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Modeling Thermodynamic Drying Bed Fluid

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Abstract

Drying process has various applications in industry. This process which is a thermal energy operation has various applications in drying food, wood, edible grains and various chemical and cellulosic materials. Consuming high amount of energy during in drying industry has turned this process to one of the high-energy-consuming operations, while it has a high industrial significance. In recent decades, thermodynamic analysis, especially exergy analysis, has turned to one of required tools in designing, analyzing and optimizing thermal systems. The following research tries to present drying process thermodynamic modeling, and especially fluid bed drying and simultaneous equations in mass and heat transfer. Also, it is tried to derive exergy returns in the form of a heat and mass transfer parameters function and its changes are studied based on inlet air heat, air specific exergy, exergy difference between input materials and output products, product weight, air humidity contents, and inlet/outlet air humidity ratio. This model could be advantageous in optimizing drying operation and determining proper application of each system, and optimized system shape and order.

Keywords: drying, thermodynamic simulation, exergy, heat and mass transfer

1.Introduction

Drying process is widely used in various thermal applications from drying food to wood and cellulosic materials. Consuming high amounts of energy in drying industry has turned this industry to one of the high-energy-consuming operations, while it has a high industrial significance. The objective of a drying machine is to deliver heat to the product, higher than what is delivered to the product under environment conditions, so that the humidity vapor pressure in the product is increased to the adequate rate so the humidity transfer from within the product is increased while drastically decrease relative humidity of the drying machine so that humidity portability is increased to finally reach a balance with product low humidity content. [1-4].

2.Modeling Thermodynamic Drying Bed Fluid

2.1.Mass Balance in Dryer Column

Dryer column volume control system is presented in Figure 1 and the following mass balance equation could be written for one input and output [9]:

To compare and analyze air heat entering dryer column, air fluidity speed and materials initial humidity content impacts on fluid bed dryer system energy and exergy returns, a thermodynamic model of this process is presented. The following fluid bed dryer system is divided into three main systems: blower, heater and dryer column. In this part, exergy balance part was maintained by using mass, energy and entropy balance in dryer column through discontinuous process presented in Figure 1. Drying process in a discontinuous fluid bed is modeled supposing complete particles interaction. During mass and energy transfer between gas and solid, the process is isobar. As it could be observed in Figure 1, control volume is marked by dotted line and particles thermodynamic state is defined by enthalpy h_m, entropy S_m and humidity content M_P [5-8].

$$\frac{dm_{cv}}{dt} = \dot{m}_{g1} - \dot{m}_{g2}$$

Equation (1)

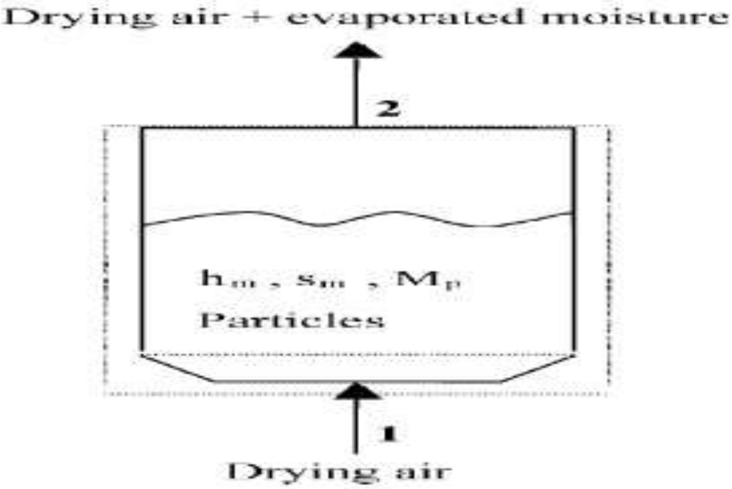

Figure 1. Scheme Thermodynamic Dryer Bed Fluid

The above equation is the volume control in which $\dot{m}_{g1}$ and $\dot{m}_{g2}$ present the input mass in point (1) and output in point (2), respectively. Accordingly, water balance in flowing air in the dryer column leads to:

$$W_d \frac{dM_p}{dt} = \dot{m}_a (X_1 - X_2)$$

Equation (2)

