

Theoretical Analysis of Mass and Heat Transfer through a Dehumidifying Plastic Dryer

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Abstract

Dehumidification of plastics resin is utilized to minimize or eliminate problems that may be caused by too much or too little moisture in a plastic material during processing. The extent to which moisture affects the quality of a molded or extruded part is determined by the specific plastic resin being processed and the intended purpose of the part. Regardless, it is highly probable that improper or incomplete drying of the raw material will create problems, whether during processing or when the product is in use, or worse.

Theoretical analysis was carried out on a dehumidify dryer and solution was developed for the problem of simultaneous heat and mass transfer for steady flow in the dehumidifying dryer with a portion of the bed occupied by a porous desiccant medium.

The close form modeling of the bed was found to be dependent on the physical characteristics of the channel and the desiccant together with the fluid to solid mass transfer within the void fraction.

The moisture-loss analysis of a dehumidifying dryer bed and airflow of a dehumidifying dryer was considered to be another fundamental drying parameter. It was discovered that enough airflow is needed through the drying hopper to maintain the plastic pellets at the desired drying temperature for the desired amount of drying time.

Keywords: Dehumidification, Dryer, Porous media, Plastic pellet, Desiccant.

Nomenclature

where,

t_c = Thickness of the Dehumidify Bed channel

t_{po} = Thickness of porous medium

C_p = Specific heat at constant pressure

D_{v-a} = Water vapour-air mass diffusivity

$D_{po(v-a)}$ = Porous media water vapour-air mass diffusivity

Δp = pressure gradient (-ve)

Q_{ad} = Heat of adsorption

K = Thermal conductivity

T = Temperature

t = Time

C_1, C_2 = Equilibrium conditions

x, y = coordinates

m_d = desiccant moisture content

q = Internal heat rate

q_L = bed lower surface heat flux

q_U = bed upper surface heat flux

\dot{m}_{wv} = Rate of production of water vapour

\dot{M}_{wv} = Rate of production of water vapour (dimensionless)

Sh = Sherwood number (dimensionless)

St_m = mass transfer - Stanton number (dimensionless)

m = water vapour mass fraction

\dot{q} = Internal heat rate (dimensionless)

u = velocity

u_b = bulk velocity

ρ = density

ψ = permeability

$\delta = \frac{\psi}{b^2}$ = permeability of the material (dimensionless)

α = thermal diffusivity

$\sigma = \frac{\mu_f}{\mu_{po}}$ = ratio of viscosity of fluid to void region

ε = diffusivity ratio

Δt = change in time

$\gamma = \frac{K_f}{K_{po}}$ = ratio of thermal conductivity of fluid to porous region

F = Fluid region

po = Porous media region (void fraction)

I. INTRODUCTION

The increase in the world population coupled with the rise in the standard of living obviously will increase the need for drying technologies. It is extremely difficult to predict the direction drying technologies will take in the next several decades. Most of the developments in this field have occurred between 1978 and 1988. New demands will be made on better energy efficiency, lower environmental impact through legislative measures, utilization of renewable energy for drying, and better-quality products at lower total costs.

Drying process is an energy intensive activity and plays a significant role in many industrial applications such as in plastic, food, paper, textile and in many other processing industries. The largest amount of investment is often spent on the drying operation itself, not the initial installation of equipment. Operations such as papermaking hold 35% of the energy consumption, whereas chemical processing only uses under 5%.

In general, the current drying processes are very inefficient. Typically, the energy efficiency is between 20% and 60% [1], depending on the type of dryer and product used for drying. Stefano De Antonellis [2] developed and investigated the simulation and energy efficiency analysis of desiccant wheel systems for drying processes of hybrid dryer system configurations based on desiccant wheels and the evaluation of primary energy consumption for different hybrid dryer systems. Both aim to reduce the overall energy consumption and both the simulation and analysis processes operate on similar ideas and use two comparable control parameters.

A lot of efforts have been made by researchers to understand the mass diffusion mechanism in solid particles and methodology for the determination and measurement of the mass diffusion coefficients for certain materials. The problem is due to the lack of accurate information to account for the transfer resistance inside desiccant particles. For solid particles resistance analysis, many different models have been proposed. For example, Pseudo-Gas-Side Controlled model by Hougen and Marshall [3], Surface diffusion resistance model by Kruckels, [4], Solid-side resistance model by Pesaran, [5] and the parabolic concentration profile model by Chant, [6]. Some models got poor prediction results.

San and Jiang [7] modeled and tested a two-column packed-bed silica gel dehumidification system. Desiccants were continuously switched between adsorption and desorption in two desiccant columns. The SSR model was used to simulate this cyclic process and periodic steady-state solutions were obtained. The effect of fluid friction on solid side resistance was given more attention when developing the heat and mass transfer model.

Jurinak [8] used an analogy solution of a rotary heat and mass exchanger and the finite difference method to simulate a counter-flow rotary dehumidifier. The desiccant matrix's properties were analyzed in detail from the aspects of isotherm shape, the heat of sorption, the maximum sorbent water content, sorption isotherm hysteresis, matrix moisture diffusivity and matrix thermal capacitance. In order to determine the desired drying temperature and drying time for the plastic pellets together with dehumidifying water vapour mass fraction and

velocity of the dryer, this study carried out the mathematical model of the dehumidification process encountered in the plastic industry.

II. CREATION OF PLASTIC PELLETS

A plastic pellet is a popular material made from petroleum products, used in the production of plastic bottles and containers. It exists as a clear amorphous material or in semi-crystalline state that is often, though not always, opaque milky white. The intrinsic viscosity of the Pellets resin is probably its most important characteristic. The intrinsic viscosity is an indication of the average length of the pellets polymer chains. The higher the intrinsic viscosity, the longer the polymer chains and the higher the performance characteristics it will possess.

