# Modelling and simulation in distributed parameters for a rotary dryer of fish meal*

H. Sandoval, W. Ipanaqué, *Member, IEEE*, C. de Prada, and J. Manrique

*Abstract*—**This paper describes the mathematical model in distributed parameters from the physical phenomena that occur inside a rotary dryer of fishmeal. The formulation is based on the studies of thermodynamics, heat transfer, mass transfer and drying kinematics that occur in the fishmeal granules, together with energy and mass balances. The nonlinear dynamic system is simulated according to the partial differential equations and the boundary conditions of the system with the orthogonal collocation method, using PROOSIS.**

***Keywords*— *Mathematical modelling; simulation; Rotary dryer; distributed parameters; orthogonal collocation; PROOSIS.***

## I. INTRODUCTION

Fishmeal is one of the main sources of protein as a food supplement in the livestock and aquaculture sector. Peru, with more than 1 million tons of fishmeal per year, represents approximately 30% of the world's production because its principal maritime source is the main raw material for the production of fishmeal: anchoveta [1]. Even though, the price has been increasing every year due to its demand and improvements in processes, which gives a product of better quality [2]. The fishmeal processing plants do not use an on-line monitoring or control system, leading a series of bad practices, which results in an increase in the percentage of ash and energy and therefore contributing to inefficiency.

The fishmeal processing plants have 2 to 3 drying stages with the rotary dryer as the last stage; this stage is the most critical in the process because it defines the moisture with which the fishmeal is going to come out to be commercialized, but it must be taken into account that it is not the only factor that defines its quality (% protein, %ash, TVN, digestibility), but if the process had better control of the drying stage to obtain suitable final moisture, chemical and microbiological stability would be ensured in the fishmeal, avoiding adverse reactions (lipid oxidation, bacterial activity, microbial growth, enzymatic or rancidity) that deteriorate the product in its storage [3].

Rotary driers tend to be a simple machine that avoids contamination of fishmeal because it is be an indirect drying, but what happens inside is extremely complex, which not only covers mass transfer and heat transfer because the fishmeal is changing its physical properties during drying, so it is necessary to make a more detailed study (thermodynamics, heat transfer, mass transfer, drying kinematics and kinematics of the particles) for obtain a mathematical model of the system, which represents the interactions between the solid metal, saturated steam, steam and fishmeal inside the dryer.

The mathematical model has been developed to know indirectly the dynamics of the parameters of the fishmeal, vapor and saturated steam (temperature, humidity, pressure, mass, speed) is important because there are problems with the capacity of data acquisition in the interior of the dryer to know the conditions to which the fishmeal is subjected throughout the process and to predict the humidity and temperature that will leave the fishmeal of the dryer, manipulating the heater pressure and the exit valve of the vapor.

For these reasons, it is necessary to obtain a mathematical model in distributed parameters of the dryer, which not only obtains the dynamics of the parameters in time, but also throughout the dryer. The formulation of the model is obtained in Partial Differential Equations. To solve this type of systems is usually used Finite Differences Method for its simplicity of implementation and allows to give a solution different classes of problems, but also show their disadvantages when trying to solve problems in multiple dimensions with irregular domains. The orthogonal collocation is another simple method used to implement PDE in programming languages for the simulation, allowing to introduce initial conditions, boundary conditions and the exchange of heat and mass in countercurrent that develops between the fishmeal and the vapor.

The historical data given by the plant and other data acquired during the drying process of the fish meal are very valuable for the validation of the model, when no studies are found regarding these or are difficult of find it experimentally because it is difficult to replicate what happens with the material inside the dryer. The purpose of simulating the process in a computer is to assist in the design of a control system or process improvements. Therefore, It is used the PROOSIS software because of its wide range of tools dedicated to modeling [4].

## II. SYSTEM DESCRIPTION

The rotary dryer of fish meal (Figure *1*) is of type indirect, countercurrent, non-mixing and continuous. This has been determined because the heat exchange occurs indirectly (between saturated steam, and vapor and fishmeal) and the flows of fishmeal and vapor go in the opposite direction.

---

*Research supported by INNOVATE PERU.

H. Sandoval, Department Electrical and Mechanical Engineer, University of Piura, Av. Ramon Mugica 131, Urb. San Eduardo, Piura, Peru. (e-mail: hector.sandoval@posgrado.udep.edu.pe).