In which W_d is the dry solid mass, M_P is the object humidity content (which is uniform in all bed), $\dot{m}_a$ is the dry air mass flow intensity and X_1 and X_2 are the absolute humidity of input and output air, respectively. Left hand of mass balance equation (Equation 2) is the water mass flow intensity, $\dot{m}_w$ in output air. Equation (3) could be rewritten as:

$$\dot{m}_w = \dot{m}_a (X_2 - X_1)$$

Equation (3)

2.2. Energy Balance in Dryer Column

In drying process, the first law of thermodynamics (law of energy conservation) applied in the control volume presented in Figure 1 is used. The main heat transfer is related to the heat of vaporization and its transfer between solid and dryer air. Also, there is heat loss to the environment. Energy intensity balance is derived by neglecting kinetic and potential energy. Since dry air mass flow and dry material mass in the bed are constant, the energy flow intensity balance could be written as [10-14]:

$$\frac{W_d (h_{m2} - h_{m1})}{\Delta t} = \dot{Q}_{evap} + \dot{m}_a (h_1 - h_2) - \dot{Q}_{loss}$$

Equation (4)

The specific enthalpies differences are equal to:

$$h_{m1} - h_0 = c_m (T_{m1} - T_0)$$

Equation (5)

$$h_{m2} - h_0 = c_m (T_{m2} - T_0)$$

Equation (6)

Energy balance equation for materials could be written as:

$$h_{m2} - h_{m1} = c_m (T_{m2} - T_{m1})$$

Equation (7)

Humid air enthalpy could be written by adding the share of each component in the mixture. Hence, humid air enthalpy is equal to [10]:

$$h = h_a + X h_v$$

Equation (8)

2.3. Entropy Balance in Dryer Column

Mass and energy are quantities which subjected to conservation law. It is however not the case for entropy. Entropy intensity balance in control volume of Figure 1 is explained as below [15]:

$$\frac{W_d (s_{m2} - s_{m1})}{\Delta t} = \frac{Q_{evap}}{T_m} + \dot{m}_a (s_1 - s_2) - \frac{\dot{Q}_{loss}}{T_b} + \dot{S}_{gen}$$

Equation (9)

The materials specific entropies are derived from the following relations:

$$s_{m1} - s_0 = c_m \ln(T_{m1} / T_0)$$

Equation (10)

$$s_{m2} - s_0 = c_m \ln(T_{m2} / T_0)$$

Equation (11)

Materials entropy balance equation could be explained as the following [12]:

$$s_{m2} - s_{m1} = c_m \ln(T_{m2} / T_{m1})$$

Equation (12)

To find humid air entropy value, the share of each component in the mixture should be measured in its own temperature and pressure:

$$s_{wa} = s_a - R_a \ln \frac{p_a}{p_0} + X \Big(s_v - R_v$$

Equation (13)

2.4.Exergy Balance in Dryer Column

Dryer column exergy balance equation is derived by combining energy and entropy balance equations. By multiplying entropy balance equation in T_0 and subtracting it from energy balance equation, there are [16-25]:

$$\frac{W_d (E_{m2} - E_{m1})}{\Delta t} = \dot{m}_a (h_1 - h_2) + \Big(1 -$$

$$- \left(1 - \frac{T_0}{T_b} \right) \dot{Q}_{loss} - T_0 \dot{m}_a (s_1 - s$$

Equation (14)

Or in a simpler form:

$$\dot{E}_{m2} - \dot{E}_{m1} = \dot{E}_{da1} - \dot{E}_{da2} + \dot{E}_{evap} - \dot{E}$$

Equation (15)

