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Mathematical Modelling and Design of Helical Coil Heat Exchanger for Production of Hot Air for Fluidized Bed Dryer

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Abstract

In global industrialization, efforts have been made to increase the rate of heat transfer in heat exchanger, minimizing the size of heat exchanger to reduce cost as well as increasing the effectiveness. Helical coil heat exchanger (HCHE) has been proven to be effective in improving heat transfer due to its large surface area. In this study, HCHE was designed to provide hot air needed for fluidized bed drying processes. The HCHE design model was fabricated and evaluated to study the efficiency of the hot air output for a laboratory fluidized bed dryer. The mathematical model for estimation of the final (output) temperature of air, T_{af}, passing through the HCHE was developed and validated experimentally. The drying of bitter kola particulates was carried out with a drying temperature of 50˚C ± 3˚C and a bed height-to-bed diameter ratio (H/D) of 1.5. The time taken to dry bitter kola particulates to 0.4% moisture content was 1 hour 45 minutes. Hence, HCHE is recommended for use in the production of hot for laboratory-scale fluidized bed dryers.

Keywords

Helical Coil Heat Exchanger, Fluidized Bed Dryer, Heat Transfer, Output Air Temperature

1. Introduction

Fluidization is the unit operation by which fine solids are transformed into a fluid-like state through contact with a gas [1]. The fluidized bed is a vessel in which the transportation of fine solids into a fluid-like state with the help of fluid velocity takes place. Studies have shown that these fluidized beds are known for their high heat and mass transfer coefficients, due to the surface area-to-volume ratio of fine particles [2] [3] [4]. Hence, a fluidized bed is therefore ideal for reaction, drying, mixing, spraying and heat transfer [5].

1.1. Production of Hot Air for Fluidization Drying

Production of hot air for a fluidized bed dryer can be achieved by a direct or indirect gas burner, a steam heat exchanger, a hot water heat exchanger, an electrical heater or using waste heat/heat recovery [6]. Air handling unit for the production of hot air for drying in fluidized bed is mostly produced by blowing a volume of air through an electric heating unit [7] [8]. This system is usually not portable due to the configuration of the blower, air duct and heater compartment. A heater separated from the blower assembly was used for hot air production to feed the fluidized bed dryer as a new alternative to produce dark brown parboiled rice [9]. Whereas some fluidized beds are designed with immersed heaters [10] [11] of which compressed air or blower systems are used to supply needed air for drying. A different approach to producing hot air for drying in a fluidized bed dryer is considered in this work for the purpose of cost saving and safety for smaller and laboratory fluidized bed dryers. The introduction of compressed air within fluidization velocities through helical coil heat exchanger (HCHE) has proven to be more economical when compared with heaters and blowers assembly for the production of hot air for drying or the procurement of the fluidized bed dryer with inherent heaters assembly [12].

1.2. Helical Coil Heat Exchanger

A heat exchanger is a device used for thermal energy (enthalpy) transfer between 1) two or more fluids, 2) a solid surface and a fluid, or 3) solid particulates and a fluid, usually at different temperatures and in thermal contact without external heat and work interactions [13] [14]. Helically coiled tubes are very effective for heat transfer applications and heat exchangers due to their excellent heat transfer performance and compact size as compared to straight tube heat exchangers [15]. The fluid flowing through helically curved tubes induces secondary flow in the tubes, which is responsible for heat transfer [16]. According to [17], the secondary flows constitute vortices structure which increases the torsion along the pipe and this secondary flow has the ability for heat transfer enhancement due to the mixing of fluid in the tube [18]. [19] noted that helically coiled tubes are useful for steam generators in power plants, chemical reactors and heat exchangers due to its larger heat transfer area per unit volume and higher efficiency in heat and mass transfer. Parameters such as heat transfer and hydrodynamic characteristics of the coil, relationship of tube radius to coil radius, coil pitch, thermal fluids, Reynolds number (Re), Prandtl number (Pr) and Dean Number (De) are necessary for the design of HCHE [20].

