

Mathematical Modelling of a Reduced Thermal Energy Consuming Spray Dryer for Evaporating Caustic Soda Solution

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Abstract: Experimental demonstration, mathematical modelling and simulation of a technique for reducing thermal energy consumption in the diaphragm cell process using a techno-economically viable process to produce 73% wt. NaOH from electrolytic diaphragm cell catholytes of about 10% wt. NaOH was carried out in this work. The technique completely eradicated the use of thermal energy in concentrating catholyte effluents from about 10% wt. NaOH solution to 50% wt. NaOH solution. This resulted in a specific energy savings of about 2.68×10^6 J/kg NaOH. The use of a spray dryer for increasing the concentration of 50% wt. NaOH solution to 73% wt. NaOH solution further improved the energy savings compared to that of multiple effect evaporators by 1.41×10^6 J/kg of solution, which corresponds to about 61.05% specific energy savings. The deviation of all simulated results from experimental data was between -0.062 and +0.084, portraying a good predictive tool for probing into the spray dryer operations. This work is expected to reduce considerably the total energy consumption of the diaphragm cell process through process integration or new processing methodology, with improved equipment designs.

Key words: Catholyte, dryer, energy, modelling, simulation, spray

INTRODUCTION

The electrochemical production of caustic soda from brine in the chlor-alkali industry, with chlorine and hydrogen as the by-products is one of the leading industrial production processes in the chemical industry. According to Alkire and Braatz (2004), electrochemical processes provide the only commercially viable means for the production of caustic soda with co-product chlorine and some chemical products. Chlorine and/or caustic soda is involved directly or indirectly in the manufacture of about 70% of all chemical products (Ohm, 2007). The chlor-alkali process is the most economically important electrosynthetic process (Minteer, 2002). The chlor-alkali (also called "chlorine-caustic") is an energy intensive process and is the second largest consumer of electricity (2400 billion kWh) among electrolytic industries. In 2006, about 84% of the total world chlorine capacity of about 59 million metric tons was produced electrolytically using diaphragm and membrane cells, while about 13% was made using mercury cells (Tilak *et al.*, 2007). The diaphragm cell alone accounted for about 62% production (Tilak *et al.*, 2007).

Steam is used principally for caustic soda evaporation in the production of the chemical. According to Patel (2009), the chlor-alkali energy cost estimate is around 60 to 70% of the total cost of production. In view of the

above areas of concern, the chlor-alkali sector which is a basic driver of the economy has to play a pro-active role in optimizing energy efficiency and reducing wastage. Among the various strategies aimed to meet energy demand, efficient use of energy and its conservations emerges out to be the least cost option. Hence, all attempts should be made to make efficient use of energy possible, so as to keep operational cost down and attain sustainability in a global competitive environment.

In energy conservation conscious countries, Energy Conservation Acts (ECAs) has specified the list of energy intensive industries and establishments as designated consumers. Chlor-alkali is one of such industry. Such designated consumers will have to carry out certain mandatory functions in which one of them is to implement techno-economically viable recommendations. Chlor-Alkali industry has to aggressively pursue the energy conservation agenda, not so much for meeting any lofty social obligation, but to ensure its own survival and growth (Patel, 2009).

Apart from the high electrical energy demands for running the electrolytic cells the thermal energy demands are also enormous. The initial product or catholyte leaving the diaphragm electrolysis cells contains only about 10-12% w/w caustic soda. The catholyte is treated further for possible impurities and must be concentrated to the saleable 50% product, 73% product or the anhydrous