In which $\dot{E}_m$ denotes materials exergy transfer rate, $\dot{E}_{evap}$ is the vaporization exergy in dryer, $\dot{E}_{loss}$ is the exergy loss to the environment and $\dot{E}_D$ is the exergy disappearance rate in dryer column. Materials input and output specific exergies are as following:

$$e_{m1} = (h_{m1} - h_0) - T_0 (s_{m1} - s_0)$$

Equation (16)

$$e_{m2} = (h_{m2} - h_0) - T_0 (s_{m2} - s_0)$$

Equation (17)

Dryer air flow specific exergies which enter the fluid bed and exit from it are as following:

$$e_{da1} = (h_1 - h_0) - T_0 (s_1 - s_0)$$

Equation (18)

$$e_{da2} = (h_2 - h_0) - T_0 (s_2 - s_0)$$

Equation (19)

In which e_{da1} and e_{da2} are specific exergy amount which are transferred in input and output. h_0 and s_0 are respectively specific enthalpy and specific entropy at reference sate temperature (T0), h1 and s1 are respectively specific enthalpy and specific entropy at dryer air temperature which enter fluid bed column (Tda1) and h2 and s2 are respectively specific enthalpy and specific entropy of dryer air at the temperature of the air which exits the column. Kinetic and potential exergy are negligible [26-30].

Heat transfer rate related to the phase change is as following:

$$\dot{Q}_{evap} = \dot{m}_w h_{fg}$$

Equation (20)

In which h_{fg} is water latent heat of vaporization based on $kj.kg^{-2}$ at humid material mean temperature at atmospheric pressure, while exergy transfer rate related to vaporization in dryer is as following:

$$\dot{E}_{evap} = \left(1 - \frac{T_0}{T_m}\right)\dot{m}_w h_{fg}$$

Equation (21)

2.5.Dryer Thermodynamic Returns

Fluid bed dryers usage potential is highly related to optimized use of energy. There are two methods to determine fluid bed dryer thermodynamic returns. First method is to calculate energy returns based on the first law of thermodynamics and the second method is the exergy returns based on the second law of thermodynamics. Dryer column energy returns which is calculated based on the first law of thermodynamics could be calculated by energy balance equation like what Calvelo and Giner [30-41] carried out. Heat retunes (which is also called energy returns), is defined in drying process as the following:

η_{th} = (Energy transmitted to solid)/(E

Hence, energy returns from energy balance equations are as following:

$$\eta_e = \frac{W_d[h_{fg}(M_{p1} - M_{p2}) + c_m(T_m}{\dot{m}_{da}(h_1 - h_0)\Delta t}$$

Equation (22)

Dryer column exergy returns is derived based on the second law of thermodynamics using exergy rate balance equations. Exergy returns is a proper criterion on dryer system performance which is derived from a thermodynamic viewpoint. “Product” and “fuel” definitions must be determined in exergy returns definition. Here, product is the vaporization exergy rate and fuel is the air exergy rate entering the dryer. Hence, dryer exergy returns is in the form a ratio between product and fuel, as Topic has expressed [10]. If product is just vaporization process exergy rate and fuel is the input air exergy rate, exergy returns based in its balance is as the following:

$$\eta_E = \frac{\dot{E}_{evap}}{\dot{E}_{da1}}$$

Equation (23)

$$\eta_{ex} = \frac{(\dot{m}_w)_{ev}[(e_w)_3 - (e_w)_2]}{\dot{m}_a e_1}$$

Equation (24)

Following input parameters are chosen for fluid bed drying process dynamic returns analysis.

The temperature of the air entering dryer column, T_1

Dryer air relative humidity, RH_1

Dryer air speed, u

The temperature of material entering the dryer, Tp

Initial materials humidity content, Mpi

Materials Wight, Wb

Environment temperature, Ta

Following parameters are derived from reference [36] data:

The temperature of the air exiting dryer column, T_2

Dryer output air relative humidity, RH_2

Dryer output air absolute humidity, X_2

The temperature of material after drying process, Tpf

Materials humidity content after drying process, Mpf

Drying duration Δt

And the following thermodynamic data for vapor and dry air from thermodynamic tables:

