OPERATIONAL CHARACTERIZATION OF A SPRAY DRYER FOR DRYING WATER, CAUSTIC SODA AND SODIUM CHLORIDE SOLUTIONS

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ABSTRACT

The spray drying of distilled water, 50% w/w NaOH, 10% w/w NaOH, and 25% w/w NaCl solution was investigated. Operating conditions, dryer design and inherent properties of the liquids affected performance operational trends and degrees of dryness. The various phenomena observed indicated the difficulty in predicting the performance or suitability of any dryer for the purpose of drying a liquid without an investigative task. The maximum values of exit mass flow rate of dried liquid, dryer temperature, heat transfer coefficient, specific energy supplied and moisture content removed were 0.015 kgs^{-1} for 25% w/w NaCl solution, 402.6 K, 4.85 $Wm^{-2}K^{-1}$, 1, 941, 937.04 Jkg^{-1} and 0.217 for distilled water, respectively. The exit mass flow rates increases with specific energy supplied for all the liquids, except for 50% w/w NaOH solution which decreases with specific energy supplied. The possibility of exploring, competing or improving quantitatively and qualitatively on the conventional mode of drying some of these liquids industrially seems promising, with the aim of overcoming their inherent and present challenges.

Keywords: spray dryer, caustic soda, sodium chloride, evaporation, energy.

INTRODUCTION

Spray drying involves the atomization of a liquid feedstock into a spray of droplets and contacting the droplets with hot air in a drying chamber. Flexibility and speed makes spray drying the process of choice for many industrial drying operations. Evaporation of moisture from the droplets and formation of dry particles is possible under controlled temperature and airflow conditions. Operating conditions and dryer design are selected according to the drying characteristics of the product as well as desired specification. Spray drying is an ideal process where the end-product must comply with precise quality standards regarding particle size distribution, residual moisture content, bulk density, and particle shape.

Spray drying can be advantageous for profit maximization and process simplification. Atomization for any drying operation is dependent on the characteristics of the feed and the drying characteristics of the drying chamber (Coulson *et al.*, 2002). Spray dryers advantages include the ability to be designed to virtually any capacity required. Feed rates ranges from a few pounds per hour to over 100 tons per hour, operation is continuous and adaptable to full automatic control, dryer designs can be made to meet various product specifications, can be used with both heat-resistant and heat sensitive products. In addition the feedstock can be abrasive, corrosive, flammable, explosive and toxic. Feedstock can be in solution, slurry, paste, gel, suspension or melt form. Product density and shape can be controlled, material does not contact metal surfaces until dried, thereby reducing corrosion problems. Drying and particle formation is achievable in one process, wide range of particle size and distribution can be obtained, while reduced running cost is possible.

Spray drying is useful for most industrial applications like in the emulsion polymerization of polyvinyl chloride (PVC), suspension polymerization of PVC, drying of ceramics, production of detergents, soaps and other surface active agents, production of pesticides, herbicides, fungicides and insecticides, drying of dyestuffs and pigments, production of fertilizers, production of organic and inorganic chemicals, as well as food and pharmaceutical industries to mention a few. Despite this vast application, further investigation on spray drying applications in finding a successful substitute to other existing industrial drying operations is imperative. This might be beneficial in reducing corrosion and energy consumption, flexible and good product control in addition to achieve easily controlled process operations at a reduced cost.

Previous researchers that have investigated spray dryer operations include Katta and Gauvin (1976) and Palencia *et al*., (2002) that studied and utilized the rate based models for spray dryer modeling and simulations. Fletcher and Langrish (2003) have worked on numerical optimization of spray dryers and Crowe *et al*., (1980) have used the particle in source model to investigate spray dryer performances. Shabde and Hoo (2006) have presented models to predict temperature and concentration profiles of hollow micro-particles during spray drying. Tolmac *et al*., (2011) have modeled and experimentally studied flat air velocity profile and high swirl air-flow pattern to dry 55% solution of starch and water with spray drying. Kajiyama and Park (2010) have also investigated the influence of air parameters on spray drying energy consumption. Spray dryer parameters for fruit juice drying had been studied by Chegini and Ghobadian (2007). Performance evaluation of a laboratory scale spray dryer under different inlet air temperatures and atomization speeds for drying some milk-juice blends and whole milk have also been reported (Bahnasawy *et al*., 2010). Reactive absorption of CO_2 with NaOH as absorbent had been evaluated experimentally in a laboratory scale spray dryer (Kavoshi *et al*., 2011). Optimization, scale-up, and design for a commercial-scale spray-drying process in the pharmaceutical industry had also been reported (Dobry *et al*., 2009).