Basis: 0.01 kg/s of catholyte

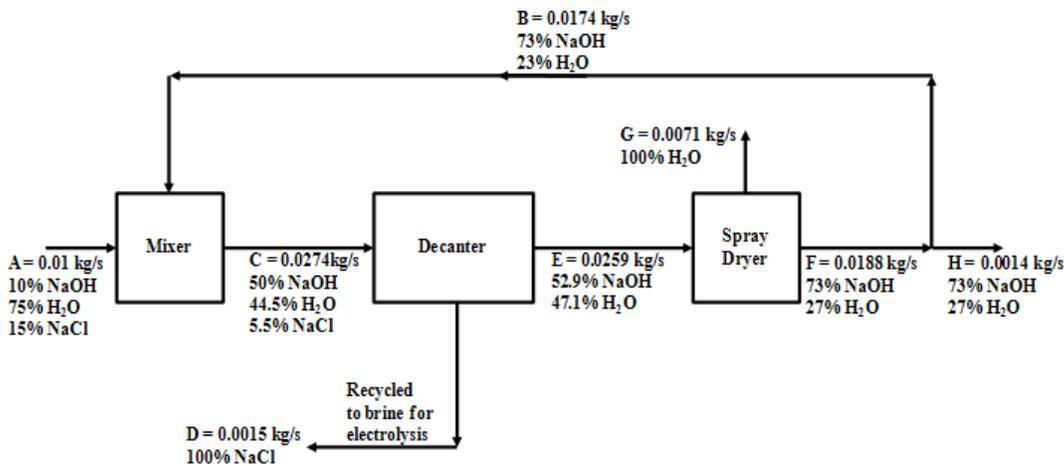


Fig. 1: Flow diagram of the technique to reduce thermal energy consumption for the evaporation of caustic soda solution in diaphragm cell process

product (above 98%) for commercial use. Conventionally, high thermal energy consuming multiple effect evaporators are utilized to achieve these higher concentrations. From about 10% w/w caustic solution, the steam consumption for concentration to 50% w/w NaOH is estimated to be 2.68×10^6 J/kg NaOH according to Tilak *et al.* (2007). As estimated from Worrel *et al.* (2000), approximately 2.35×10^6 and 3.1×10^6 J/kg of energy is required to produce 73 and 100% w/w NaOH solution respectively.

Models are invariably helpful in the difficult task of transforming understanding of principles into properly designed equipments. Modelling is worthwhile because it promotes an orderly state of mind with which to deal with the unknown, and because it provides a quantitative guide for explaining important scientific and engineering judgments. Many models especially the very complicated ones, can describe a given set of data equally well, but the real test of a model's usefulness lies in the success of the design based upon it (Newman, 1991; Olufemi *et al.*, 2010). Some approaches in spray dryer modeling have been identified by Oakley (2004) as the mass and energy balance models, equilibrium models, rate based models and particle-source-in-cell models. Some other researchers that have investigated spray dryer modeling and/or design include Katta and Gauvin (1976), Crowe (1980), Palencia *et al.* (2002), Fletcher and Langrish (2003) and Shabde and Hoo (2006) to mention a few.

This work is set-out to propose, validate and put forward successful implementation of technoeconomically viable recommendations in the chlor-alkali industry. The possibility of this is to be explored by theoretical and experimental demonstration of the reduction of thermal energy usage in the evaporation of caustic soda solution produced from diaphragm cells.

MATERIALS AND METHODS

Experimental work: This work was performed in the Unit Operations Laboratory of the Department of Chemical Engineering, University of Lagos, Akoka, Lagos, Nigeria. Figure 1 described the flow diagram of the technique to reduce thermal energy in the diaphragm cell process. For a catholyte input of 0.01 kg/s with 10% w/w NaOH, about 0.0014 kg/s with 73% w/w NaOH product is produced. The process is hinged on the fact that at 50% w/w NaOH, almost all the NaCl in the product catholyte mixture from the electrochemical processing will be precipitated (Tilak *et al.*, 2007). This implies that almost all the NaCl from the cell can be removed by simply concentrating at this stage to about 50% w/w NaOH without the need for evaporation. This was achieved by mixing the catholyte (about 10% w/w NaOH) with 73% w/w NaOH to concentrate it to 50% w/w NaOH solution. The precipitated NaCl was decanted and recycled to the brine electrolysis cell, while the 50% w/w NaOH is evaporated in a spray dryer to 73% w/w NaOH. The initial quantity of 73% w/w NaOH needed to concentrate the catholyte from 10 to 50% w/w NaOH is then recycled. The 0.01 kg/s NaOH initially at 10% w/w from the cell is now produced as the final product with 73% w/w NaOH from the spray dryer operation.

Schematic operational diagram of the spray dryer is shown in Fig. 2. The spray dryer contacts tiny droplets of the 50% w/w NaOH solution after atomization with hot air in a countercurrent manner. The spray dryer is a 0.85 m height vertical cotton wool lagged stainless steel cylindrical (0.12 m diameter) vessel. The tiny droplets enabled a higher surface area of the solution to be contacted and evaporated, thereby enhancing the drying operation. Inlet air at 299 K was used throughout. Inlet air