Intrinsic viscosity retention of the pellets during processing is critical; anything that may degrade or lower it during processing must be monitored and controlled, and the most common cause of intrinsic viscosity degradation is the presence of water in the pellets. The pellets are lipophilic which means that they readily adsorb chemicals from the surrounding seawater which bond on its surface. The Pellets is extremely sensitive to absorbed water, and one of the toughest challenges to dry. It causes hydrolytic degradation at elevated melt temperatures. Thus, the most important issue is proper drying prior to melt processing.

It is known that common chemicals that accumulate on the pellets can be highly toxic with concentrations on the pellets up to a million times the level of the surrounding seawater. These chemicals are known as Persistent Organic Pollutants (POPs) and include PCBs (Poly Chlorinated Bromide) which are chemicals such as flame retardants, DDT an insecticide that was banned in the 1970s after it was routinely used worldwide and PAH (Polycyclic Aromatic Hydrocarbon) which are created when products like coal, oil, gas, and garbage are burned [11].

Pellets can also have chemicals added to them during the manufacturing process, chemicals such as Nonylphenol (NP) is used as an antioxidant and plasticizer in some plastic products and has known endocrine-disrupting potential.

The creation of plastic pellets is currently widely practiced, but only on an industrial scale. The pellets created get processed by dehumidifying them at 120°C for 5 hours and then sent into an extrusion barrel at 260°C, resulting in pellets with diameters between 2 mm and 3 mm [9]. Dehumidifying the plastic serves to remove moisture from the plastic. Moisture in the resin creates pellets of inconsistent quality. The process takes place at 120°C as to not

break the polymer chains inside the material. Dehumidifying at a higher temperature would take less time but degrade material properties. The extrusion barrel operates at the melting point of the pellet to increase formability. While the Poly Pelletizer does not utilize a dehumidifying stage, the 2 shreds are stored in a dry environment for at least a week before utilization for testing. The system operated as close to the temperature of the extrusion barrels used in industry to most closely emulate the process. During conventional ways of extrusion such injection-molding or pelletizing of recycled plastics, there is a significant degradation of the material properties. The more times that a plastic is melted down, the more that the polymer chains it consists of will break down. If this is done at too high a temperature, or done too many times, the material properties will become unusable [10]. The Poly Pelletizer sought to minimize this issue by operating as close to the melting point of the plastic as possible to prevent further breaking of polymer chains. Throughout the world, we find high amounts of plastic pollution in our environment which requires an efficient and practical way to recycle it. It is extremely important to separate the different types of plastics before proceeding with any recycling processes because having the wrong types of plastics mixed together in certain processes can ruin the resulting product. Another important process is cleaning the plastics before trying to recycle them. If there are other substances such as glues or oils, they will degrade the material properties of the plastic once recycled and reprocessed [11]. These practices are all being implemented in the Poly Pelletizer project.

A. The Basics of Drying Plastic Pellets

When a **Plastic** pellet is exposed to the atmosphere it will readily absorb water vapor from the surrounding air due to its hygroscopic nature. The migration of water vapor into the pellets occurs over time and will eventually slow and stop when the moisture content reaches a state of equilibrium with that of the surrounding air. At the equilibrium point, the water vapor within the granule will be evenly distributed throughout the pellet's interior [9].

The water molecules around the pellets are attracted to the polymer chains, forming a strong intermolecular bond as shown in Figure 1. That bond is what makes the drying of **Plastic** Pellets very difficult. Even a small amount of moisture in the pellets will cause a chemical reaction (hydrolysis) when the polymer is heated above its melt temperature.

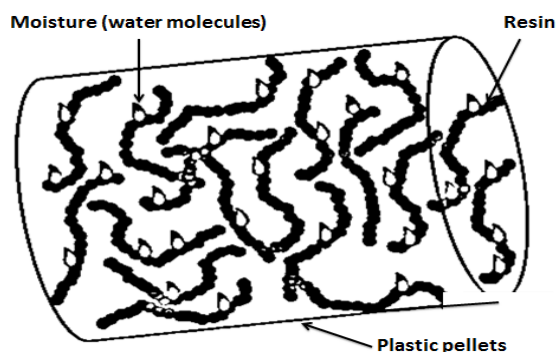


Fig. 1: Water Molecules Bond to the Plastic Polymer Chain

The drying process involves four fundamental parameters:

- (i) Drying temperature
- (ii) Dew point
- (iii) Drying time
- (iv) Airflow

Temperature is probably the major consideration in drying any hygroscopic polymer. When the temperature of **Plastic** Pellets is increased, its molecules will begin to move about more vigorously, reducing the attraction the water molecules have for the polymer chains, and allowing the water molecules to escape the bonds, as shown in Figure 2.

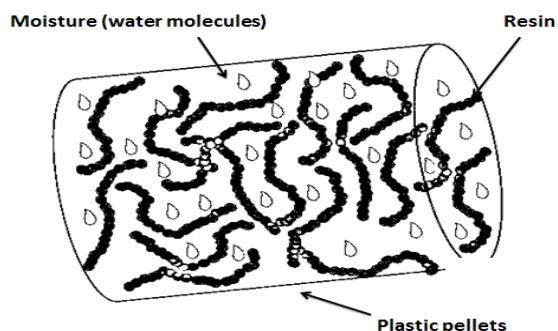


Fig. 2: Hot drying air loosen the bonds between moisture and the resin, allowing the molecules to move freely through the pellet

The polymer temperature therefore has a very strong influence on the diffusion rate of the water molecules through the polymer. The water molecules can travel more freely through the polymer at higher temperatures, when the polymer's attraction for the water molecules has been reduced.