It is a known fact that heat transfers on HCHE are affected by the coil and tube sizes, mass flow rates of fluids, number of turns as well as the thermal fluids used [21]. Different configurations of HCHE such as square helical coil, conical helical coil, double pipe helical coil, tube-in-tube helical coil, coil in the flue and conventional helical coil exchangers in which their usefulness depend on. HCHE has different applications such as in heating ventilation and air-conditioning (HVAC) systems, the power generation industry, the nuclear industry, chemical processing plants, heat recovery systems, refrigeration, the food industry, and residual heat removal systems [22] [23]. Also, the compact structure and high heat transfer coefficient gave HCHE advantages over other exchangers when cost saving and space are of essence. The objective of this work shall focused on the mathematical modelling of a helical coil-in-bath heat exchanger for the purpose of providing controlled output air temperatures for drying processes on a laboratory-scaled fluidized bed dryer.

2. Methodology

2.1. Mathematical Modelling of Helical Coil-in-Bath Heat Exchanger

In this design, heating fluid is a fixed volume of water in the electric heating shell with no provision of flowing in or out as conventional heat exchanger, while air is the heated fluid passing through copper tubing wound as helical coil. In the design, the following assumptions were considered:

1) Heat transfer to the external environment was negligible.

2) Room and ambient temperature were constant at 25˚C.

3) The properties of the water were pure and of neutral pH.

4) Heat transfer was in steady state. In steady state, the same amount of heat Q must pass through each section of the coil. Heat transfer is by convection across the hot and cold film and by conduction through the solid wall.

5) Steady temperature throughout the process (heat-up and cool-down phases have not been considered).

6) Heat exchanger fouling was not considered

7) No mass flow rate for water.

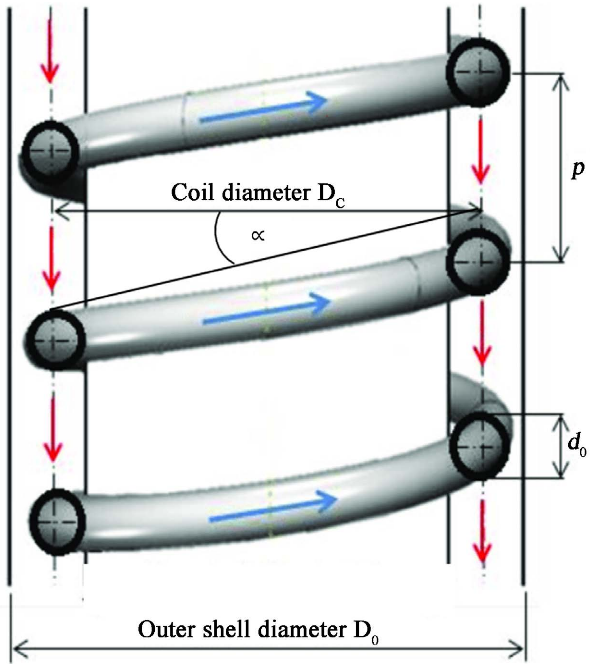
8) Heat of vaporization was negligible.

The geometry of this heat exchanger shown in **Figure 1** consist of copper tubing with pipe diameter (d_o) that had been bended into a coil of diameter D_c and placed inside a shell with outside diameter (D_o). The coil pitch (P) was defined as the distance between adjacent turns and calculated as the length of the heat exchanger divided by the number of turns. The inclination of the turns of the coil (α) could be seen in Equation (1); and the inclination of the coil was determined by the length of the heat exchanger and the number of turns.

$$\alpha = \tan^{-1}\frac{P}{D_c} \tag{1}$$

Considering a cross section of helical coil as shown in **Figure 1** each integration step corresponds to half a coil turn. Its area can be calculated from Equation 2 given that tube nominal size and coil perimeter.

$$A_{step} = \frac{\text{tube perimeter} \times \text{coil perimeter}}{2} = \frac{\pi \cdot D_c \times \pi \cdot d_0}{2} \tag{2}$$



Source: [24].

Figure 1. Cross section of helical coil heat exchanger.

This design shall consider two heat transfer processes, namely:

1) Heat transfer from the hot bath (water) to the wall of the coil

2) Heat transfer from the wall of the coil to the air flowing inside it.

Generally, the mean rate of heat transfer (Q) from the hot bath to the cool air passing through the coil can at constant pressure for a given time frame Δt is given in Equation (3).

$$Q = m_a Cp_w \left(dT \right) / \Delta t \quad (3)$$

where Q—Mean heat transfer rate (kW) (kJ/s) (HP) (Btu/s); m_a—Mass of the air (kg) (lb); C_{pv}—Specific heat capacity of the fluid (kJ/kg˚C) (Btu/(lb.˚F); dT—Change in temperature of the fluid (˚C) (˚F); t—Total time over which the heating process occurs (seconds).