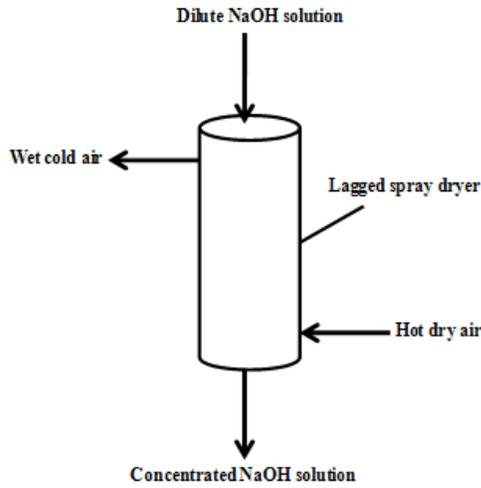


Fig. 2: Schematic operational diagram of the stainless steel spray dryer

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 is used to measure the temperature of the inlet air and the outlet air at the entry and exit points of the spray dryer, respectively. The pressure inside the dryer was 101,325 N/m², while the inlet air mass flow rate was 0.048 kg/s. The tiny droplets enabled a higher surface area of the solution to be contacted and evaporated, thereby enhancing the drying operation. The final wt% of NaOH after each run was determined by titration with 2 M hydrochloric acid. The thermal energy requirement of the spray dryer was also determined.

Mathematical model development: In developing a model equation for the spray dryer under consideration, the mass and energy balance model approach is used. This involves taking mass and heat balance around the spray dryer.

The following assumptions are made in the development of the model:

- The drying process begins only when steady state has been attained.
- There is a negligible amount of solvent in the incoming heating air.
- The particles produced after atomization are uniform.
- The effects of wall collisions, particle agglomeration and ionic effects are negligible.
- The heat lost from the unit to the surroundings is accounted for due to dryer lagging.
- The droplets are exposed to the same amount of heat (uniform heat distribution).
- The feed liquid is well-mixed and all droplets contain the same amount of solvent and solute.

By making an extensive heat balance around the spray dryer:

Heat input from heated Air (Q_{IA}) + Heat input from inlet liquid (Q_{SI}) =
 Heat used for heated liquid (Q_{HC}) + Heat used for drying liquid (Q_{DC}) +
 Heat lost to surrounding through lagged walls (Q_{SR}) +
 Heat lost by outflow of hot air (Q_{OA}) +
 Heat lost by outlet liquid after drying (Q_{SO}) +
 Heat lost by evaporated water from liquid (Q_{WO})

$$\Rightarrow Q_{IA} + Q_{SI} = \quad (1)$$

$$Q_{HC} + Q_{DC} + Q_{SR} + Q_{OA} + Q_{SO} + Q_{WO} \quad (2)$$

$$Q_{IA} = \dot{m}_{IA} C_{pIA} T_{IA} \quad (3)$$

$$Q_{SI} = \dot{m}_c C_{pc} T_{IA} \quad (4)$$

$$Q_{HC} = \dot{m}_c C_{pc} T_{MA} \quad (5)$$

where the mean dryer temperature:

$$T_{MA} = \frac{T_{OA} + T_{IA}}{2} \quad (6)$$

$$Q_{DC} = \dot{m}_c \lambda_c \quad (7)$$

$$Q_{SR} = h_A A_w (T_{IO} - T_{SR}) \quad (8)$$

$$A_w = \pi D_{IO} l \quad (9)$$

$$T_{IO} = T_{MA} - \frac{(Q_{IA} + Q_{SI} - Q_{OA}) k A_w}{\Delta x} \quad (10)$$

$$Q_{OA} = \dot{m}_{OA} C_{pOA} T_{OA} \quad (11)$$

$$Q_{SO} = \dot{m}_c C_{pc} T_{OA} \quad (12)$$

$$Q_{WO} = \dot{m}_{WO} C_{pwo} T_{OA} \quad (13)$$

But

$$\dot{m}_{wo} = \dot{m}_c - \dot{m}_{CF} \quad (14)$$

Substituting Eq. (3) to (14), rearranging, and re-writing $\dot{m}_{CF} = \frac{dm_{CF}}{dt}$, which represents the rate of change of the final mass flow rate of the solution being dried per time, Therefore,

$$\frac{dm_{CF}}{dt} = - \frac{[h_A A_w (T_{IO} - T_{SR}) + \dot{m}_{OA} C_{pOA} T_{OA} - \dot{m}_A C_{pIA} T_{IA} - \dot{m}_C (C_{pC} T_{MA} - \lambda_C - C_{pwo} T_{OA})]}{C_{pwo} T_{OA}} \quad (15)$$

Equation (15) is the model equation for the final mass flow rate of the dried solution from the spray dryer after drying. The final amount of water evaporated can also be evaluated using Eq. (14).