Heating the pellets to the optimum recommended drying temperature is a prerequisite to good drying. The higher the drying temperature, the more quickly and thoroughly the pellet will dry. There are, however, practical limitations to the range of drying temperatures acceptable for the pellet. If the drying temperature is too high, thermal degradation and/or

oxidation may occur. If the drying temperature is low, the pellet will give up its moisture more slowly.

The dew point temperature is the second fundamental drying parameter. This term describes the moisture content of the drying air. The dew point temperature is the “saturated air temperature” at which condensation will occur. For example, if you were to gradually reduce the air temperature of the room in which you are sitting, you would eventually reach a temperature at which condensation would occur. This is called the saturated air temperature, or dew point.

Another more common example: When you leave the house on an early summer morning and see “dew” on the grass it is because the temperature of the air fell below the saturated air temperature or dew point during the night and condensation occurred.

How does the low-dew point air from a dryer remove the moisture from the pellets in the drying hopper? First, the drying air is dehumidified to very low residual moisture content by filtering the air through a moisture-adsorbing desiccant material. Then, the drying air is heated to the desired drying temperature. Heating the dehumidified air reduces its relative humidity to an extremely low level and further increases the drying air’s moisture-absorption capacity.

When pellets are surrounded with low-dew point air, which has been heated to 300 degree Fahrenheit or higher, the vapor-pressure differential between the surface of the pellets and the drying air is greatly increased. Once the polymer has been heated and the attraction between the water molecules and the polymer chains has been sufficiently reduced, the freed water molecules will begin to migrate toward the area of low vapor pressure at the surface of the pellets, as shown in Figure 3. When the water molecules reach the surface of the pellets they will be quickly swept away by the drying air.

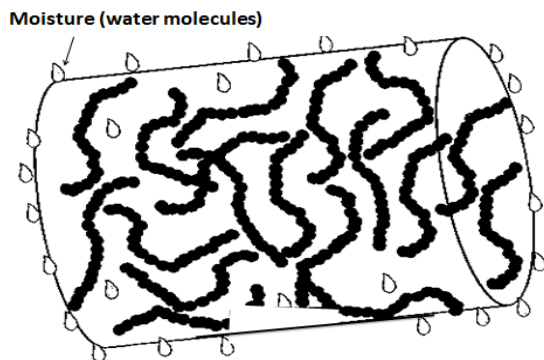


Fig. 3: Stream of dry air swept away the moisture content at the plastic pellets surface

The pellets do not dry instantaneously; the drying time, which is the third fundamental drying parameter, is critical to the drying process. When the pellets in the drying hopper have been surrounded with a steady stream of heated, low-dew point air, sufficient time must be provided to allow the heat from the surrounding air to migrate to the interior of the pellets.

The pellets do not conduct heat very well. It therefore takes time for the heat from the surrounding air to be absorbed and distributed throughout the pellet’s interior.

It is important to note that the time the pellets spend in the drying hopper is not necessarily effective drying time. The effective drying time is the amount of time the pellets are exposed to air at the correct drying temperature and dew point while in the drying hopper [9].

Figure 4 is a visual representation of low airflow, excessive airflow, and optimum airflow within a drying hopper. The drying hopper with low airflow will not provide enough drying time at the desired drying temperature. The drying hopper with excessive airflow is heating all of the material within the hopper to the set point drying temperature and wasting energy by passing excessive heat back to the dryer. The drying hopper with optimum airflow is developing a vertical temperature profile that is providing the desired amount of drying time and using the fresh, cool incoming material as a heat sink to cool the return air leaving the drying hopper.

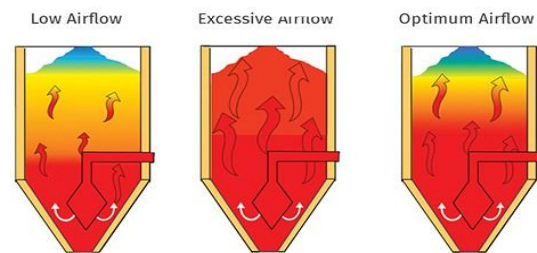


Fig. 4: The Importance of Proper Airflow: Insufficient airflow (left), Excessive airflow (center) and optimal airflow (right)

III. OPERATING A DEHUMIDIFYING DRYER

There are three air circuits in a well-designed dehumidifying dryer:

- (i) Closed-loop drying-air circuit
- (ii) Single-pass regeneration-air circuit
- (iii) Desiccant cooling circuit

The drying air entering the drying hopper has been dehumidified to a low dew point and heated to the selected drying temperature prior to entering the drying hopper as shown in Figure 5.

The hot, dry air enters the drying hopper and is dispersed throughout, enveloping each and every Plastic pellet within the hopper. As the hot, dry air travels upward through the hopper, the drying air gives up its heat to the pellets.

As the wet incoming pellets begin to absorb the heat from the drying air, they will begin to give up their moisture to the hot, low-dew point drying air.

When the drying air exits the top of the hopper, it has given up a substantial amount of its heat to the pellets, and in exchange the drying air has absorbed the moisture given up by the resin.

Nearly all dehumidifying polymer dryers used in the plastics industry utilize a closed-loop drying-air circuit. The reason for this is that the moisture content of the air exiting the top of the drying hopper will always be drier than the ambient air. The dew point levels in the return-air circuit of a typical plastic drying system are usually in the range of zero to -29 degree Celsius while ambient dew point levels usually run much higher.

Therefore, it makes economic sense to employ a closed-loop drying-air circuit to salvage and reuse the moderately dry return air exiting the drying hopper rather than using much wetter ambient air in a single-pass drying-air circuit.