Considering the thin wall approximation for the helical coil in the bath, conduction heat transfer of coil thickness is not considered in the model. This is due to the high conductivity of copper (≈400 W/mK) and the small reduced thickness of the coil wall (typically < 1 mm). Hence, the heat extracted by a heat exchanger can be expressed as shown in Equation (4).

$$Q = m_w Cp_w \left(T_{hw} - T_{cw} \right) = m_c Cp_c \left(T_{hc} - T_{cc} \right) \quad (4)$$

where m_w—mass of water, m_c mass of copper coil, T_{hw}—hot water initial temperature, T_{cc}—initial copper coil temperature, T_{hc} is the temperature of the heated coil or the film temperature, Cp_w—specific heat capacity of water and Cp_c—heat capacity of copper.

Considering convective heat transfer from the hot water to air through the heated coil with the film temperature (T_{film}), the final air temperature (T_{af}) can be obtained from Equation (5) having selected T_{film}, T_{ai} and T_{hw}

$$Q = h_w A_{total}\left(T_{hw} - T_{film}\right) = h_a A_{total}\left(T_{af} - T_{ai}\right) \tag{5}$$

where h_w is the convective heat transfer coefficient of water is, h_a is convective heat transfer coefficient of air and T_{ai} is initial air temperature.

The heat transfer area A_{total} of the HCHE can be obtained by estimating the overall heat transfer coefficient, U, (W/m^2·˚C) (Btu/h˚F) from the Typical Overall Heat Transfer Coefficients in Heat Exchangers Table [25] from the basic heat exchanger as shown Equation (6).

$$Q = U \times A_{total} \times \Delta T_m \tag{6}$$

Assuming a counter flow for HCHE, the log mean temperature difference ΔT_m LMTD, can be derived by imputing the streams temperatures $\left(T_{hw} - T_{af}\right)\left(T_{film} - T_{ai}\right)$, where, T_{ai} is the air initial temperature of air, T_{af} is the final temperature of the air.

$$\Delta T_m = \frac{\left(T_{hw} - T_{af}\right) - \left(T_{film} - T_{ai}\right)}{\ln\left[\frac{T_{hw} - T_{af}}{T_{film} - T_{ai}}\right]} \tag{7}$$

2.2. The Heat Transfer in the Exchanger

The heat gain by air, (Q_a) is defined in Equation (8)

$$Q_a = U_a A_{total}\left(T_{af} - T_{ai}\right) \tag{8}$$

where U_a is the heat transfer coefficient of air, A_{total} is the heat transfer area, (T_{af} − T_{ai}) is the temperature difference.

2.3. The Final Air Temperature, T_{af} in the HCHE

The heat gain by air (Q_a) considering specific heat capacity of air at constant pressure, Cp_v and the mass flow rate $\dot{m}_a$, is defined as:

$$Q_a = \dot{m}_a Cp_v\left(T_{flim} - T_{ai}\right) \tag{9}$$

Equating Equations (8) and Equation (9), T_f, the output air temperature can be derived as:

$$T_f = \frac{\dot{m}_a Cp_v\left(T_{flim} - T_{ai}\right)}{U_a A_{total}} + T_{ai} \tag{10}$$

Equation (10) is the proposed mathematical model to estimate the final (output) temperature of air, T_{af}, passing through the coil with mass flow rate m_a. Hence, T_{af}, can be estimated through iterations of Equation (10) with values of (U_a) obtained from the overall heat transfer table [26].

2.4. Design Parameters for the Helical Coil Heat Exchanger

Standard Copper, L type 3/8 inch was considered for the helical coil due to its good heat transfer properties. Design parameters as shown in **Table 1**.

2.5. Fluidized Bed Design Parameters

To study the effect of output air from the HCHE on fluidized drying. The fluidized bed design parameters [27] as shown in Table 2 were adopted.

2.6. Experimental Procedure for Drying in Fluidized Bed Dryer

Drying operations and determination of moisture content of materials was considered in the followings according to [27]:

1) Remove any excess water from the sample by decanting or using a filter.