This work focused on the study of the performance of a fabricated spray dryer for drying distilled water, 50% w/w NaOH, 10% w/w NaOH, and 25% w/w NaCl solution as well as the characteristics observed with the various liquids in the drying operations.

MATERIALS AND METHODS

Schematic operational diagram of the spray dryer is shown in Figure-1. The spray dryer is a vertically placed 0.85m height cotton wool lagged stainless steel cylindrical (0.12m diameter) vessel. Inlet air at 299 K was sent into the dryer through a blower and a 3 kW electric heater in order to increase the temperature of the air for the drying process. A thermocouple with two probes was used to measure the temperature of the inlet air and the outlet air at the two ends of the spray dryer. The pressure inside the dryer was 101, 325 Nm^{-2}, while the inlet air mass flow rate was 0.048 kgs^{-1}. The spray dryer contacts tiny droplets of the solutions from the dryer atomizer with hot air in a countercurrent manner. The tiny droplets enabled a higher surface area of the solution to be contacted and evaporated, thereby enhancing the drying operation.

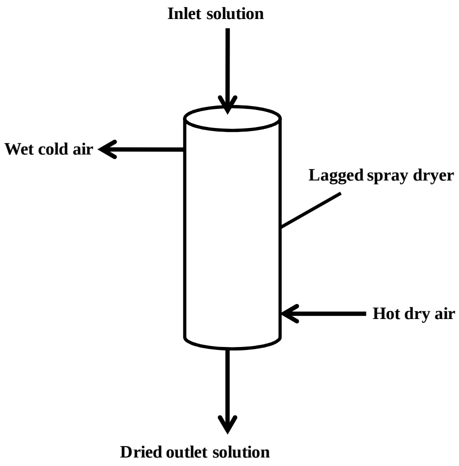


Figure-1. Schematic operational diagram of stainless steel spray dryer.

The first step in the procedure was to switch on the blower and heater. The inlet and exit air temperature was then allowed to reach steady state before the commencement of all drying operations. Constant heat supply rate was used throughout the experiment for all runs, so as to explicitly determine how the inherent physical and chemical properties of the various liquids will respond and reflect qualitatively and quantitatively to the drying operation.

The liquids dried in this experiment include distilled water, 50% w/w caustic soda, 10% w/w caustic soda and 25% w/w sodium chloride solution. The exit mass flow rate of the dried solution, exit air temperature, inlet air temperature and the temperature of surrounding air were recorded for all runs with various inlet mass flow rates of the liquids dried.

Some measured parameters were evaluated using the following expressions:

Some heat quantities are given as:

$$Q_{IA} = \dot{m}_{IA} C_{pIA} T_{IA} \quad (1)$$

$$Q_{SI} = \dot{m}_C C_{pC} T_{IA} \quad (2)$$

$$Q_{OA} = \dot{m}_{OA} C_{POA} T_{OA} \quad (3)$$

The mean dryer temperature is given as:

$$T_{MA} = \frac{T_{OA} + T_{IA}}{2} \quad (4)$$

Surface area of dryer wall is given as:

$$A_W = \pi D_{IO} l \quad (5)$$

The temperature of the inner diameter of the insulation material during operation is given as:

$$T_{IO} = T_{MA} - \frac{(Q_{IA} + Q_{SI} - Q_{OA}) k A_W}{\Delta x} \quad (6)$$

The percent moisture content removed is given as:

$$x = \frac{(\dot{m}_C - \dot{m}_{CF})}{\dot{m}_C} \times 100\% \quad (7)$$

The specific energy supplied is given as:

$$Q_{SP} = \frac{(Q_{IA} + Q_{SI} - Q_{OA})}{\dot{m}_C} \quad (8)$$

The heat transfer coefficient of air is given by McCabe *et al*., (2001) as:

$$h_A = \left[k_{AR} b (Gr.\mathrm{Pr})^n \right] / l \quad (9)$$

The Grashof number (Gr) of the surrounding air is given as:

$$Gr = \frac{l^3 \rho_{AR}^2 g \beta_{AR} (T_{IO} - T_{SR})}{\mu_{AR}^2} = \frac{l^3 \rho_{AR}^2 g \left(\frac{1/\rho_2 - 1/\rho_1}{(T_{IO} - T_{SR}) \left(1/\rho_1 + 1/\rho_2 \right) / 2} \right) (T_{IO} - T_{SR})}{\mu_{AR}^2} \quad (10)$$