The Dust Collector shown in Figure 5 is critical to long-term performance of the heat exchanger. Incoming containers of virgin pellets will commonly contain fines, and reground scrap plastics often contains large quantities of fines. If these fines are allowed to enter the return-air heat exchanger, many of the fines will adhere to the cooling coils of the heat exchanger. Over a period of time the fines will build up and insulate the cooling coils from the air passing through the heat exchanger, reducing the device's efficiency. Therefore, it is a good decision to include a dust collector in the system to keep the cooling coils clean and free of fines.

Typical Plastic drying temperatures range from 149 to 177 degree Celsius. When the drying air exits the top of the drying hopper, it has already given up a substantial amount of its heat content to the pellets. The air temperature exiting the top of a typical plastic drying hopper will normally be in the range of 93 to 121 degree Celsius. Even at that reduced temperature, the air is still too hot to return it directly to the dehumidifying dryer.

Dehumidifying dryers are sensitive to high return-air temperatures. The reason is the desiccant's moisture-adsorbing performance is greatly compromised when operating at high temperatures, and it is enhanced when operating at relatively low temperatures.

The optimum return-air temperature is in the range of 38 to 54 degree Celsius, where the dryer's desiccant is capable of adsorbing approximately 15% of its own weight in water.

A dehumidifying dryer's desiccant is sensitive to contamination. The purpose of the return-air filter is to protect the dryer's desiccant. If the plastic fines are allowed to bypass the dryer's return-air filters and enter dryer's desiccant, the fines will build up and restrict air flow through the desiccant. Depending on the regeneration temperature, the fines may begin to melt or release volatiles and permanently damage the desiccant. Therefore, it is critical that any fines present in the return air be filtered out before the air reaches the desiccant.

The dryer's return-air filter is the second filter in a plastic dryer's return-air circuit, the first being the dust collector. As a general statement, the return-air filters are the most service-intensive components of a plastic pellet dryer. Depending on the amount of fines in the material being dried, the return-air filter may require cleaning or replacement as frequently as every shift or as little as every several months.

Maintaining the dryer's unrestricted airflow is critical to its performance. The only prudent way to determine a reasonable schedule for filter maintenance is to monitor the condition of the return-air filter on a daily basis over a period of time. Then develop a filter maintenance schedule that fits your application.

The air blower moves the drying air through the drying-air circuit. The dryer's blower must move a large enough volume of air through the drying-air circuit to overcome the heat losses in the dryer, air-delivery tubing, and the sidewalls of the drying hopper.

The dryer's blower must also move a large enough volume of air to heat the incoming pellet material from its initial temperature (usually ambient) to the desired drying temperature of 149 to 177 degree Celsius. The blower must also be able develop enough pressure to force the requisite volume of airflow through the drying hopper, which could be as high as 20 to 30 inches of water column when a heavy loading of regrind and fines is being dried.

The desiccant is the heart of the dehumidifying dryer. It is the substance that removes the moisture from the

drying air that is returning from the drying hopper. This moisture needs to be removed from the return air in order to reduce the air's dew point back into the range of -34 to -40 degree Celsius.

The most common type of desiccant used in dehumidifying-air polymer dryers is molecular-sieve desiccant made from a synthetic zeolite material. The molecular sieve will filter out molecules from the drying air that are smaller than the desiccant's pores.

Manufacturers of plastic bottles used for soft drinks and water are concerned with the acetaldehyde (AA) levels in the plastic preforms they are producing because AA will change the flavor of the bottled drink. Virgin plastic pellet normally has AA levels in the range of 1 to 3 ppm, while reground plastic pellet may have an AA level of 10 to 15 ppm or more. Dryers used for plastic bottle production usually employ a 13X desiccant, which adsorbs both AA and water molecules from the dryer's return-air circuit.

Typical pellet drying temperatures are in the range of 149 to 177 degree Celsius. Either electrical or natural-gas heaters can be employed in a plastic pellet dryer. Electrical heaters are less complex and less costly than gas heaters, but their downside is the skyrocketing cost of electricity. Depending on your location, the cost of electricity can be several times more than natural gas.

An indirect heat exchanger in the drying-air circuit separates the combustion air from the drying air, which will guarantee no combustion exhaust gases will come into contact with and contaminate the pellet being dried.

An indirect heat exchanger in the regeneration-air circuit is also important. It separates the combustion air from the regeneration air, which will guarantee that no combustion exhaust gases will come into contact with your dryer's desiccant.

The regeneration-air circuit of a pellet dryer utilizes ambient plant air in a single-pass circuit to purge the adsorbed moisture from the desiccant out to the atmosphere.

Regeneration air is drawn in from the atmosphere and first filtered of any possible contaminants prior to contacting the desiccant.

The regeneration blower moves the air through the single-pass regeneration-air circuit. A sufficient volume of airflow is required to elevate the desiccant's temperature in order to heat the desiccant and purge its adsorbed moisture.

Heating the desiccant to a high temperature is necessary for regeneration. These heaters must have enough heating capacity to raise the temperature of the regeneration air to the factory-set regeneration temperature in order to achieve complete desiccant regeneration.

As the temperature of the desiccant is increased it will begin releasing its adsorbed moisture. The released moisture will be purged to the atmosphere through the moisture exhaust port.

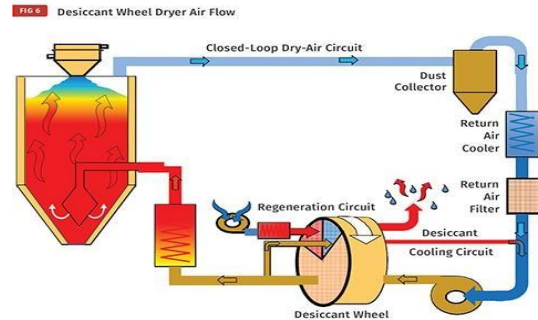


Fig. 5: Closed – Loop Drying-Air Circuit

IV. DEHUMIDIFYING PLASTIC DRYER BED MODEL GOVERNING EQUATIONS

The equations are written for both fluid and porous region separately as shown in the model in Figure 6 and then introduce proper boundary conditions at the interface for solutions. The fluid flow into the channel is assumed to be steady with regards to heat and mass transfer.

