad (16)$$

$$Ex_o = 1.0029 + 5.4\times10^{-5}T_{dao}\left[\left(T_{dao} - T_\infty\right) - T_\infty \ln\frac{T_{dao}}{T_\infty}\right] \quad (17)$$

The proportion of exergy used during drying process to exergy of the drying air supplied to the system has been defined as exergetic efficiency [20, 31]. Exergetic efficiency can be expressed as follows.

$$\eta_{exergy} = 1 - \frac{Ex_l}{Ex_i} \quad (18)$$

An additional parameter that is used by Hammond and Stapleton [32] and Erbai and Icier [33] is the exergetic improvement potential of the drying process. This parameter is expressed as follow.

$$IP = \left(1 - \eta_{exergy}\right)\left(Ex_i - Ex_o\right) \quad (19)$$

Table 1. Uncertainties of the parameters during cassava chips drying.

Parameters	Unit	Comment
Measured parameters		
Uncertainty on temperature	°C	±0.37
Uncertainty on relative humidity	%RH	±0.14
Uncertainty on air velocity	ms^{-1}	±0.17
Uncertainty on weight loss	g	±0.50
Calculated parameters		
Uncertainty on air mass flow rate	%	±0.75
Uncertainty on energy utilization	%	±2.98
Uncertainty on energy utilization ratio	%	±3.91
Uncertainty on energy efficiency	%	±1.76
Uncertainty on exergy inflow and outflow	%	±2.79
Uncertainty on exergy loss	%	±3.26
Uncertainty on exergy efficiency	%	±1.89

2.6 Experimental uncertainty

Several factors such as instrument selection, condition, calibration, environment, observation, reading, and test planning, might cause errors and uncertainties. For drying experiments with multipurpose convective tray dryer, parameters such as air temperatures, relative humidity, weight losses, and air velocities were measured using proper instruments. According to Akpinar [23], the uncertainty of the result is expressed as Eq. (20), where w_R is the uncertainty of the results and w_1, w_2, w_n are the uncertainty in the independent variables. The result *R* is a given function of the independent variables x_1, x_2, x_n.

$$w_R = \left[\left(\frac{\partial R}{\partial x_1}w_1\right)^2 + \left(\frac{\partial R}{\partial x_2}w_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n}w_n\right)^2\right]^{1/2} \quad (20)$$

During drying process, total uncertainties of the measured and calculated parameters were summarized in Table 1. It was confirmed that all uncertainties found to be in acceptable ranges.

3. Results and discussion

3.1 Chips weight reduction and energy utilization

The temporal changes of energy utilization and chips weight loss during the drying process using the multipurpose convective tray dryer at a drying temperature of 50 °C and 1.22±0.01 kg/s of average drying air mass flow rate is presented in Fig. 2. The energy utilization is on the left y-axis and the weight loss on the right y-axis, as functions of drying time. The cassava chips in all drying compartments decreased from 12 kg to approximately 5.46 kilograms in the ranges of 9.53-24.66 kJ/s of the energy utilization during 345 min of drying. In the course of

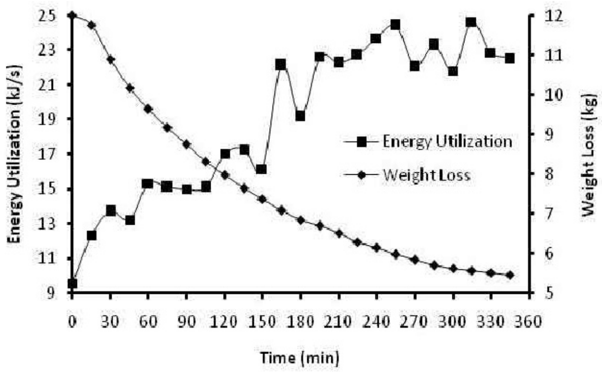

Fig. 2. The changes of energy utilization and chips weight loss during cassava chips drying process.

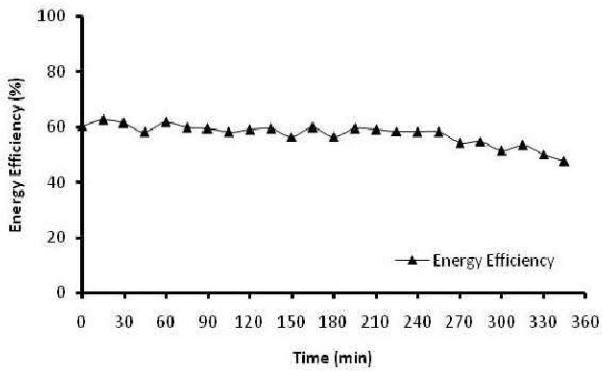

Fig. 4. The variation of energy efficiency during cassava chips drying process.