The Prandtl number is also given as:

$$\mathrm{Pr} = \frac{C_{PA} \mu_{AR}}{k_{AR}} \quad (11)$$

Air properties κ_{AR}, μ_{AR}, C_{PA} and ρ_{AR} were evaluated at the mean film temperature, T_{fm}, given as:

$$T_{fm} = \frac{T_{IO} + T_{SR}}{2} \tag{12}$$

The constants b and n in Equation (9) are estimated as follows:

$b = 0.59$ if $10^4 < (Gr \bullet \Pr) < 10^9$, $b = 0.13$ if $10^9 < (Gr \bullet \Pr) < 10^{12}$

$n = 0.25$ if $10^4 < (Gr \bullet \Pr) < 10^9$, $n = 0.333$ if $10^9 < (Gr \bullet \Pr) < 10^{12}$

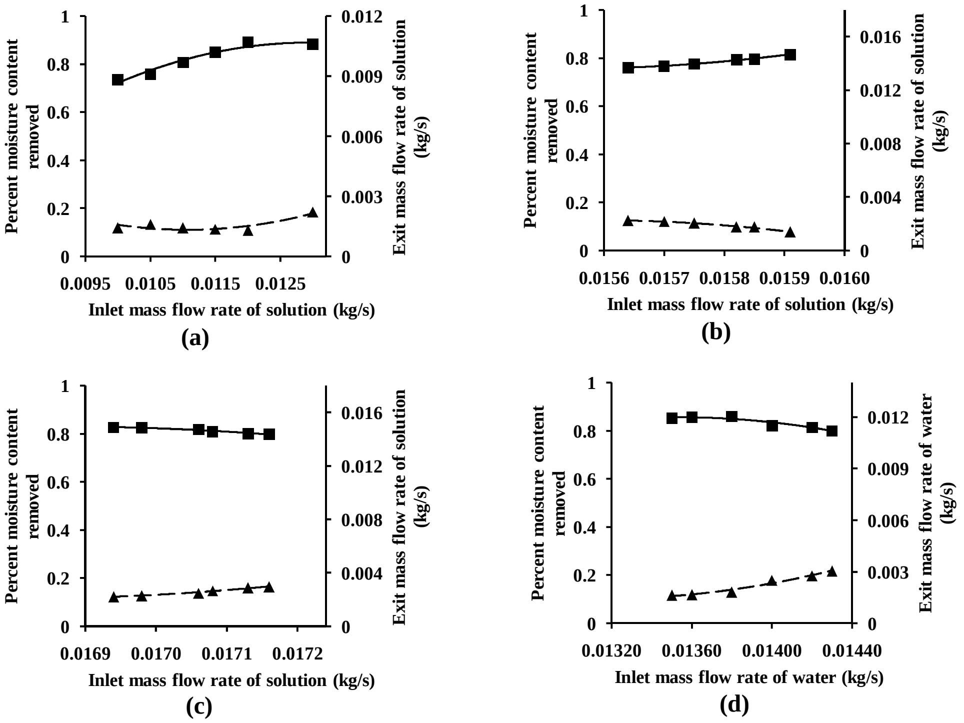
RESULTS AND DISCUSSIONS

All experimental results are presented graphically with markers and a line of best fit to represent the various plotted data.

i. Variation of percent moisture content removed and exit mass flow rate of the various liquids with their inlet mass flow rates

As presented in Figure-2, the triangular markers and dotted lines represents the experimental data of the percent moisture content removed as they vary with the inlet mass flow rates of their different liquids, respectively. The square markers and continuous lines represents the experimental data of the exit mass flow rate of the liquids as they vary with their inlet mass flow rates, respectively. The plots exhibited various degrees of dryness and performance operational trends, which is a reflection of the operating conditions, dryer design characteristics and inherent properties of the various liquids. The plots indicated the possibilities of increasing the percent moisture content removed further, maintaining a higher exit mass flow rates with corresponding higher inlet mass flow rates, considering the fact that the slopes were moderate.