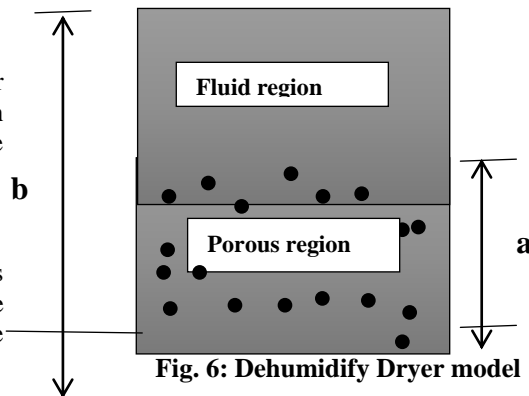


Fig. 6: Dehumidify Dryer model

Porous Region: Conservation equation for the porous region of the dehumidifying bed can be written as follows:

$$\left(\frac{d^2 u}{dy^2} \right)_{p_o} - \left(\frac{\sigma}{\psi} u \right)_{p_o} = \frac{1}{\mu} \Delta p \dots \dots \dots (1)$$

$$\left[(\rho C_p) u_{p_o} \frac{dT}{dx} \right] = K_{p_o} \frac{d^2 T_{p_o}}{dy^2} + \dot{q} \dots \dots (2)$$

$$u_{po} \frac{dm}{dx} = D_{po(v-a)} \frac{d^2 m_{po}}{dy^2} + \frac{\dot{m}_{wv}}{\rho} \dots\dots\dots (3)$$

The conservation equation for the fluid portion of the dehumidifying bed channel is as follows:

$$\mu \left[\frac{d^2 u}{dy^2} \right]_F = -\Delta p \dots\dots\dots (4)$$

$$\left[u_F \frac{dT}{dx} \right] = \alpha_F \frac{d^2 T_F}{dy^2} \dots\dots\dots (5)$$

$$u_F \frac{dm}{dx} = D_{(v-a)} \frac{d^2 m_F}{dy^2} \dots\dots\dots (6)$$

The rate of production of water vapour and heat rate are the source term and can be written as follows:

$$\dot{m}_{wv} = (\rho u)_{po} St_m \sum m_{po,s} - m_{po,b} \dots\dots (7)$$

$$\dot{q} = h_{ads} \left((\rho u)_{po} St_m \sum m_{po,s} - m_{po,b} \right) \dots (8)$$

Where,

St_m = Stanton number for mass transfer between the solid and fluid in the void fraction

h_{ads} = enthalpy of the adsorption for the desiccant

Boundary conditions:

At $y = 0$, $u_{po} = 0$, and $K_m \frac{dT_{po}}{dy} = -q_L$

$$\frac{dm_{po}}{dy} = 0 \dots\dots\dots (9)$$

At $y = b$, $u_F = u_{po}$, and $\sigma \frac{du_f}{dy} = \frac{du_{po}}{dy}$

$$T_f = T_{po}, \text{ and } \gamma \frac{dT_f}{dy} = \frac{dT_{po}}{dy}$$

$$m_f = m_{po}, \text{ and } \varepsilon \frac{dm_f}{dy} = \frac{dm_{po}}{dy} \dots\dots\dots (10)$$

At $y = a$, $u_F = 0$, and $K_f \frac{dT_F}{dy} = q_v$

$$\frac{dm_f}{dy} = 0 \dots\dots\dots (11)$$

Carrying an energy and mass balance on the channel element Δx of the bed, the following expressions were obtained:

$$\frac{dT_b}{dx} = \frac{1}{(\rho C_p)_F u_b} [q_L + q + b\dot{q}]$$

$$\frac{dm_b}{dx} = \frac{1}{\rho u} \frac{t_{po}}{t_c} \dot{m}_{wv} \dots\dots\dots (12)$$

The boundary conditions and the governing equations of the dehumidifying bed were made dimensionless to produce the following relation.

as y tends to ay , $\Delta p \rightarrow \frac{\mu_F \alpha_F}{a^3} \Delta p$

as u tends to $\frac{\alpha_F u}{a}$, $T \rightarrow \frac{(q_L + q_U) a}{K_F} T \dots\dots (13)$

The conservation equation 's scaling gives:

$$\left[\frac{d^2 u}{dy^2} \right]_F = -\Delta P \dots\dots (14)$$

$$\left[\frac{d^2 T}{dy^2} \right]_F = \frac{u_F}{u_b} (1 + \dot{q}) \dots\dots\dots (15)$$

$$\frac{d^2 m_F}{dy^2} = \varepsilon \dot{M}_{wv} \left[\frac{u_F}{u_b} \right] \left[\frac{t_{po}}{t_c} \right] \dots\dots\dots (16)$$

$$\frac{d^2 u_{po}}{dy^2} - \left[\frac{\frac{\mu_F}{\mu_m}}{\frac{\psi}{b^2} \left(\frac{t_{po}}{t_c} \right)^2} \right] u_{po} = -\frac{\mu_F}{\mu_m} \Delta p \dots\dots (17)$$

$$\frac{d^2 T_{po}}{dy^2} = \frac{K_F}{K_m} \left[\left(\frac{u_{po}}{u_b} \right) (1 + \dot{q}) - \frac{t_c \dot{q}}{t_{po}} \right] \dots\dots (18)$$

$$\frac{d^2 m_{po}}{dy^2} = \dot{M}_{wv} \left[\left(\frac{u_F}{u_b} \right) \left(\frac{t_{po}}{t_c} \right) - 1 \right] \dots\dots\dots (19)$$

where,

$$\dot{M}_{wv} = \frac{\dot{m}_{wv} a^2}{\rho D_{po(v-a)}} \dots\dots\dots (20)$$

$$\dot{q} = \frac{b q}{q_L + q_U} \dots\dots\dots (21)$$

Since, $q = Q_{ad} \dot{m}_{wv} = \frac{\rho Q_{ad} D_{v-a}}{a^2} \dot{M}_{wv} \dots\dots (22)$

$$\therefore \dot{q} = \frac{b \dot{M}_{wv} \rho Q_{ad} D_{po(v-a)}}{(q_L + q_U) a^2} \dots\dots\dots (23)$$

