# Energetic vs. Exergetic Efficiency of Food Drying Via Forced Convection with and without Electrohydrodynamic Enhancement

**Madeline Mitchell and Erik Bardy**
*Grove City College*

## Abstract

This study investigated differences in efficiency quantified using an exergetic vs energetic model approach for food drying via forced convection with and without ElectroHydroDynamic (EHD) enhancement. An energetic efficiency could vary depending on the process used to condition the primary airflow. In an exergetic model, this is simplified by looking at the state difference between the primary airflow and ambient conditions. This study is a preliminary look into the variability of energetic efficiency values compared to an exergetic model. Two primary airflow conditioning processes were chosen to build an energetic efficiency model - dehumidification by saturated cooling, and by desiccant material. Energetic efficiency values were computed by recasting data from a previous study used to compute exergetic efficiency. Results showed that energetic efficiency values varied greatly for method 1 compared to method 2. It was therefore concluded that an exergy model can normalize efficiency among different air treatment processes.

## Keywords

Food drying, electrohydrodynamic, air conditioning, energetic efficiency, exergetic efficiency

## Introduction

Drying food is a high-energy process that is used globally to reduce the amount of water mass in food to extend shelf life; reduce packaging, storage, handling and transportation costs; and increase out-of-season availability[1]. Developed countries have reported using up to 20% of industrial energy for thermal dehydration operations[2]. Over time, several methods for drying food have been invented in an effort to increase efficiency and product quality[3], including but not limited to: direct sunlight[4-6], heat pump drying[7], and microwave-assisted drying[8]. Even with the many available options, forced convection type dryers are by far the most popular method used, accounting for over 85% of industrial dryers[1, 9]. Forced convection drying uses high airflow velocities to dry food through convection, which results in high energy consumption[10] and low efficiency[11].

One approach to reduce energy consumption in convective drying is through the use of high voltage electrostatics, or ElectroHydroDynamic drying (EHD). EHD drying involves the use of a wire-electrode suspended above the food product to create an electrostatic field. The electrode is supplied with a high voltage creating an electron flow from the electrode to a conductive plate located under the food product. The high resistivity of the air results in a low current. Combining the high voltage and low current results in a low required power input. The electrostatic field induces a secondary airflow above the food product, which increases the convective heat transfer coefficient. This allows for a significant decrease in the primary airflow velocity and energy consumption, as well as an increase in energetic efficiency[3].

To quantify the increase in efficiency of EHD drying as compared to forced convective drying it would be necessary to choose a model that appropriately quantifies the efficiency in terms of food product drying rate, and energy consumption in conditioning the primary airflow. An efficiency quantified using an energy model approach, the first law of thermodynamics, would require knowledge of the type of process used to condition the primary airflow used for dehumidifying the food product. For example, a process such as dehumidification by saturated cooling requires the air to be cooled to its saturation point to remove moisture followed by a reheat process to bring the air up to the desired temperature. Dehumidification by a desiccant, on the other hand, forces air to pass over a desiccant material, such as zeolite or alumina pillared clay, which can remove up to 90% of the moisture. Another dehumidification process processes includes the use of a heat pump, which uses a refrigerant to absorb heat from the air, thus decreasing the relative humidity (RH). This process is most effective for a high desired RH value, and so was not examined in this study[7]. In each of these processes, the energy consumption to dehumidify the primary airflow would be different yielding varying values for the efficiency.

A study by Bardy et al.[3] proposed using an exergetic model, which quantifies efficiency in terms of the state difference between the conditioned primary airflow and a defined "dead state." In that particular study, the drying rate of methylcellulose gel via forced convection with and without EHD drying was studied. A sample of methylcellulose gel was placed in a drying channel where the primary airflow was psychrometrically controlled at a temperature and RH of 30ºC and 17%, respectively. For FC drying the primary airflow velocities varied from 1 – 3 m/s in increments of 0.5 m/s. For EHD drying, a total of three different wire-electrode configurations were used. Configuration 1 was one electrode perpendicular to the primary air flow; configuration 2 was two electrodes parallel to the primary air flow; configuration 3 was one electrode parallel to the primary air flow. Each configuration had an applied voltage of 16 kV with a primary airflow velocity of 0.3 m/s. An exergetic model was used to quantify and compare the differences in efficiency of FC vs EHD drying. The exergetic model approach eliminated the need to define the process used for conditioning the primary airflow.