- Dry air enthalpy h_α and water vapor enthalpy h_v which ether the dryer
- Dry air enthalpy h_0 and h_{v0} enthalpy in environment temperature
- Vaporization enthalpy h_{fg} at material temperature T_m
- Dry air entropy S_α and water vapor entropy S_v which enter the dryer
- Dry air entropy S_0 and S_{v0} entropy at environment temperature

3.Conclusion

Figure 2 presents process exergy returns changes with dryer air mass flow intensity in various solid material weights. Increase in flow decreases exergy returns and higher increase in air mass flow intensity does not affect exergy returns, significantly. This is due to the fact that increase in mass flow intensity leads to increase in exergy of system input which in turn decreases exergy returns, according to equation 24. Moreover, increase in product weight (mass) impacts exergy returns, significantly; that is, by the increase in mass, exergy returns increases, as well. In this case, the exergy used for drying product increases by the increase in product mass and as a result exergy returns increases, as well

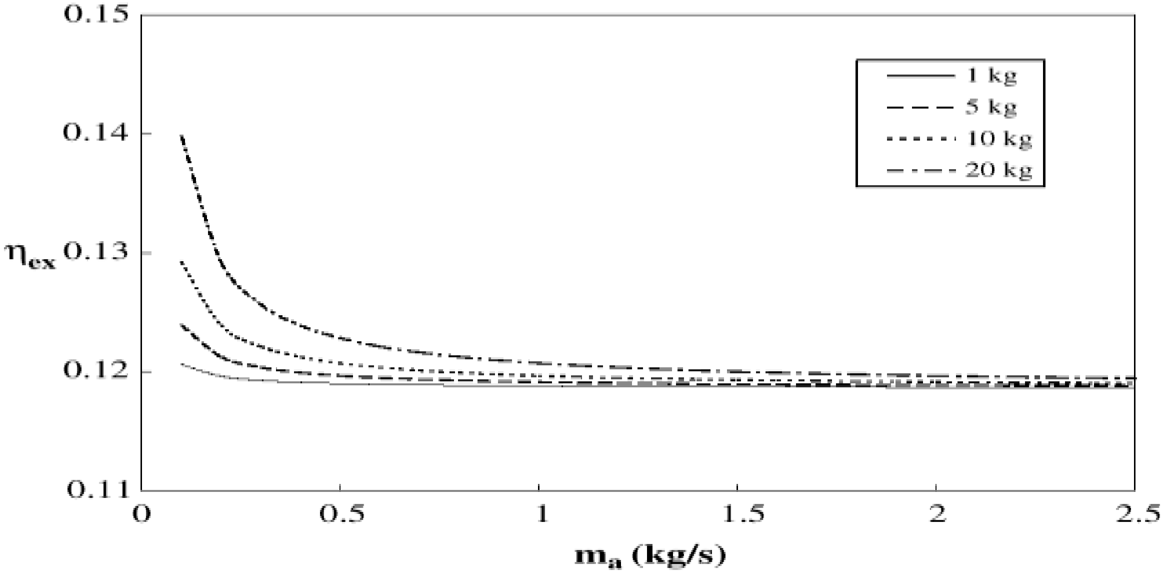

Figure 2. Process Exergy Returns Changes with Dryer Air Mass Flow Intensity in Various Solid Material Weights

Figure 3 presents exergy returns changes with dryer input air temperature and also in various solid material flows. The curves behavior is similar to curves in Figure 2. Increase in dryer air temperature increase exergy returns, since exergy returns is inversely proportional to dryer air exergy intensity. As it was expected, exergy returns changes evenly by the higher increase in dryer temperature. Moreover, exergy returns magnitude increases significantly by the increase in products mass.