The fluid total velocity for the entire dehumidifying bed channel can be written as:

$$u_b = \int_0^\eta u_{po} dy + \int_\eta^1 u_F dy \dots\dots\dots (24)$$

Using factor analysis, the boundary conditions becomes:

at $y = 0$, $u_{po} = 0$,

$$\frac{dT_{po}}{dy} = - \left[\frac{K_F \left(\frac{q_L}{q_V} \right)}{K_m \left(\frac{q_V}{q_V} \right)} \right]$$

$$\frac{dm_{po}}{dy} = 0 \dots\dots\dots(25)$$

at $y = \eta$,

$$u_F = u_{po}, \quad \sigma \frac{du_F}{dy} = \frac{du_{po}}{dy}$$

$$T_F = T_{po}, \text{ and } \gamma \frac{dT_F}{dy} = \frac{dT_{po}}{dy}$$

$$m_F = m_{po}, \text{ and } \varepsilon \frac{dm_F}{dy} = \frac{dm_{po}}{dy} \dots\dots\dots(26)$$

At $y = 1$, $u_F = 0$, and $\frac{dT_F}{dy} = \frac{1}{1 + \frac{q_L}{q_U}}$

$$\frac{dm_F}{dy} = 0 \dots\dots\dots(27)$$

Therefore, the dimensionless rate of water vapour production gives:

$$\dot{M}_{wv} = \frac{a^2 (\rho u_{po} S t_m)}{\rho D_{po(v-a)}} \sum (K_1 T_{po} + K_2 - m_{po}) \dots\dots\dots(28)$$

V. RESULTS AND DISCUSSIONS

The fluid flow in the dehumidifying bed has a governing equation with solutions and this was obtained by solving for the velocity field and bulk velocity analytically followed by the energy and mass species equation. Finally, the bulk temperatures and bulk water vapour mass fraction were calculated. The velocity in the fluid region was obtained as follows:

$$u_F = - \frac{\Delta P}{2} (y^2 - 1) + c_1 (y - 1) \dots\dots\dots(29)$$

Where, $c_1 = G_F \Delta p$

$$\text{and } G_F = \left[\frac{t_{po}}{t_c} - 1 - \frac{\tanh\left(\beta \frac{t_{po}}{t_c}\right)}{\beta} \sigma \right]^{-1} \left[\left\{ \left(\frac{t_{po}}{t_c} \right)^2 - 1 \right\} 2 + \frac{\psi}{b^2} \left(\frac{t_{po}}{t_c} \right) - \sigma \left(\frac{t_{po}}{t_c} \right) \frac{\tanh\left(\beta \frac{t_{po}}{t_c}\right)}{\beta} \right]$$

$$- \left(\frac{t_{po}}{t_c} \right) \frac{\psi}{b^2} \text{Cosh}\left(\beta \frac{t_{po}}{t_c}\right) + \frac{\tanh\left(\beta \frac{t_{po}}{t_c}\right)}{\beta} \left(\frac{\psi}{b^2} \right) \text{Sinh}\left(\beta \frac{t_{po}}{t_c}\right) \dots\dots\dots(30)$$

The velocity in the porous region was obtained as follows:

$$u_{po} = \Delta p \delta \left(\frac{t_{po}}{t_c} \right)^2 [1 - \text{Cosh}(\beta y)] + c_2 \text{Sinh}(\beta y) \dots\dots\dots(31)$$

Where, $c_2 = G_{po} \Delta p$

$$G_{po} = \frac{\sigma \left[\frac{\tanh\left(\beta \frac{t_{po}}{t_c}\right)}{\beta} \right] \left(G_F - \frac{t_{po}}{t_c} \right)}{\text{Sinh}(\beta)} + \frac{\psi}{b^2} \left(\frac{t_{po}}{t_c} \right)^2 \frac{\tanh\left(\beta \frac{t_{po}}{t_c}\right)}{\beta} \dots\dots\dots(32)$$

$$\text{Where, } \beta = \sqrt{\frac{\alpha \left(\frac{t_{po}}{t_c} \right)^2}{\frac{\psi}{b^2}}} \dots\dots\dots(33)$$

Therefore, the solution of the velocity in the fluid region with respect to the dimensionless bulk velocity gives:

$$\frac{u_F}{u_b} = [z_F + z_{po}]^{-1} \left[- \frac{y^2}{2} + G_F \right] \dots\dots\dots(34)$$

where,

$$z_F = \int_0^1 \left\{ - \frac{y^2}{2} + G_F y + \frac{1}{2} - G_F \right\} dy \dots\dots\dots(35)$$