The percent moisture content removed is given as:

$$x = \frac{(\dot{m}_c - \dot{m}_{CF})}{\dot{m}_c} \times 100\% \quad (16)$$

The specific energy supplied is given as:

$$Q_{SP} = \frac{(Q_{IA} + Q_{SI} - Q_{OA})}{\dot{m}_c} \quad (17)$$

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

$$h_A = [k_{AR} b (Gr \cdot Pr)^n] / l \quad (18)$$

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

$$Gr = \frac{l^3 \rho^2_{AR} g \beta_{AR} (T_{IO} - T_{SR})}{\mu^2_{AR}} = \frac{l^3 \rho^2_{AR} g \left(\frac{\frac{1}{\rho_2} - \frac{1}{\rho_1}}{(T_{IO} - T_{SR}) \left(\frac{1}{\rho_1} + \frac{1}{\rho_2} \right) / 2} \right) (T_{IO} - T_{SR})}{\mu^2_{AR}} \quad (19)$$

ρ_1 = density of air at T_{SR} (kg/m)

ρ_2 = density of air at T_{IO} (kg/m)

$$Pr = \frac{C_{PA} \mu_{AR}}{k_{AR}} \quad (20)$$

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

$$T_{fm} = \frac{T_{IO} + T_{SR}}{2} \quad (21)$$

and

$$T_w = \frac{T_{MA} + T_{IO}}{2} \quad (22)$$

The constants b and n in Eq. (19) are estimated as follows:

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

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

The deviation of modelled value (X_{MD}) from corresponding experimental value (X_{EXP}) is given as:

$$\Delta E_x = \frac{X_{MD} - X_{EXP}}{X_{EXP}} \quad (23)$$

Also

$$w_b = C_b / \rho_c \quad (24)$$

RESULTS AND DISCUSSION

The First Order Ordinary Differential Equation (O.D.E) in Eq. (15) that gives rate of change of the final mass flow rate of the solution being dried per time was solved by using the Fourth Order Runge-Kutta method. This was implemented on MATLAB software program version 7.9.0.529 (R2009b). All the specific heat capacity values were evaluated as a function of temperature as presented by Perry *et al.* (1997) at 101,325 N/m² which was the operating pressure inside the dryer throughout the whole operation. Experimental results and simulated results were presented graphically. All experimental results were presented with markers, while simulated results were presented with lines. The experimental results of the spray dryer operation for concentration of 50% w/w NaOH to higher concentrations with a maximum value of about 73% w/w NaOH solution were considered with thermal energy requirements estimated.

In Fig. 3 the variation of final weight percent of NaOH with inlet mass flow rate of solution being dried was plotted. It could be observed that the final weight percent of NaOH increased with inlet mass flow rate of the 50% w/w NaOH solution that is being dried. The simulation obtained is a good match of the experimental operation, as all deviations of simulated from experimental data was between -0.062 and +0.084.

In Fig. 4, the final weight percent of the NaOH solution increased almost linearly with the difference in volume of the final and initial solution being dried. This revealed that as more solution is being passed through the dryer, more water is being removed, resulting in a more concentrated solution. This means that the dryer has enough capacity to dry more solution at an increased

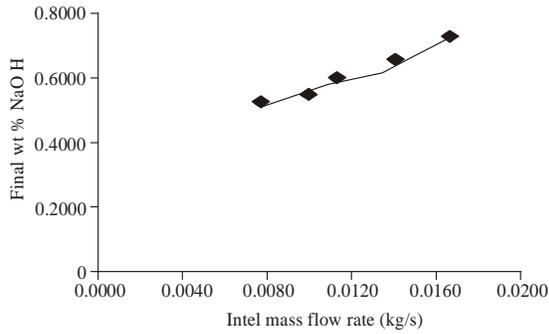


Fig. 3: Variation of final weight percent of NaOH with inlet mass flow rate of solution being dried