The moisture content removed from the highest to the lowest values were 21.70%, 18.46%, 16.30% and 12.49% for inlet mass flow rates of 0.0143 kgs^{-1} distilled water, 0.013 kgs^{-1} 50% w/w NaOH, 0, 0172 kgs^{-1} 25% w/w NaCl and 0.0156 kgs^{-1} 10% w/w NaOH solution, respectively. It was observed that the moisture content removed seems to increase with inlet mass flow rate for the liquids, except for 10% w/w NaOH, as shown in Figure-2. The exit mass flow rates increases with inlet mass flow rates for 50% and 10% w/w NaOH solution, while it decreases with inlet mass flow rates for 25% w/w NaCl solution and distilled water. Typical inlet mass flow rates used by Tolmac et *al.*, (2011) ranged from 0.027 to 0.044 kgs^{-1}, while those used in this work was between 0.01 and 0.172 kgs^{-1}.



(a) (b) (c) (d)

Figure-2. Variation of percent moisture content removed and exit mass flow rate of the various liquids with their inlet mass flow rates. (a) 50% w/w NaOH solution. (b) 10% w/w NaOH solution. (c) 25% w/w NaCl solution. (d) Distilled water.

ii. Variation of percent moisture content removed and exit mass flow rate of the various liquids with specific energy supplied

In Figure-3, the triangular markers and dotted lines represent the experimental data of the percent moisture content removed as they vary with the specific energy supplied, respectively. The square markers and continuous lines represent the experimental data of the exit mass flow rate of the liquids as they vary with the specific energy supplied, respectively. The utilization of the specific energy supplied resulted in the trends obtained, in addition to other operating parameters, dryer design characteristics and inherent properties of the various liquids. The drying operation indicated that the highest specific energy required by the various liquids were 1, 941, 937.04 Jkg^{-1} for distilled water, followed by 1, 079, 689 Jkg^{-1} for 50% w/w NaOH solution, 813, 745.87 Jkg^{-1} for 25% w/w NaCl solution and lastly 410, 596.75 Jkg^{-1} for 10% w/w NaOH solution.

The observed highest exit mass flow rate of dried liquids with respect to their corresponding specific energy supplied were 0.01488 kg/s with a specific energy of 813, 745.87 Jkg^{-1} for 25% w/w NaCl solution, 0.01468 kgs^{-1} with a specific energy of 410, 596.75 Jkg^{-1} for 10% w/w NaOH solution, 0.01203 kgs^{-1} with a specific energy of 1, 829, 906.52 Jkg^{-1} for distilled water and 0.0107 kgs^{-1} with a specific energy of 937, 862.5 Jkg^{-1} for 50% w/w NaOH solution. This implies that the highest exit mass flow rates of the liquids were not all produced by their highest specific energy supplied. From Figure-3, the moisture content removed seems to decrease with specific energy supplied. The exit mass flow rate of the dried liquids however seems to increase with specific energy supplied for all the liquids, except for 50% w/w NaOH solution which showed a non-linear decrease with specific energy supplied.