2) Weigh container empty, then with material. The material is then empty into the fluidized bed.

3) Put the sample in the dryer at a pre-determined bed depth compatible with the operating range of the dryer.

4) Measure about 6500 - 13,000 ml of the required thermal fluid is used in the bath HCHE depending on the size and pitch of the helical coil.

5) Select the helical coil of the required surface area and couple it on the lid of the HCHE to the inlet and outlet (inlet of the coil is the side of the coil first turn

Table 1. Design parameters for the helical coil heat exchanger.

S/N	Parameters	Value
1	Inclination of the Coil α	8.5˚
2	Total heat transfer area, A_{total}	0.2 m^2
3	Coil diameter d_{hx}	0.2 m
4	Coil Pitch P_{hx}	2.5 cm
5	Shell diameter d_{fpipe}	0.25 m
6	Mass of water	15 kg
7	Mass of copper coil	2 kg
8	Pipe diameter d_{pipehx}	0.0127 m
9	Number of turns	10

Table 2. Design parameters of the fluidized bed column.

S/N	Parameters	Value
1	Nozzle diameter D_{noz}	20 mm
2	Fluidized bed diameter D_w	75 mm
3	$D_w/36$	2.08
4	H_w	165 mm
5	Pressure drop across the distributor plate ΔP grid	2500 Pa
6	Transport Disengaging Height, TDH	0.8 m
7	Bed height, L_B	0.15 m
8	Total Bed Height H_t	0.95 m

and the other side is the outlet).

6) Insert the coupled helical coil into the bath and secure it.

7) Switch on the mains supply.

8) Switch on the heater and adjust the heater temperature controller to the value required.

9) Start the compressor to compress the air above 100 psi.

10) Open the upstream valve of the air flow meter and adjust the flow rate to achieve good fluidization.

11) Measure air flow rate and pressure drop from the instruments.

12) Start the stop watch and commence the drying process. At the set time, close the valve to shut the air.

13) Remove the contents and re-weigh, continue repeating the drying cycle until a constant weight is obtained.

N/B: The difference in initial and final weights of the material can be expressed as the moisture content on wet or dry basis. The total drying time for the material can be calculated by multiplying the interval cycle time by the number of cycles required.

2.7. Particulate Material Selection and Preparation

For this study, kola particulates material was selected and the material (bitter kola) was prepared using local grating method, *i.e.* grating the bitter kola manually on the grater.

2.8. Drying of Bitter Kola Particulates

The drying study for the fluidized bed dryer was evaluated using bitter kola particulate materials. The ratio of the bed height-to-bed diameter (H/D) was 1.8. The initial bitter kola mass was 266 g with the mean particle size of 744 μm. The drying temperature was 50˚C ± 3˚C. At the initial drying period of the first 30 minutes, fluidization of the bed material was supported by vibrating the bed with a staring rod. This was due to the damp non spherical and elongated nature of the particulate material. From 35 minutes, the particles where loose and the mixing was improved up to 50 minutes. Thereafter, fluidizations were adequate till the end of drying time of 1 hour 45 minutes.

3. Results and Discussion

The time taken for dying of bitter kola particulates material was 1 hour 45 minutes and the mass was recorded at 5 minutes interval. It was assumed that the equilibrium moisture content was 1.0 g; hence the moisture content and the drying rate for each corresponding time intervals were determined. The relationship of moisture content and time is shown in **Figure 2**. The figure showed a steady state drying characteristics curve, while **Figure 3** showed drying rate curve for the bitter kola particulates. These typical drying curves corroborate the drying characteristics in the literature [28].

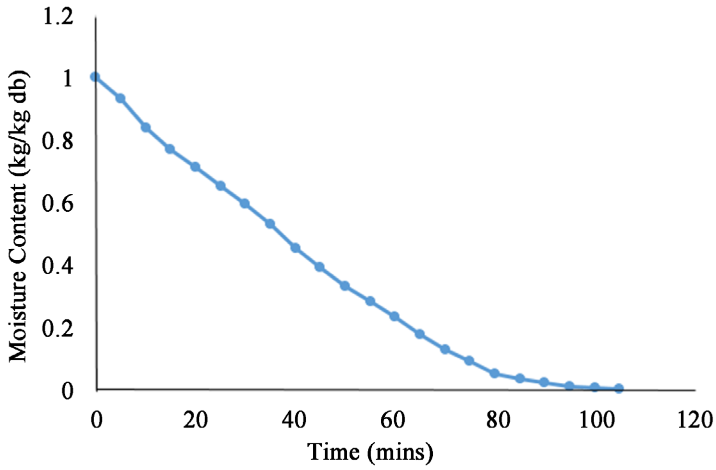


Figure 2. Steady state drying curve for bitter kola particulate material.