The purpose of this study was to compare the variability in quantifying efficiency by an energy model compared to an exergy model approach for FC vs EHD drying. Two energetic efficiency models were built using two different methods for conditioning the primary airflow; method 1 was dehumidification by saturated cooling, and method 2 was dehumidification by a desiccant material. Data collected from Bardy et al.[3] was recast using the energetic efficiency models and compared to the originally published exergetic efficiency values[3].

## Energy Modeling

For this study, an expression for the energetic efficiency of a drying process was proposed by modifying the exergetic efficiency model presented by Bardy et al.[3] Equation 1 shows the energetic efficiency ($\eta$) as the ratio of the energy used for evaporating water content in the food sample ($\Delta E_{used}$) to the total energy consumed ($\Delta E_{Total}$). The energy used for evaporating the water content was assumed to be due to the latent heat of vaporization as shown in equation 2, where $h_{fg}$ = latent heat of vaporization of liquid water in the methylcellulose gel, and $dm/dt$ =

methycellulose gel drying rate. The total energy consumed ($\Delta E_{Total}$) was attributed to the energy required to condition the primary airflow ($\Delta E_{air}$). In the case of EHD drying, the power supplied to the wire-electrode was included ($\Delta E_{electrode}$) as shown in equation 3, where V = EDH applied voltage, and dI/dt = EHD current change rate.

$$\eta = \frac{\Delta E_{used}}{\Delta E_{Total}} \tag{1}$$

$$\Delta \mathrm{E}_{\mathrm{used}} = \int \frac{dm}{dt}(t) * \mathrm{h}_{\mathrm{fg}}\, dt \tag{2}$$

$$\Delta \mathrm{E}_{\mathrm{electrode}} = \int V \frac{dI}{dt}\, dt \tag{3}$$

To quantify the energy used for conditioning the primary airflow, a first law analysis was performed for using method 1 and method 2, as the conditioning process. For method 1, the ambient air ($h_1$, assumed at T = 20 ºC, RH = 50%) is cooled until it reaches the saturation temperature ($h_2$). At that point, the air is dehumidified until the desired specific humidity is reached ($h_3$), then the air is reheated to the conditions of the air entering the drying channel ($h_4$, T = 30ºC and RH = 17%). This process is shown on a psychrometric chart in Figure 1. Equation 5 shows the resulting energy used ($\Delta E_{air}$), where $\dot{m}_{air}$ = the primary airflow mass flow rate. For method 2, ambient air ($h_1$, assumed at T = 20 ºC, RH = 50%) flows over a desiccant material, which removes 90% of the water content and causes an increase in temperature ($h_{2(2)}$). The air is then cooled slightly ($h_{3(2)}$) before being mixed with ambient air to reach the desired the state of the primary airflow into the drying channel ($h_4$, T = 30ºC and RH = 17%). This process is shown on a psychrometric chart in Figure 2. Equation 5 shows the resulting energy used ($\Delta E_{air}$) where k = the fraction of air passing through the desiccant material before being mixed with the bypassed ambient air.

$$\Delta \mathrm{E}_{\mathrm{Total}} = \begin{cases} \Delta \mathrm{E}_{\mathrm{air}} + \Delta \mathrm{E}_{\mathrm{electrode}} \rightarrow \text{EHD drying} \\ \Delta \mathrm{E}_{\mathrm{air}} \rightarrow \text{FC drying} \end{cases} \tag{4}$$

$$\Delta \mathrm{E}_{\mathrm{air}} = \int \left[ \begin{cases} \dot{m}_{air} * \{ |\mathrm{h}_{2(1)} - \mathrm{h}_1| + |\mathrm{h}_{3(1)} - \mathrm{h}_{2(1)}| + |\mathrm{h}_4 - \mathrm{h}_{3(1)}| \} \rightarrow \text{Method 1} \\ \dot{m}_{air} * \mathrm{k} * \{ |\mathrm{h}_{2(2)} - \mathrm{h}_1| + |\mathrm{h}_{3(2)} - \mathrm{h}_{2(2)}| \} \rightarrow \text{Method 2} \end{cases} \right] dt \tag{5}$$