W. Ipanaqué, Department Electrical and Mechanical Engineer, University of Piura, Av. Ramon Mugica 131, Urb. San Eduardo, Piura, Peru. (e-mail: william.ipanaque@udep.pe).

C. de Prada, Systems Engineering and Automatic Control DPT, EII, Universidad de Valladolid. C/ Real de Burgos s/n, Valladolid, 47011, Spain (e-mail: prada@autom.uva.es).

J. Manrique, Department Electrical and Mechanical Engineer, University of Piura, Av. Ramon Mugica 131, Urb. San Eduardo, Piura, Peru. (e-mail: jose.manrrique@udep.pe).

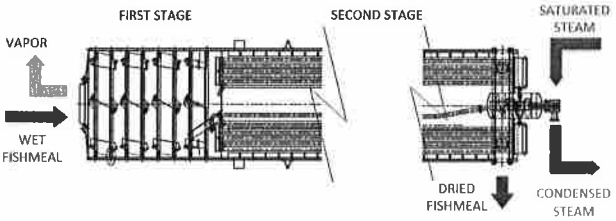

Figure 1. Diagram of fish meal rotary dryer

The wet meal enters through the top of the dryer to a first drying stage, where the meal is removed because of paddles to mix the meal granules and have a uniform moisture; in this stage only the jacket gives energy to vapor and meal in the form of heat. In the second stage there is a greater area of heat transfer by the tubes located radially inside the cylinder; jacket and tubes are supplied with saturated steam on the opposite side to the ingress of meal. The flow of meal and vapor are countercurrent because the meal moves to one extreme due to the action of gravity as the cylinder rotates continuously with a small slope and the vapor is induced to the opposite side because of the action of the air extractor.

The transfer of energy to the meal in the form of heat is not only done directly by conduction, but also the energy is transferred to the vapor and the vapor to the flour by convection this is given because the meal is diametrically elevated by the paddles on the inner surface of the cylinder and the flow of vapor goes in a perpendicular direction, this supplied energy helps to release in gaseous way that the moisture found in the surface and the pores of the meal, and the conforming part the vapor, giving rise to the mass transfer Figure 2.

## III. MATHEMATICAL MODELLING

Inside of the rotary dryer the properties of the materials change along the process in the direction of the flow z, for that a model based on PDE in time and space is written, obtaining a Model Parameters Distributed. The development of the model starts by dividing the system into n volumes of width $\delta l$ Figure 3 considering for each stage an arbitrary number of volumes, which will have the same PDE. To simplify the model we must assume general considerations

- Rotary dryer is an indirect continuous, continuous countercurrent and non-mixing system.
- The heat transfer is done by convection and conduction, the radiation is not considered.

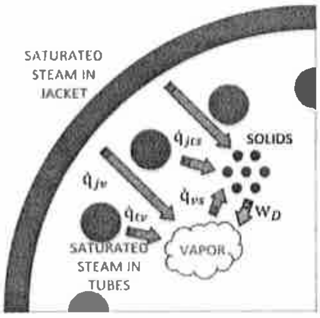

Figure 2. Heat and mass transfer

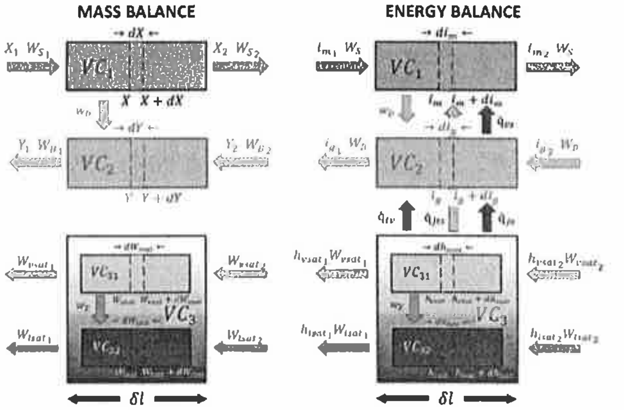

Figure 3. Diagram of mass and energy balances in the VCs

- The meal is perfectly mixed in each volumen.
- Effects by energy kinetic and potential are negligible.
- Not assumed heat losses by the environment.
- There are not chemical reactions.