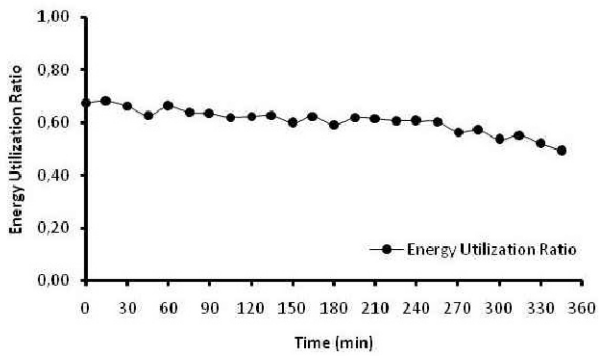

Fig. 3. The variation of energy utilization ratio during cassava chips drying process.

starting phase of drying (0-210 min), the energy utilization was increased. It was due to the energy supplied to the drying compartment mostly was used for the free water evaporation of the cassava chips, and so the energy utilization increased.

If compared to the previous report by Aghbashlo et al. [21], who conducted an energy and exergy analysis of potato slices drying in continuous band dryer at the same temperature (50 °C) with a drying air mass flow rate (1.22 kg/s), the present study showed higher utilization of energy. A similar comparison result also obtained when the energy utilization of the present study is compared to previous reports at the same temperature (50 °C), e.g., olive leaves [33] or native cassava starch [9].

3.2 Energy utilization ratio

The temporal variation of the energy utilization ratio during the drying of cassava chips using multipurpose convective tray dryer at 50 °C of drying temperature is presented in Fig. 3, which shows that the energy utilization ratio ranged between 0.49-0.68. With increasing drying time, the energy utilization ratio tended to decrease. The same result was also reported by Akpinar [16], who conducted energy and exergy analyses of red pepper slices drying in a convective dryer.

The values of the energy utilization ratio indicate that the energy obtained from the heat exchangers was productively utilized for thin-layer drying of cassava chips at the subjected temperature. Fig. 3 shows that at least up to half of the energy supplied was being used during the drying process. However, it also indicates that approximately 0.3-0.5 of the energy is still available in the outlet of the drying compartments. Further developments are needed to increase the energy utilization. It would be advantageous if the enthalpy could be further exploited through further modification, e.g., a recycling hot air system. If compared to previous reports at the same drying temperature, e.g., native starch drying by Aviara et al. [9], the energy utilization ratio of the present study is comparable. But it is superior to that of the drying of potato slices reported by Aghbashlo et al. [21] at the same temperature (50 °C) and drying air mass flow rate (1.22 kg/s) and olive leave drying by Erbai and Icier [33].

3.3 Energy efficiency

Fig. 4 shows the temporal variation of energy efficiency during the drying of cassava chips using multipurpose convective tray dryer at a drying temperature of 50 °C. The energy efficiency during drying process ranged between 47.48 %-62.62 %. It was also observed that energy efficiency tended to decrease with increased drying time. The energy efficiency of the present study was quite higher than that previously reported for potato slices [21] at the same temperature (50 °C) and drying air mass flow rate (1.22 kg/s) and native cassava starch [9] drying at the same temperature (50 °C).

3.4 Exergy inflow, outflow and loss

Fig. 5 shows the temporal changes of exergy inflow, outflow and loss during the cassava chips drying process using multipurpose convective tray dryer at a drying temperature of 50 °C. The parameters are shown in Fig. 5 were calculated depending on the ambient and inlet temperature. The inflow and outflow of exergy to the drying compartments ranged from 5.67-11.34 kJ/s and 2.21-8.04 kJ/s, respectively, rely on the temperatures of inlet and outlet. It was also noticed that the exergy inflow into the drying compartments, as well as the the exergy outflow from the drying compartments, slowly gained with the drying

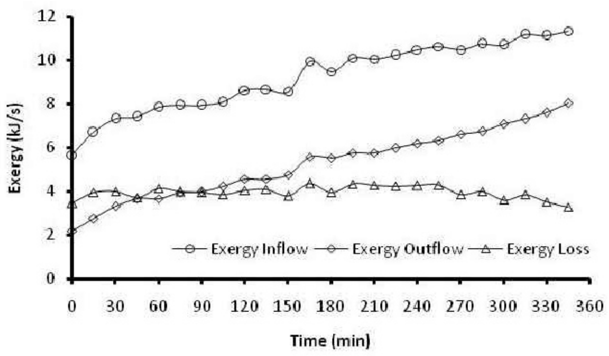

Fig. 5. The changes of exergy inflow, outflow and loss during cassava chips drying process.