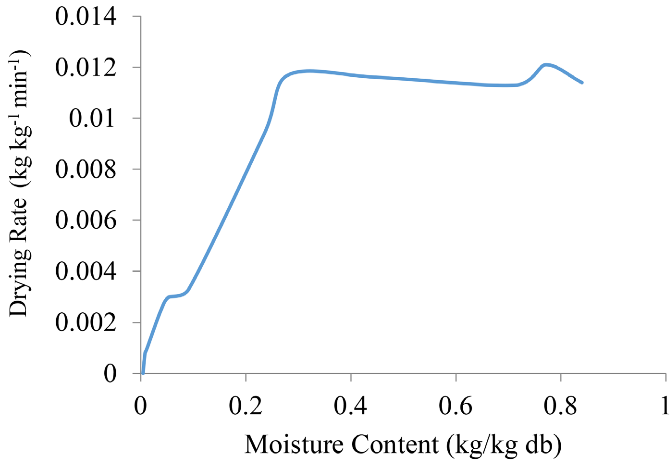


Figure 3. Drying rate curve for bitter kola particulate material.

4. Conclusions

The design of HCHE for the production of hot air was considered as an alternative to conventional heaters and blowers assembly for the production of hot air for fluidized bed. This study was considered to compare the efficiency and economics of HCHE. From the study,

1) The design was efficient and cost-effective for low-temperature applications.

2) The HCHE air output is suitable for laboratory or small-sized fluidized bed dryers due to the volume of air that could pass through the helical coil

3) It also shows that heated air depends on the flow rate and the medium temperature.

4) A mathematical model to estimate the final (output) temperature of air, T_{af}, passing through the coil with mass flow rate m_a was developed.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Abbreviations, Acronyms and Symbols

A—Cross-sectional area of the cylindrical bed (m^2)

A_{step}—Area correspondent to each helical coil step

A_{total}—Total area of the helical coil

Btu—British thermal unit

C—Celsius

Cp_w—Water heat capacity (J/g˚C)

Cp_v—Specific heat of air (J/g˚C)

Cp_c—Specific heat capacity of copper (J/g˚C)

D—Diameter of the cylindrical bed (m)

db—Dry basis

De—Dean Number

d_o—Pipe diameter

D_c—Coil of diameter

D_o—Shell diameter.

D_{noz}—Gas nozzle diameter or the gas entry pipe

D_w—Bed diameter.

F—Fahrenheit

g—Grammes

h—Hour

H—Depth or height of bed (m)

HCHE—Helical coil heat exchanger

HVAC—Heating ventilation and air-conditioning systems,

h_a—Force convection air heat transfer (W/(m^2K))

h_w—Heat transfer of free convection by water (W/(m^2K))

H_t—Bed height (m)

H_w—Distance of the nozzle from the distributor plate

LMTD—Log mean temperature difference

L_B—Operating bed depth (m)

m_c—Mass of copper coil (kg)

m/s—Meters per second

M_a—Air mass flow

M_w—Mass of water

$\dot{m}_a$—Mass flow rate of air

P—Coil pitch

P_{grid}—Pressure drop across the grid (Pa)

Pr—Prandtl number (-)

Re—Reynolds number (-)

Q—Mean heat transfer rate (kW) (kJ/s) (HP) (Btu/s);

t—Time (s)

T_{ai}—Initial air temperature

T_{af}—Air temperature inside the tube

T_c—Initial temperature of coil (˚C)

T_{film}—Film boundary (coil wall) temperature (˚C)

T_{hw}—Water temperature (˚C)

TDH—Transport Disengaging Height

T_m—Log mean temperature difference

U—Overall heat transfer coefficient

Greek Letters

α—Angel of inclination of the coil

Δ—Delta or change

Superscripts

^{0}—Degree