Also, the solution of the velocity in the porous region with respect to the dimensionless bulk velocity gives:

$$\frac{u_{po}}{u_b} = [z_F + z_{po}]^{-1} \left[\frac{\psi}{b^2} \left(\frac{t_{po}}{t_c} \right)^2 \{1 - \text{Cosh}(\beta y)\} + G_{po} \text{Sinh}(\beta y) \right] \dots\dots\dots(36)$$

where,

$$z_{po} = \int_0^\eta \left\{ - \frac{\psi}{b^2} \left(\frac{t_{po}}{t_c} \right)^2 \text{Cosh}(\beta y) + G_{po} \text{Sinh}(\beta y) + \frac{\psi}{b^2} \left(\frac{t_{po}}{t_c} \right) \right\} dy \dots\dots\dots(37)$$

The mass fraction of the water vapour for the fluid region can be written as:

$$m_F = \varepsilon \dot{M}_{wv} \frac{t_{po}}{t_c} [z_F + z_{po}]^{-1} \left\{ \frac{\left(y^4 - \left(\frac{t_{po}}{t_c} \right)^4 \right) G_F \frac{y^3}{3}}{24} + \frac{\left(\frac{t_{po}}{t_c} \right)^3}{6} (1 - 2G_F) \left(y^2 - \left(\frac{t_{po}}{t_c} \right)^2 \right)}{4} + \frac{(2 - 3G_F) \left(y - \frac{t_{po}}{t_c} \right)}{6} \right\} + m_i \dots\dots\dots(38)$$

Also the mass fraction of the water vapour for the porous region can be written as:

$$m_{po} = \dot{M}_{wv} \frac{t_{po}}{t_c} [z_f + z_{po}]^{-1} \left\{ \frac{\left(\frac{\psi \left(\frac{t_{po}}{t_c} \right)^2 \left(y^2 - \left(\frac{t_{po}}{t_c} \right)^2 \right)}{b^2 \left(\frac{t_{po}}{t_c} \right)} \right)}{2} + \frac{G_{po} \left(y - \frac{t_{po}}{t_c} \right) - \frac{\psi \left(\frac{t_{po}}{t_c} \right)^2}{b^2 \left(\frac{t_{po}}{t_c} \right)} \left(\text{Cosh}(\beta y) - \text{Cosh} \left(\beta \frac{t_{po}}{t_c} \right) \right)}{\beta^2} + \frac{y^2 - \left(\frac{t_{po}}{t_c} \right)^2}{2} + m_i \right. \\ \left. + \frac{G_{po}}{\beta^2} \left(\left(\text{Sinh}(\beta y) - \text{Sinh} \left(\beta \frac{t_{po}}{t_c} \right) \right) \right) \right\} \dots\dots\dots(39)$$

when $y = \frac{t_{po}}{t_c}$, $m_F = m_{po} = m_i$ (40)

By integrating the energy equations twice, the equation to determine temperature of the fluid region was determined:

$$T_f = (1 + \dot{q}) [z_f + z_{po}]^{-1} \left\{ \frac{\left[\frac{y^4 - \left(\frac{t_{po}}{t_c} \right)^4}{24} + \frac{G_f \frac{y^3}{6} - \left(\frac{t_{po}}{t_c} \right)^3}{6} + \frac{(1 - 2G_f) \left(y^2 - \left(\frac{t_{po}}{t_c} \right)^2 \right)}{4} \right]}{1 + \frac{q_L}{q_U}} + T_i \right. \\ \left. + \frac{(2 - 3G_f) \left(y - \frac{t_{po}}{t_c} \right)}{6} \right\} \dots\dots\dots(41)$$

$$T_{po} = \frac{K_f}{K_m} (1 + \dot{q}) [z_f + z_{po}]^{-1} \left\{ \frac{\left(\frac{\psi \left(\frac{t_{po}}{t_c} \right)^2 \left(y^2 - \left(\frac{t_{po}}{t_c} \right)^2 \right)}{b^2 \left(\frac{t_{po}}{t_c} \right)} \right)}{2} - \frac{1}{\beta^2} \left(\text{Cosh}(\beta y) - \text{Cosh} \left(\beta \frac{t_{po}}{t_c} \right) \right) \right\} \\ + \frac{G_{po}}{\beta^2} \left(\left(\text{Sinh}(\beta y) - \text{Sinh} \left(\beta \frac{t_{po}}{t_c} \right) \right) \right) - \frac{y^2 - \left(\frac{t_{po}}{t_c} \right)^2}{2 \left(\frac{\psi}{b^2} \right)} \\ - \frac{\frac{\psi}{b^2} \left(\frac{q_L}{q_U} \right) \left(y - \frac{t_{po}}{t_c} \right)}{1 + \frac{q_L}{q_U}} + T_i \dots\dots\dots(42)$$

∴ $T_F = T_{po} = T_i$ when $z = \frac{t_{po}}{t_c}$ (43)

The water vapour production rate of the channel was determined using the equation:

$$\dot{M}_{wv} = \frac{u_{b,po} a^2}{D_{v-a}} St_m \sum [K_1 T_{po,b} + K_2 - m_{po,b}] \dots\dots(44)$$

Also, the internal heat rate of the channel was determined using the equation:

$$\dot{q} = \frac{b Q_{ad}}{q_L + q_U} \rho u_{b,po} St_m \sum [K_1 T_{po,b} + K_2 - m_{po,b}] \dots\dots(45)$$

The mass fraction of fluid in porous region can be written as:

$$\frac{dm_{po,b}}{dx} = \frac{t_{po}}{\rho u_b} \rho u_{b,po} St_m \sum [K_1 T_{po,b} + K_2 - m_{po,b}] \dots\dots(46)$$

Also the bulk temperature of fluid in porous region can be written as:

$$\frac{dT_{po,b}}{dx} = \frac{q_L + q_U}{\rho C_p u_b a} + \frac{Q_{ad}}{\rho C_p u_b a} \rho u_{b,po} St_m \sum [K_1 T_{po,b} + K_2 - m_{po,b}] \dots\dots\dots(47)$$

Equations (46) and (47) can be finally solved numerically to determine the equation that governs the temperature and the mass fraction of fluid in the porous region of the dehumidifying bed dryer. This results in dehumidification of plastics.