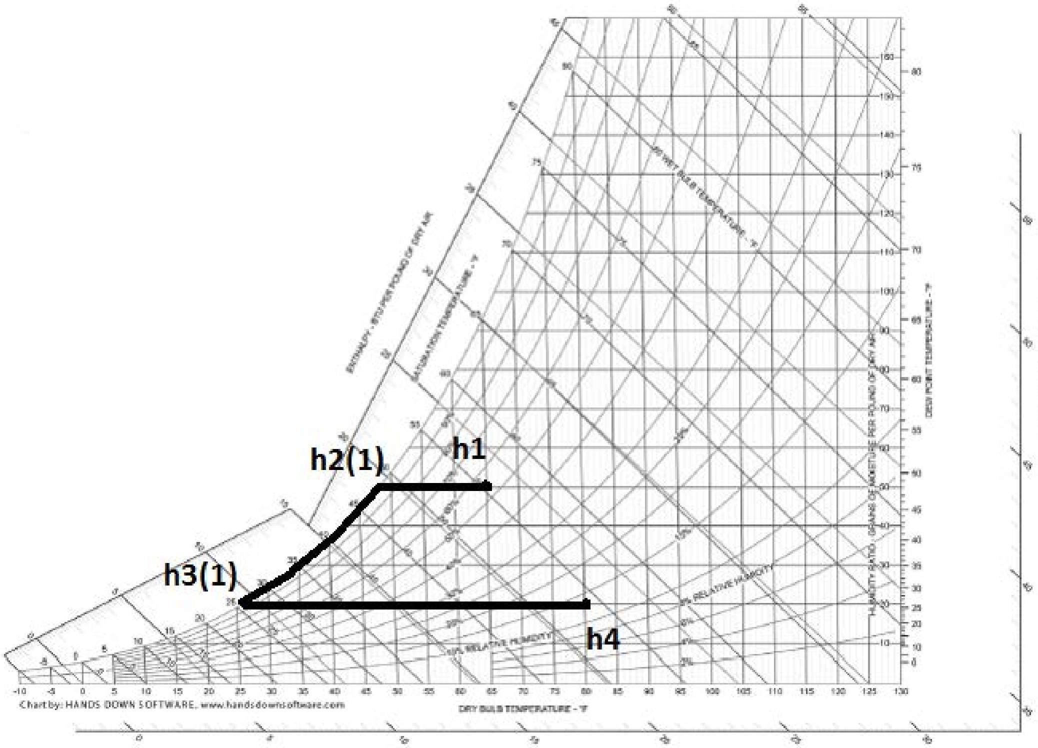


Figure 1: Psychrometric chart plotting the process of method 1

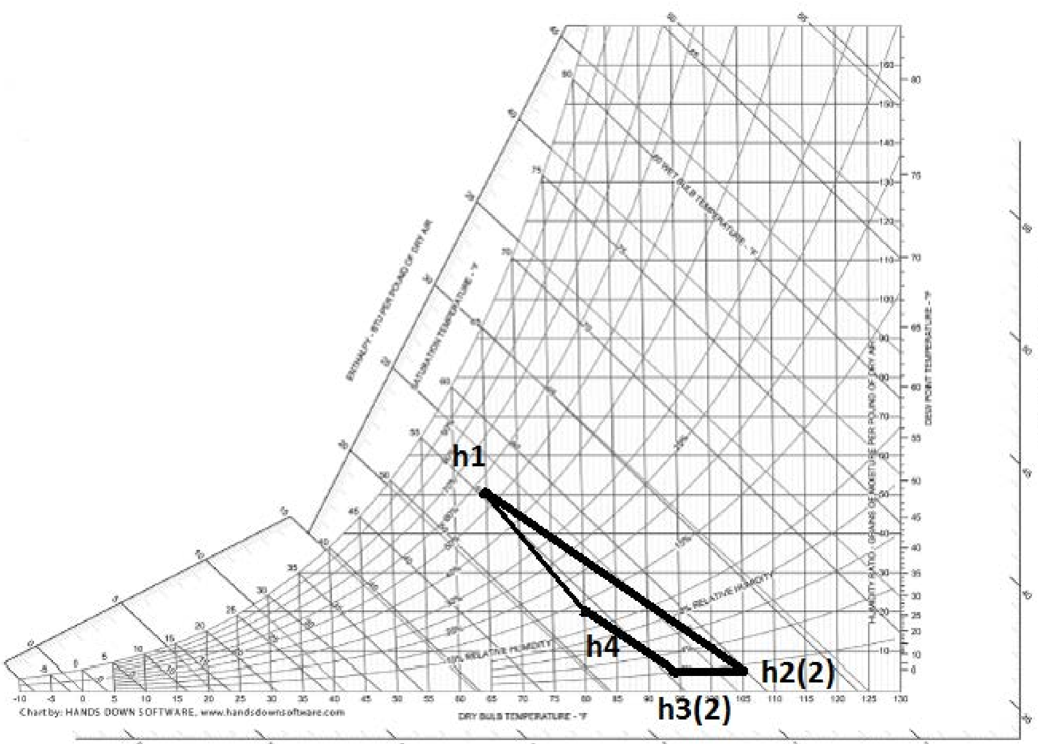


Figure 2: Psychrometric chart plotting the processes of method 2.

## Results and Discussion

Figure 3 shows the energetic efficiency, using methods 1 and 2 for conditioning the primary airflow, compared to the exergetic efficiency determined by Bardy et al.[3] for EHD drying for the three different wire-electrode configurations. As can be seen, the energetic efficiency for method 1 ranged from 8 – 9%, whereas values were less than 1% for method 2. The exergetic efficiency, on the other hand, ranged between 4 – 5%.