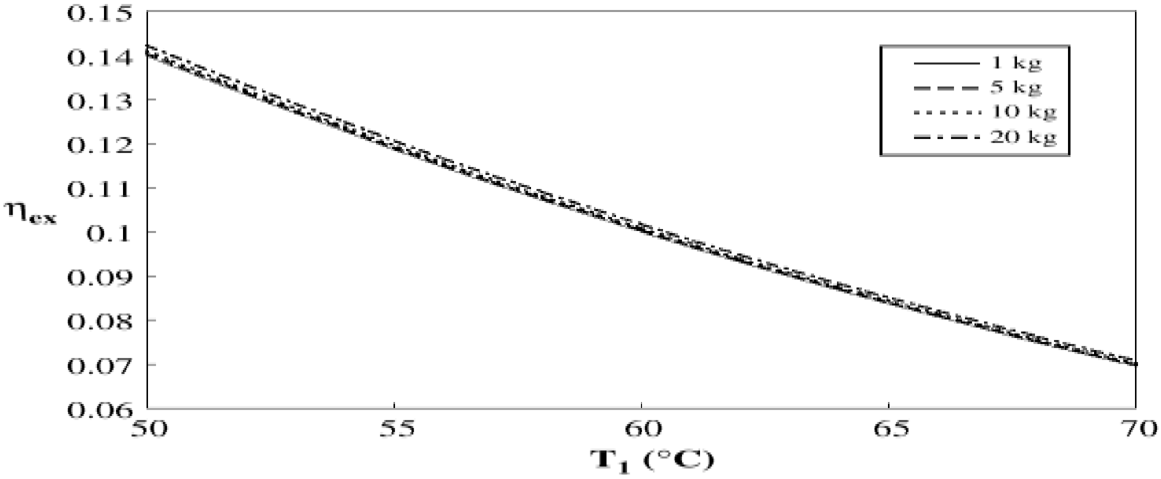

Figure 3. Exergy Returns Changes with Dryer air Temperature in various solid material Weights

Figure 4 presents dryer exergy returns changes comparing to the dryer air specific exergy components which enter the system in product mass changes between 1 and 20 kilograms. As it is expected, by the increase in vaporization specific exergy increase, humidity contents changes in dryer air various mass flow intensities in system. In this regard, increase in specific exergy difference leads to decrease in returns. At a certain value of specific exergy difference, the higher the dryer mass flow is, the lower the exergy returns will be and this is due to the fact that if dryer air flow intensity increases, more energy is consumed and exergy loss increases. Figure 5 presents exergy returns by product mass changes in various dryer air flow intensities. As it could be observed, specific exergy difference between product and output exergy with dryer air exergy in constant product mass is a fixed value. Figure 6 presents exergy retunes with input solid material humidity content and vaporized water mass flow intensity. By the increase in humidity content, it increases. As a result, in fixed conditions, input air energy used in system increases and this in turn leads to increase in system exergy returns.

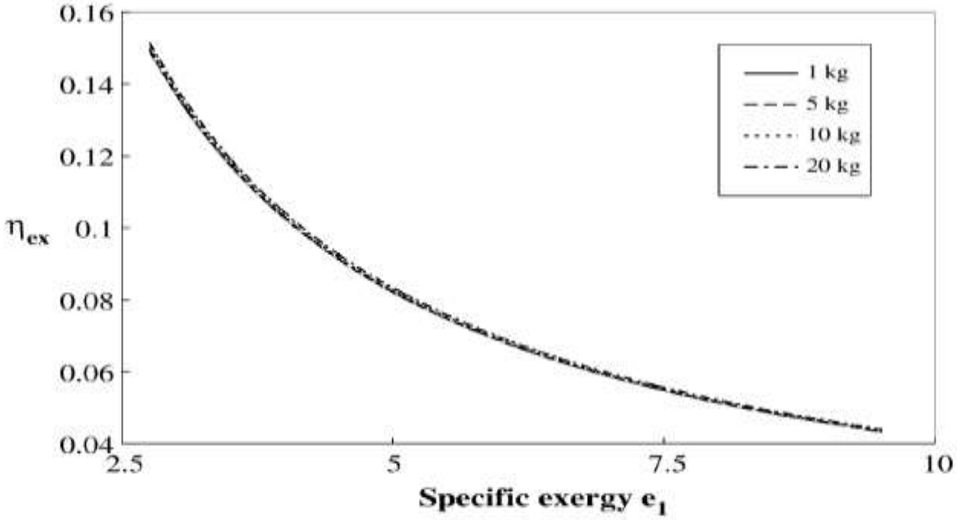

Figure 4. Dryer Exergy Returns Changes Comparing to the Dryer Air Specific Exergy Components which Enter the System in Various Solid Material Weights