An expression for Sherwood number for the mass transfer from the porous region of the dehumidifying bed channel to the fluid region can be derived from the solution of temperature and mass transfer of the bed.

$$Sh = \frac{k}{a \rho D_{v-a}} = \frac{m_{b,F} - m_i}{\frac{dm_F}{dy}} \quad \text{when } y = \frac{t_{po}}{t_c} \dots\dots\dots(48)$$

Figure 7 shows the moisture-loss analysis of a dehumidifying dryer bed. Small samples of the plastic pellet being dried were taken from the hopper every hour during static drying and the residual moisture was analyzed. The drying parameters are described on the chart attached to the figure. The dramatic drop in residual moisture was experienced during the first hour of drying, from 0.18% to 0.04%, after which the rate of decline slows significantly, requiring another 4 hour to drop below the desired moisture level of 0.005%

The airflow of a dehumidifying dryer is another fundamental drying parameter to be considered. This is absolutely crucial to the drying process. The airflow of a dehumidifying dryer is the medium that transfers the heated, low-dew point drying air from the dryer to the pellets in the drying hopper. Insufficient airflow will not transfer enough heat from the dryer's heat source to the pellets in the drying hopper. With insufficient airflow through the drying hopper, the system will not be able to maintain the desired vertical temperature profile within the hopper to provide the required drying time.

Excess airflow will transfer an excessive amount of heat from the dryer's heaters to the bed of material in the drying hopper. The excess heat that is not absorbed by the pellets will exit the drying hopper, resulting in high return-air temperatures, poor desiccant performance, wasted heat energy, high

dryer operating costs, and the possibility of overheating and damaging the dryer's process-air blower.

The volume of airflow needed to adequately dry the pellets will vary from one drying system to the next, depending upon several factors, including the incoming pellet temperature, drying hopper design, heat losses within the drying system, and hourly throughput (kg/hr) through the hopper. Enough airflow is needed through the drying hopper to maintain the pellets at the desired drying temperature for the desired amount of drying time.

The desiccant's temperature on completion of the regeneration cycle is elevated and its residual moisture content is at a very low level. The desiccant must be cooled prior to being moved into the process-air stream as shown in Figure 8. If hot desiccant is moved into the on-stream position it will not adsorb moisture from the air returning from the drying hopper. The moisture present in the air returning from the hopper will pass right through the hot desiccant, resulting in high-dew point air being recirculated into the drying hopper. A small controlled volume of air from the drying-air circuit is bled through the desiccant in the cooling position. Some older designs of dryers use ambient air to cool the desiccant after regeneration, which results in preloading the desiccant with some ambient moisture as the desiccant's temperature is reduced during cooling.

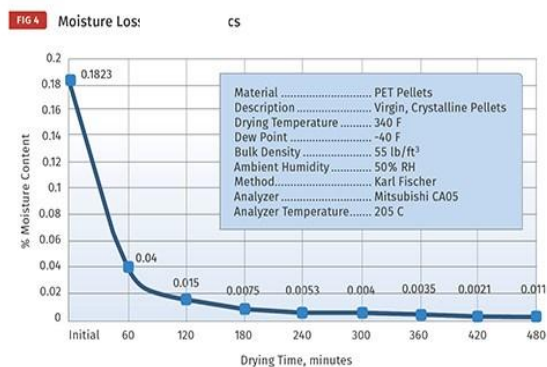


Fig. 7: Effects of Drying Time on Moisture Content

The benefit of cooling the hot, freshly regenerated desiccant with a slipstream from the drying-air circuit is that the desiccant is being cooled with the moderately dry air from the dryer's return-air circuit, rather than ambient plant air, which may have very high moisture content, depending on local weather conditions.

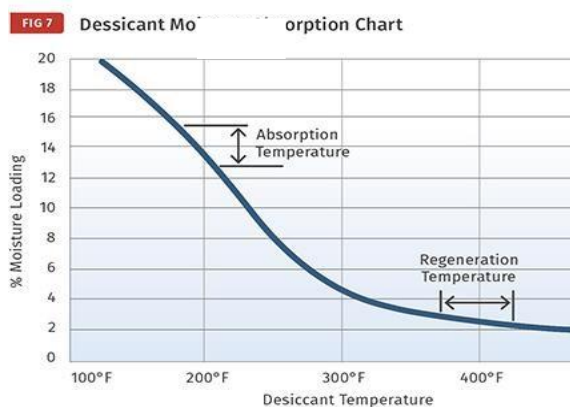


Fig. 8: Effects of Percentage Moisture Loading on Desiccant Temperature

VI. CONCLUSIONS

Numerical solution of heat and mass transfer through the flow of fluid in the channel of a dehumidifying dryer was developed and analysed. The physical situation was modelled as fluid flow in a channel with the lower region of the channel been occupied by a porous medium. The solution obtained yields the fluid temperature and mass fraction of water vapour at every location in the channel of the dryer.

The solution of the theoretical analysis could be used to conduct a sensitivity study involving the fluid to solid mass transfer coefficient in the dehumidifying dryer; also the water vapour to air mass diffusivity in the channel can be used to determine the importance in correctly prescribing these terms. The solution of the theoretical analysis and that of mixture content equation of the channel can also be utilized to determine the time response of the system. The moisture-loss analysis of a dehumidifying dryer bed and airflow of a dehumidifying dryer was considered to be another fundamental drying parameter. It was discovered that enough airflow is needed through the drying hopper to maintain the pellets at the desired drying temperature for the desired amount of drying time.

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