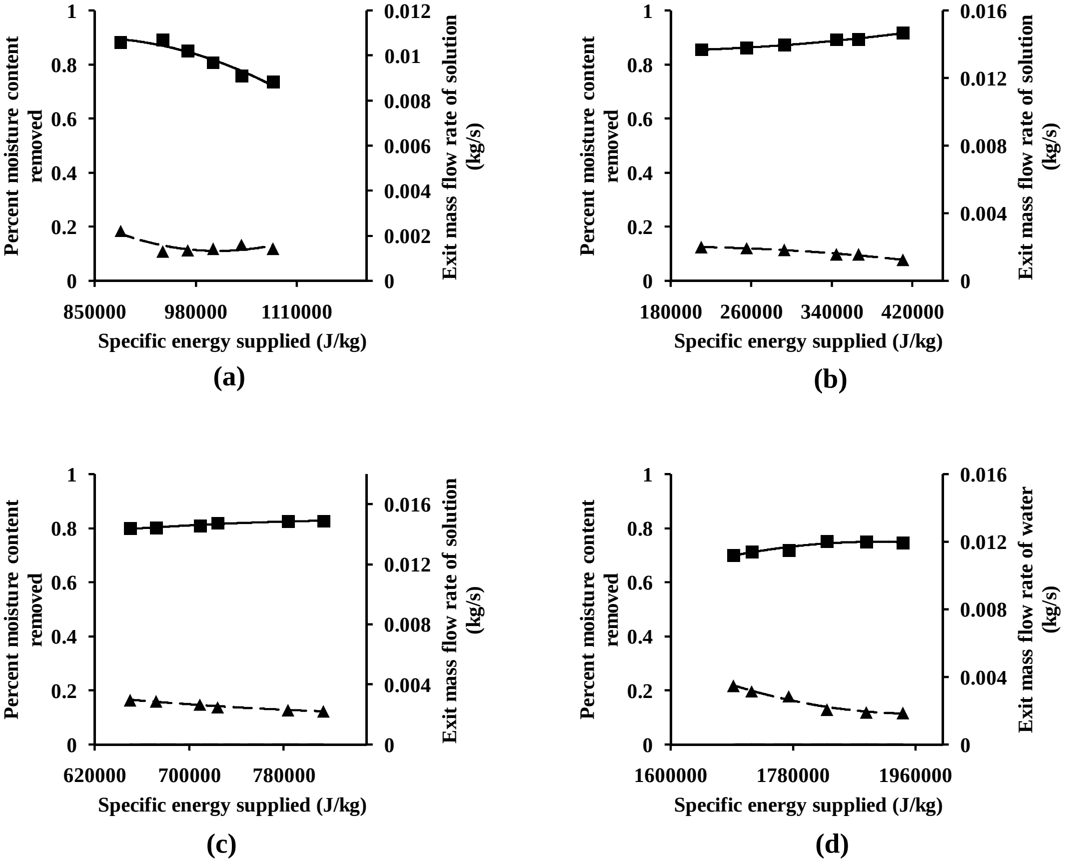


Figure-3. Variation of percent moisture content removed and exit mass flow rate of the various liquids with specific energy supplied. (a) 50% w/w NaOH solution. (b) 10% w/w NaOH solution. (c) 25% w/w NaCl solution. (d) Distilled water.

iii. Variation of exit mass flow rates for the various liquids with mean dryer temperature

In Figure-4, the markers and lines represent the experimental data of the exit mass flow rate of the liquids as they vary with the mean dryer temperature, respectively. The exit mass flow rate of the liquids seems to increase with mean dryer temperature for 10% w/w NaOH solution and distilled water, whereas the case is reversed for 50% w/w NaOH and 25% w/w NaCl solutions. This is a reflection of the operating conditions, dryer design and inherent properties of the various liquids. The drying operation indicated that water was dried with the highest temperature, followed by 10% w/w NaOH, then 25% w/w NaCl and lastly 50% w/w NaOH solution. The mean dryer temperature ranged from 330 to 402.6 K, which closely resembled those used by Tolmac et *al.*, (2011) from 353 - 403 K, for the drying of water and starch solution.