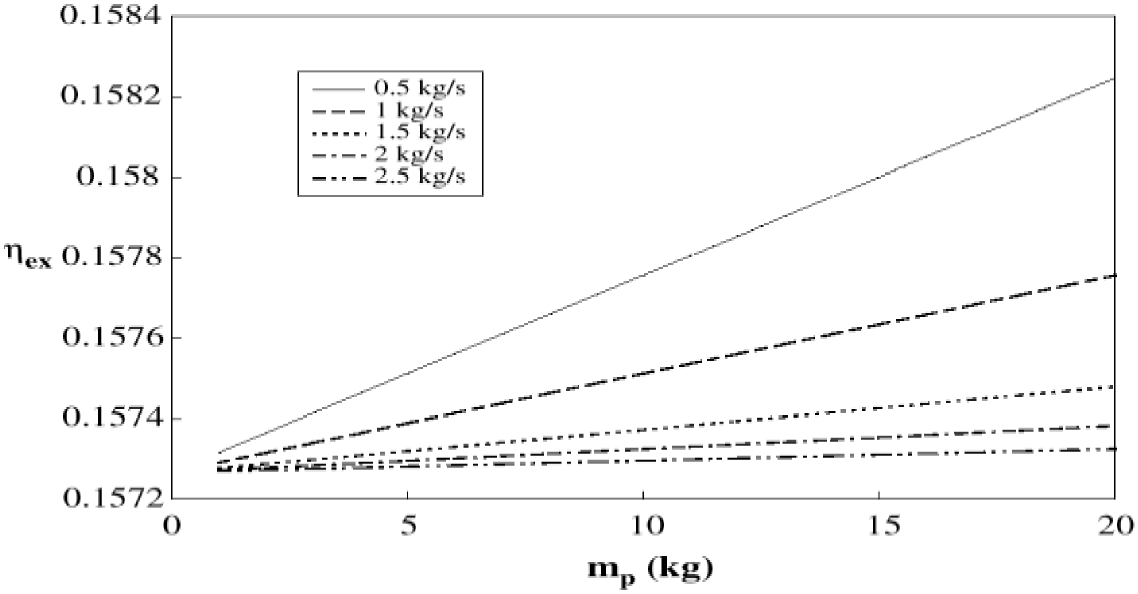

Figure 5. Exergy Returns by Product Mass Changes in Various Dryer Air Flow Intensities