Figure 4 shows the energetic vs exergetic[3] efficiencies of FC drying for primary airflow velocities between 1 – 3 m/s. At a primary airflow velocity of 1 m/s, the energetic efficiency associated with method 1 was at a value of 0.26%, whereas it was at 2.37% for method 2. The exergetic efficiency was at 1.43%. As the primary airflow velocity increased, all efficiencies decreased to a minimum value of 0.10% for the energetic efficiency associated with method 1, and 0.97% for method 2. The exergetic efficiency was at 0.60%. The decrease in efficiency as primary airflow velocity increases was anticipated due to increased energy consumption to condition the primary airflow.

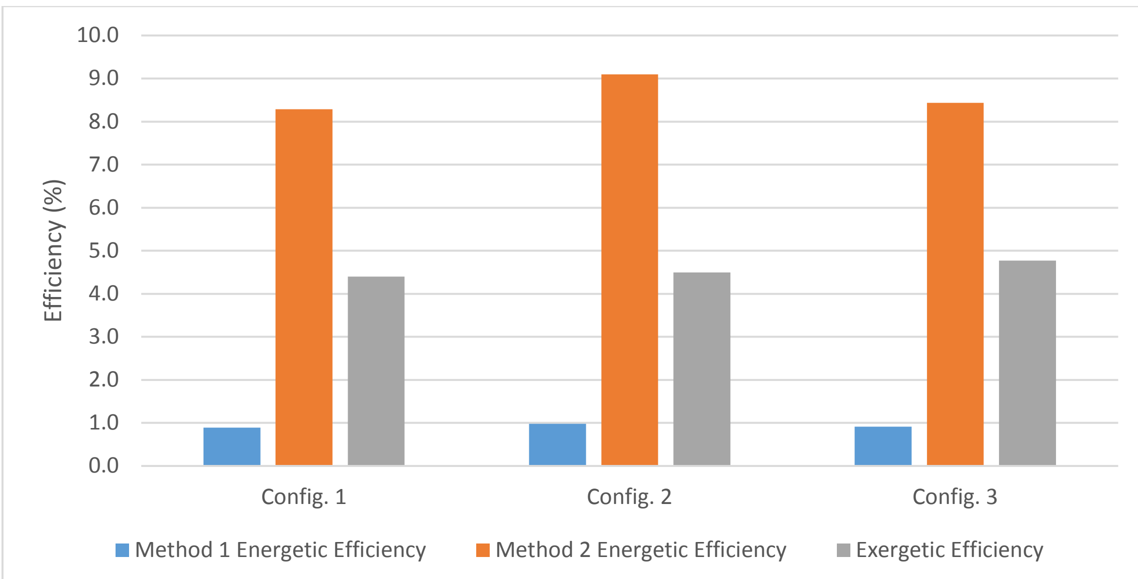


Figure 3: Energetic vs. Exergetic efficiencies for EHD drying.