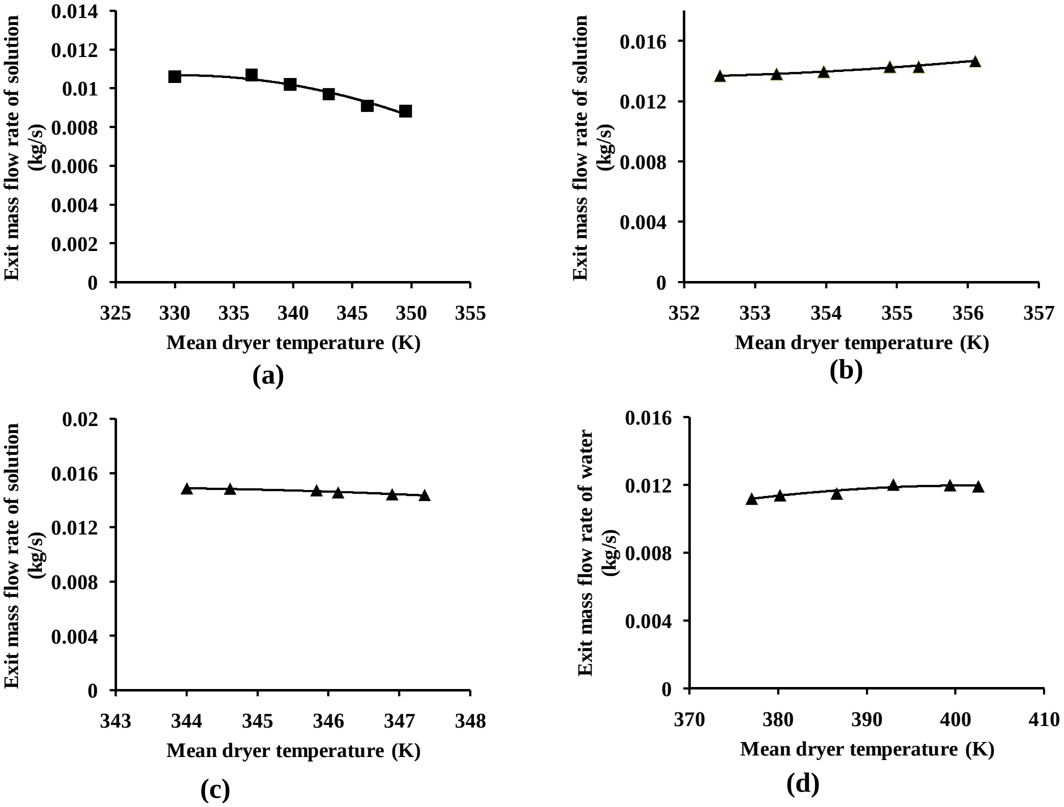


Figure-4. Variation of exit mass flow rates for the various liquids with mean dryer temperature. 50% w/w NaOH solution. (b) 10% w/w NaOH solution. (c) 25% w/w NaCl solution. (d) Distilled water.

iv. Variation of percent moisture content removed from the liquids with heat transfer coefficient

The markers and lines in Figure-5 represent the experimental data of the percent moisture content removed as they vary with the heat transfer coefficient, respectively. The percent moisture content removed seems to increase with heat transfer coefficient for 25% w/w NaCl solution, whereas it decreases for distilled water, 50% w/w NaOH and 10% w/w NaOH solution. This is a reflection of the operating conditions, dryer design and inherent properties of the liquids. The heat transfer coefficient however is a complex variable which is affected by the properties of the surrounding air and dryer design. This fact is reflected in the empirical correlation presented by McCabe *et al.*, (2001) in Equation (9), which is a good predictive tool for estimating heat transfer coefficients to air in vertical shapes under natural convection like the case in this work. The heat transfer coefficient ranged from 3.37 to 4.85 $Wm^{-2}K^{-1}$.