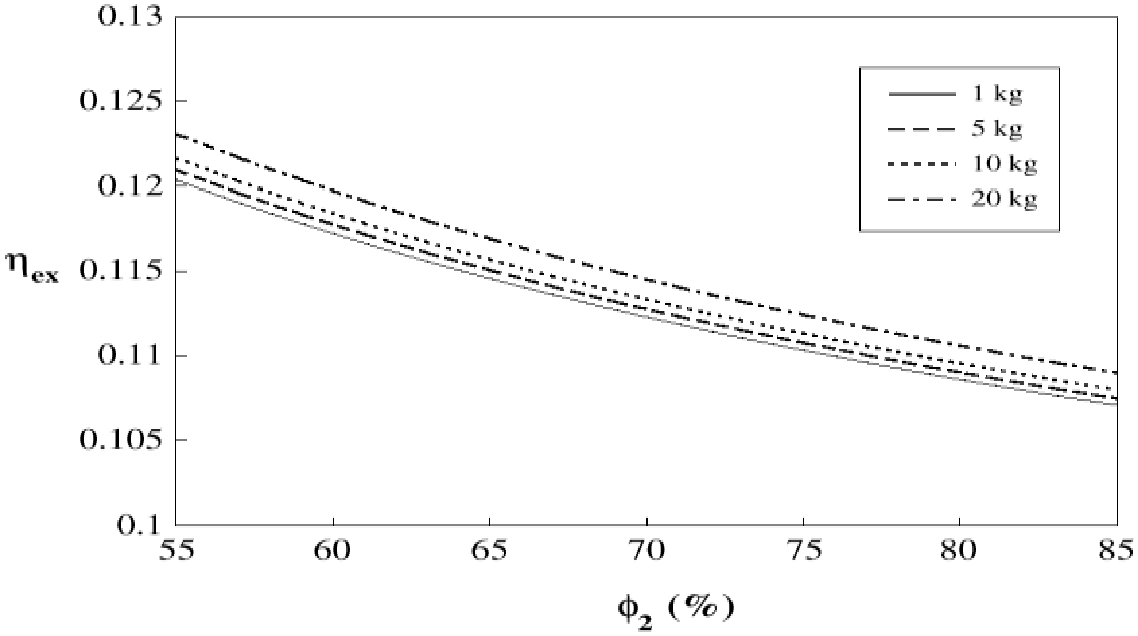

Figure 6. Exergy Retunes with Input Solid Material Humidity Content and Vaporized Water Mass Flow Intensity

Figure 7 presents drying process exergy retunes changes comparing to the dryer air relative humidity which enter the machine in various air mass intensities. As if could be observed in the figure, there is a linear relation between exergy returns and humidity ratio. It should be noted exergy returns changes is quite small by the increase in dyer air humidity ratio (it decreases slightly). Here, not only exergy analysis usage in dryer system thermodynamic assessment was studies, a general view on exergy returns and performance was presented in this study. This work shapes a part of great research on dryer systems thermodynamic studies and especially fluid bed dryers which are of widespread usage in agriculture. Analysis methods and result presented here are advantageous to engineers who (i) try to optimize dryer systems design and its components and (ii) try to determine proper applications of optimized dryer system in general engineering systems. Some exergy analysis advantageous that could exist are:

- It provides more accurate values of lost heat in dryer systems using mass and energy conservation along with the second law of thermodynamics to analyze system design and behavior.
- It provides more useful and meaningful information on energy analysis considering dryer system loss returns and performance.
- It reflects a more accurate economic and thermodynamic value on dryer system performance.
- It reflects a better method and a more accurate thermodynamic method on dryer system performance.

It is a proper method to clarify this task in order to bring into attention to what extent can dryer system with higher performance be designed with reduction of low performance items.

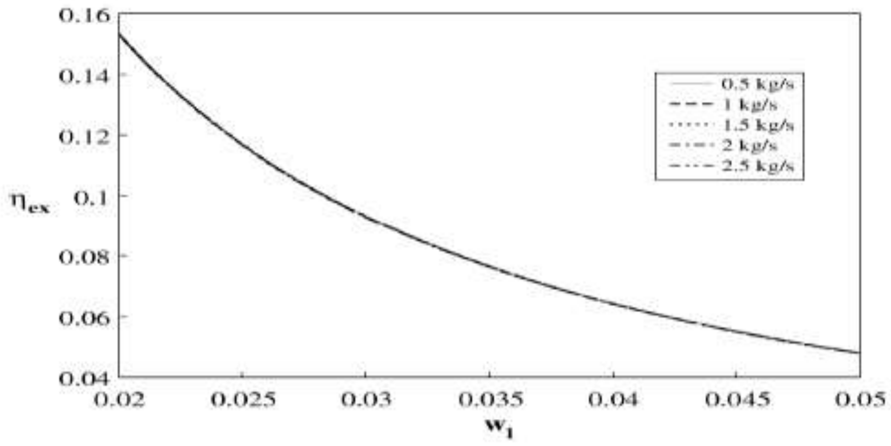

Figure 7. Drying Process Exergy Returns Changes Comparing to the Dryer Air Humidity Ratio

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