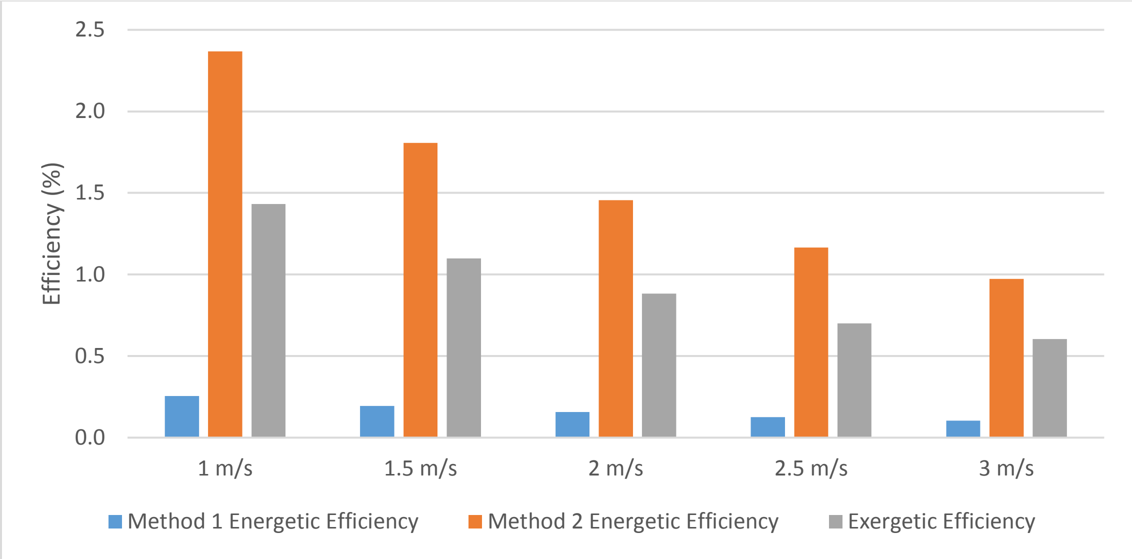


Figure 4: Energetic vs. Exergetic efficiencies for FC drying.

As can be seen in both Figures 3 and 4, the energetic efficiency associated with method 1 and 2 for any particular case varies significantly. For example, the energetic efficiency associated with method 2 was approximately nine times greater than method 2 for all EDH drying configurations. This shows a significant difference in the perceived energetic efficiency in drying when comparing two different air conditioning processes. In addition, the energetic efficiency associated with method 2 would change if the energy required to regenerate the desiccant material was taken into account. An exergetic efficiency does not take into account the process path for the conditioning of the primary airflow velocity. It is therefore initially concluded that an exergetic approach to quantifying drying efficiency is a good way to normalize the effectiveness of a food drying process since it expresses its terms as a function of state difference rather than the path taken during a process. Further study is needed to experimentally determine the energy consumption of various air treatment methods to further strengthen this conclusion.

## Conclusion

This study focused on comparing the energetic vs. exergetic efficiency of a food drying process. Data from Bardy et al.[3] on the exergetic efficiency of the drying of methylcellulose gel was recast in the form of an exergetic efficiency for two different primary airflow treatment methods. It was found that the energetic efficiency varied significantly when comparing values quantified using method 1 compared to method 2. It was therefore initially concluded that an exergetic approach to quantifying drying efficiency is an effective was to normalize values among different primary airflow treatment processes since it is a function of the thermodynamic state different rather than the path taken from the process. This conclusion should be further strengthen by experimental measurement for several different air treatment processes.

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## Madeline Mitchell

Ms. Madeline Mitchell is a senior in the Department of Mechanical Engineering at Grove City College on track to graduate in May 2017. Ms. Mitchell has been involved in research under the direction of Dr. Erik Bardy since Fall 2016.

## Erik Bardy

Dr. Erik Bardy is a Professor in the Department of Mechanical Engineering at Grove City College and Assistant Director of the Grove City College European Study Center in Nantes, France. Dr. Bardy completed a Ph.D. in Mechanical Engineering from the State University at Buffalo in 2006, along with a M.S.M.E (with filiation to EUDIL in Lille, France) and B.S.M.E. from the same University.