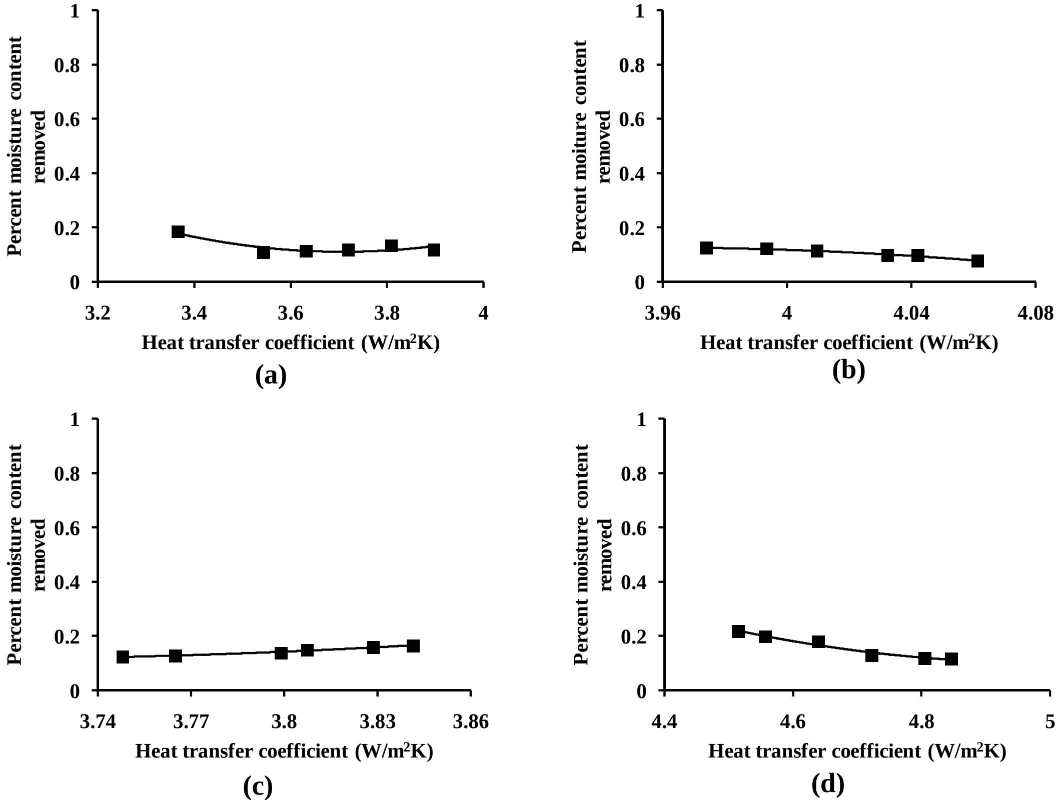


Figure-5. Variation of percent moisture content removed from the various liquids with heat transfer coefficient. (a) 50% w/w NaOH solution. (b) 10% w/w NaOH solution. (c) 25% w/w NaCl solution. (d) Distilled water.

CONCLUSIONS

The flexible dryer operation exhibited various degrees of dryness and performance operational trends, which is a reflection of the operating conditions, dryer design characteristics and inherent properties of the various liquids. The various phenomena exhibited by the selected liquids used for operating the spray dryer showed that it is very difficult to predict the performance or suitability of any dryer for the purpose of drying a liquid without carrying out an investigative task, as it was done in this work. The plotted results indicated the possibilities of increasing the percent moisture content removed further, maintaining a higher exit mass flow rates with corresponding higher inlet mass flow rates, considering the fact that the slopes were moderate. The highest exit mass flow rates of the liquids were not all produced by their highest specific energy supplied. The mean dryer temperature utilized ranged from 330 to 402.6 K, while the heat transfer coefficient ranged from 3.37 to 4.85 $Wm^{-2}K^{-1}$.

The results obtained in this work can serve as a guide in operating and predicting the suitability of some spray dryers as well as their performances. The usefulness of the study is such as to enable the design and operation of better or higher capacity dryers so as to compete or even surpass the conventional mode of drying some of these selected liquids industrially.

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Nomenclature

A_W = Surface area of dryer wall (m^2)
b = Constant
C_{PA} = Specific heat capacity of the surrounding air ($Jkg^{-1}K^{-1}$)
C_{PIA} = Specific heat capacity of the inlet air ($Jkg^{-1}K^{-1}$)
C_{POA} = Specific heat capacity of the outlet air ($Jkg^{-1}K^{-1}$)
C_{PC} = Specific heat capacity of the liquid being dried ($Jkg^{-1}K^{-1}$)
D_{IO} = Outer diameter of spray dryer vessel (m)
g = Acceleration due to gravity (ms^{-2})
Gr = Grashof number
h_A = Heat transfer coefficient of drying operation ($Wm^{-2}K^{-1}$)
l = Length of dryer (m)
$\dot{m}_C$ = Inlet mass flow rate of liquid to be dried (kgs^{-1})
$\dot{m}_{CF}$ = Exit mass flow rate of dried liquid (kgs^{-1})
$\dot{m}_{IA}$ = Mass flow rate of inlet air (kgs^{-1})

$\dot{m}_{OA}$ = Mass flow rate of outlet air (kgs^{-1})
n = Constant
Pr = Prandtl number
Q_{IA} = Heat input from heated air (W)
Q_{OA} = Heat lost by outflow of hot air (W)
Q_{SI} = Heat input from feed liquid (W)
Q_{SP} = Specific energy supplied (Jkg^{-1})
T_{fm} = Mean film temperature of surrounding air (K)
T_{IA} = Temperature of inlet air (K)
T_{IO} = Outside temperature of insulation material during operation (K)
T_{MA} = Mean air temperature inside dryer (K)
T_{OA} = Temperature of outlet air (K)
T_{SR} = Temperature of surrounding air (K)
x = Percent moisture content removed
β_{AR} = Coefficient of volumetric thermal expansion of surrounding air (K^{-1})
λ_c = Latent heat of vaporization of liquid being dried (Jkg^{-1})
π = 3.142
k = Thermal conductivity of dryer wall ($Wm^{-1}K^{-1}$)
k_{AR} = Thermal conductivity of surrounding air ($Wm^{-1}K^{-1}$)
ρ_{AR} = Density of surrounding air (kgm^{-3})
ρ_1 = density of air at T_{SR} (kgm^{-3})
ρ_2 = density of air at T_{IO} (kgm^{-3})
Δx = Thickness of dryer wall (m)
μ_{AR} = Viscosity of surrounding air ($kgm^{-1}s^{-1}$)

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