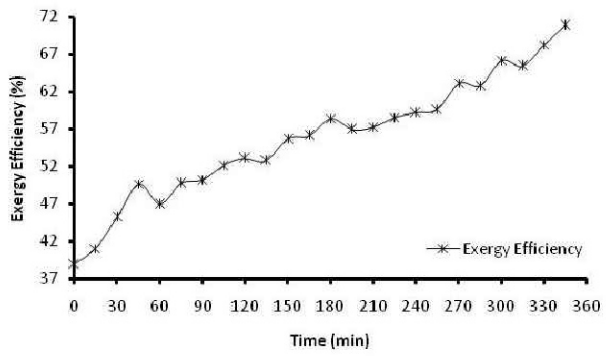

Fig. 6. The variation of exergetic efficiency during cassava chips drying process.

time. Additionally, the exergy loss ranged between 3.30-4.37 kJ/s during the drying process was stable. If compared to previous reports for the same drying temperature (50 °C), e.g. native cassava starch drying [9], all exergy parameters of the present study are higher.

3.5 Exergetic efficiency

The temporal variation of the exergetic efficiency of the drying of cassava chips using multipurpose convective tray dryer at a drying temperature of 50 °C is presented in Fig. 6. The exergetic efficiency during the drying process ranged from 38.90 %-70.86 %. It was also observed that the exergetic efficiency tended to increase with increasing drying time. If compared to previous report for the same drying temperature (50 °C), e.g., native cassava starch drying [9], the exergetic efficiency of the present study is higher.

As stated by Dincer [8], three sources may be identified for exergy inefficiencies of an air drying system. One of major possible source of inefficiency is the dryer body itself, when the temperature of dryer body is higher than the surroundings temperature. Further modifications are required to improve the thermodynamic performance of dryer, e.g. isolating the dryer body, designing and opting better components. Another improvement that may also be beneficial is finding the optimum drying conditions for cassava chips by considering the combination of drying temperature and air mass flow rate without ignoring the properties of the dried cassava chips product.

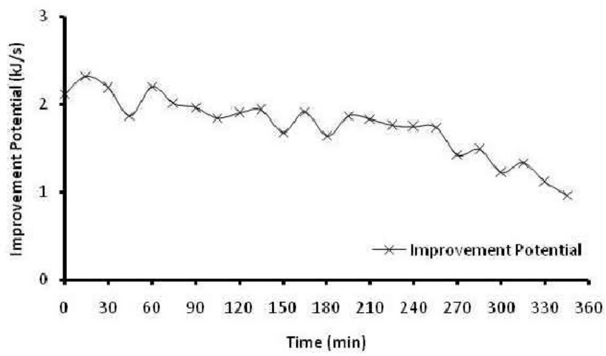

Fig. 7. The variation of exergetic improvement potential during cassava chips drying process.

3.6 Improvement potential

Fig. 7 shows the temporal variation of the exergetic improvement potential the cassava chips drying process using multipurpose convective tray dryer at a drying temperature of 50 °C. The exergetic improvement potential during the drying process had a range of 0.96-2.33 kJ/s. The figure showed that the exergetic improvement potential tended to decrease with increasing drying time. If compared to previous report for the same drying temperature (50 °C), e.g., native cassava starch drying [9], the exergetic improvement potential of the present study is comparable.

4. Conclusions

The energy and exergy analyses of cassava chips drying were investigated in a multipurpose convective tray dryer at 50 °C. The energy utilization, exergy inflow, exergy outflow, and exergy efficiency increased with increasing drying time. The energy utilization ratio, energy efficiency, and exergetic improvement potential tended to decrease with increasing drying time. A stable exergy loss was observed during the drying process. Further research and development are still needed for better drying performance, e.g., finding the optimum drying conditions for drying cassava chips.

Nomenclature

Q : Energy inflow, J/s
$\dot{W}$: Rate of mechanical work output, J/s
M : Mass flow rate, kg/s
h : Enthalpy, J/kg
v : Velocity, m/s
ρ : Density of drying air, kg/m^3
V : Volumetric flow rate of drying air, m^3/s
Cp : Specific heat of drying air, J/kg

T : Temperature, °C
W : Humidity ratio of drying air, kg H_2O/kg Air
EU : Energy utilization, J/s
EUR : Energy utilization ratio
n : Efficiency, %
E : Energy, J/kg
Ex : Exergy, J/kg
U : Internal energy, J/kg
S : Entropy, J/kg
P : Pressure, N/m^2
Z : Elevation, m
g : Gravitational acceleration, 9.81 m/s^2
IP : Exergetic improvement potential, J/s

Subscripts

ao : Air outlet
o : Outlet
ai : Air inlet
i : Inlet
a : Air
da : Drying air
sat : Saturated
∞ : Ambient condition
dai : Drying air inlet
dao : Drying air outlet

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