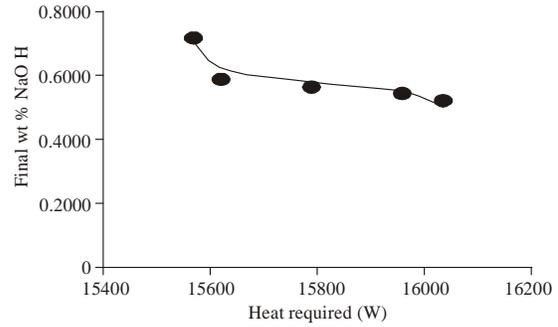


Fig. 6: Variation of final weight percent of NaOH with quantity of heat required

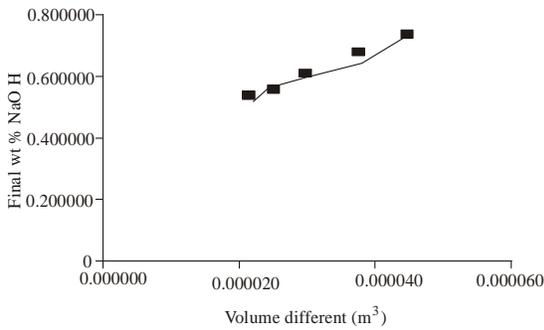


Fig. 4: Variation of final weight percent of NaOH with difference in final and initial volume of solution

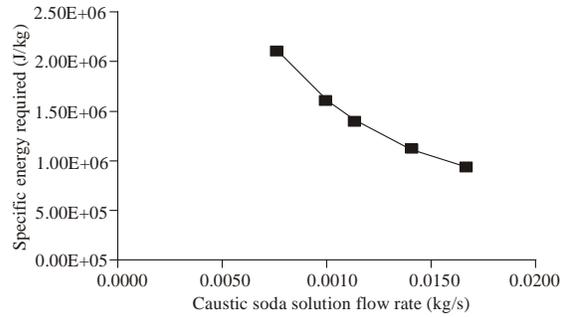


Fig. 7: Variation of specific energy required with caustic soda solution flow rate

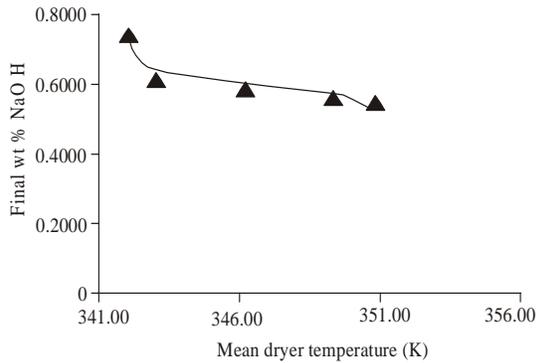


Fig. 5: Variation of final weight percent of NaOH with dryer mean temperature

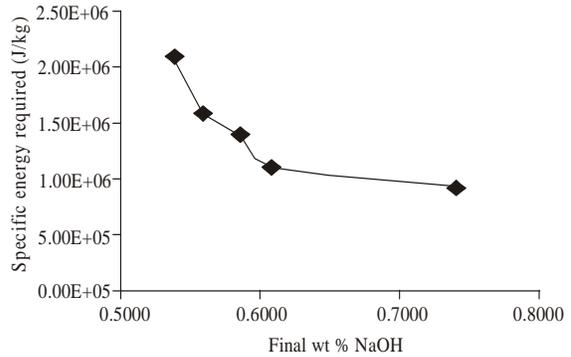


Fig. 8: Variation of specific energy required with final weight percent of NaOH

rate than those used presently. The simulation seems to predict the experimental operation properly.

The final weight percent of NaOH is shown to decrease with mean temperature of the dryer between inlet and exit hot air stream in Fig. 5. The reason for this is because higher concentrated NaOH product will require more heat exchange with the drying air inside the dryer chamber, thereby reducing the effluent air temperature further. Similarly, the simulation seems to predict the experimental operation properly.

The same explanation for the previous figure is the same reason why the final weight percent of NaOH in Fig. 6 decreased with the quantity heat required. If the mean dryer temperature is reduced, definitely the quantity of heat will be reduced in a direct proportion. Similarly, the simulation seems to predict the experimental operation properly.

The variation of the specific energy required for concentrations from above 50 to about 73% w/w NaOH in the dryer is shown to decrease with caustic soda solution mass flow rate in Fig. 7. Interestingly, this means

that operating the dryer at higher mass flow rate indicated a reduction in specific energy consumption. Experimental results seem to be matched perfectly by the simulated data as it can be seen.

Figure 8 clearly showed that the specific energy required decreased with final weight percent of NaOH solution produced. At about 73% w/w NaOH product from the spray dryer, the specific energy consumption is about 9.37×10^5 J/kg. By using multiple effect evaporators instead to obtain 73 from 50% w/w NaOH solution, the specific energy required is estimated to be 2.35×10^6 J/kg (Worrel *et al.*, 2000). This indicated that the specific energy savings by using the spray dryer is approximately 1.41×10^6 J/kg better. This represents about 60.15% reduction in specific energy required by the spray dryer for the same operation compared to that of multiple effect evaporators. The spray dryer seems to be more effective in this regard. As observed, the model seems to be a very good predictive tool in probing into the operations of the spray dryer.

CONCLUSION

The technique of reducing thermal energy consumption in the diaphragm cell process has indicated a techno-economically viable process to produce 73 from about 10% w/w NaOH electrolytic diaphragm cell catholytes. The technique completely eradicated the use of thermal energy in concentrating catholytes effluents from about 10% w/w NaOH solution to 50% w/w NaOH solution. This represents a specific energy savings of about 2.68×10^6 J/kg NaOH corresponding to approximately 99%+ thermal energy savings. Furthermore, the use of a spray dryer in increasing the concentration from 50 to 73% w/w NaOH solution further improved the energy savings compared to that of multiple effect evaporators by 1.41×10^6 J/kg of solution. This corresponds to about 61.05% in the specific energy savings for the same operation compared to the usage of multiple effect evaporators. The total thermal energy saved by the technique presented in this study can thus be stated as 2.68×10^6 J/kg NaOH for producing 50% w/w NaOH solution from about 10% w/w NaOH solution and 1.41×10^6 J/kg of solution for producing 73% w/w NaOH solution from 50% w/w NaOH solution using a spray dryer. The maximum negative and positive deviations for all simulated data from their corresponding experimental data is between -0.062 and +0.084, respectively. This portrays the model to be a very good predictive tool in probing into the operations of the spray dryer. The work presented here is expected to reduce the thermal energy required by the diaphragm cell process through process integration or new process methodology.

ACKNOWLEDGMENT

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NOMENCLATURE

A_w	= Surface area of dryer wall (m^2)
b	= Constant
C_b	= Concentration of catholyte (kg/m)
C_{PA}	= Specific heat capacity of the surrounding air (J/kgK)
C_{PIA}	= Specific heat capacity of the inlet air (J/kgK)
C_{POA}	= Specific heat capacity of the outlet air (J/kgK)
C_{PIA}	= Specific heat capacity of the inlet air (J/kgK)
C_{PC}	= Specific heat capacity of the liquid (J/kgK)
C_{PWO}	= Specific heat capacity of evaporated water from liquid (J/kgK)
g	= Acceleration due to gravity (m/s^2)
Gr	= Grashof number
h_A	= Heat transfer coefficient of drying operation (W/m^2K)
l	= Length of dryer (m)
\dot{m}_c	= Inlet mass flow rate of liquid (kg/s)
\dot{m}_{CF}	= Exit mass flow rate of liquid (kg/s)
\dot{m}_{IA}	= Mass flow rate of inlet air (kg/s)
\dot{m}_{OA}	= Mass flow rate of outlet air (kg/s)
\dot{m}_c	= Mass flow rate of inlet liquid (kg/s)
\dot{m}_{WO}	= Mass flow rate of evaporated water from liquid (kg/s)
N	= Constant
Pr	= Prandtl number
Q_{DC}	= Heat used for drying liquid (W)
Q_{HC}	= Heat used for heating liquid (W)
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_{SO}	= Heat lost by outlet liquid after drying (W)
Q_{SP}	= Specific energy supplied (J/kg)
Q_{SR}	= Heat lost to surrounding through lagged walls (W)
Q_{WO}	= Heat lost by evaporated water from liquid (W)
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)

w_b = Percentage by weight of NaOH in catholyte
 x = Percent moisture content removed
 X_{EXP} = Experimental values
 X_{MD} = Modelled values

Greek symbols:

β_{AR} = Coefficient of volumetric thermal expansion of surrounding air (K^{-1})
 λ_C = Latent heat of vapourisation of liquid being dried (J/kg)
 π = 3.142
 k = Thermal conductivity of dryer wall (W/mK)
 k_{AR} = Thermal conductivity of surrounding air (W/mK)
 r_{AR} = Density of surrounding air (kg/m^3)
 ρ_c = Density of catholyte (kg/m^3)
 ΔE_x = Deviation of modelled value (X_{MD}) from corresponding experimental value (X_{EXP})
 Δx = Thickness of dryer wall (m)
 m_{AR} = Viscosity of surrounding air (kg/ms)

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