### A. *Mass and energy balances*

#### 1) *Dry solid*

The mass flow of dry solids $W_S$ is determined from feed of fishmeal and its initial moisture for each volume.

$$W_{S_1} - W_{S_2} = \frac{dm_S}{dt} \tag{1}$$

$W_S$ is calculated

$$W_S = \frac{m_S . v_s}{\delta l} \tag{2}$$

$v_s$ is the axial displacement of solids calculated as $v_s = L/\tau_r$, where $\tau_r$ is the residence time of solids in the dryer, can be calculated theoretically [5] or experimentally.

#### 2) *Dry air*

The air intake system is caused by the extractor and holes that allow air entering the dryer.

$$W_{B_1} - W_{B_2} = \frac{dm_B}{dt} \tag{3}$$

$W_B$ is calculated

$$W_B = \frac{m_S v_{prom}}{\delta l} \tag{4}$$

#### 3) *Wet solid or meal $VC_1$*

Considered the schematic presented on Figure 3, the mass and energy balance is determined by the flow of dry solids $W_S$ that crosses the VC, with moisture of the fishmeal (per unit mass of dry basis) X and wet solid enthalpy (per unit mass of dry basis) $i_m$.

$$i_m = (c_S + c_{Al}X)T_s - \Delta h_s X \tag{5}$$

$c_S, c_{Al}$ are the specific heats of dry fishmeal and liquid water respectively and $\Delta h_s$ is latent heat of sorption. To obtain simpler equations, the following assumptions were adopted

- The particles are spherical of uniform size.
- The particles do not expand along of the process.
- The adsorption isotherm is independent of temperature
- The vapor pressure generated by evaporation of water from the solids is homogeneous along the dryer.
- There is a dispersion of solids because of the rotation of the dryer.
- The cylinder has a static inclination that determines the fishmeal flow rate.

$$W_{S_1}X_1 - W_{S_2}X_2 - w_D A_S = \frac{dm_S X}{dt} \tag{6}$$

$$W_{S_1}\, i_{m_1} - W_{S_2}\, i_{m_2} + \dot{q}_{vs}A_S + \dot{q}_{jts}A_c - w_D h_{Av} A_S = \frac{dm_S i_m}{dt} \tag{7}$$

$w_D$ is the drying rate, $h_{Av}$ is the enthalpy of steam emanating from the solid and $A_S$ is the superficial area of solids. For a differential space element $dz$ of the VC and simplifying

$$-W_S\frac{\partial X}{\partial z} - X\frac{\partial W_S}{\partial z} - w_D a_S = (1-\varepsilon)\rho_S S_H \frac{\partial X}{\partial t} + \frac{\partial X}{\partial z}\frac{\partial m_S}{\partial t} \tag{8}$$

$$\begin{aligned} -W_S\frac{\partial i_m}{\partial z} - i_m\frac{\partial W_S}{\partial z} + \dot{q}_{vs}a_S + \dot{q}_{jts}a_c - w_D h_{Av} a_S \\ = (1-\varepsilon)\rho_S S_H \frac{\partial i_m}{\partial t} + \frac{\partial i_m}{\partial z}\frac{\partial m_S}{\partial t} \end{aligned} \tag{9}$$

$S_H$ is the cross section of fishmeal and $\rho_S$ is the density of dry fishmeal or solids.

### 4) *Humid gas or vapor $VC_2$*

Considered the schematic presented in Figure 3, the mass and energy balance is determined by the flow of dry air $W_B$ that crosses the VC, with absolute humidity of vapor (per unit mass of dry gas) $Y$ and enthalpy of humid gas (per unit mass of dry gas) $i_g$.

$$i_g = (c_B + c_A Y)T_v + \Delta h_{v0} Y \tag{10}$$

$c_B, c_A$ are the specific heats of dry air and vapor respectively and $\Delta h_{v0}$ is latent heat of vaporization. To obtain simpler equations, the following assumptions were adopted

- The vapor pressure equals atmospheric pressure.
- The temperature gradients in the cross sections of the vapor are negligible.

$$-W_B Y_1 + W_B Y_2 + w_D A_S = \frac{dm_B Y}{dt} \tag{11}$$

$$\begin{aligned} -W_B\, i_{g_1} + W_B\, i_{g_2} + \dot{q}_{jv}A_j + \dot{q}_{tv}A_t - \dot{q}_{vs}A_S + w_D h_{Av} A_S \\ = \frac{dm_B i_g}{dt} \end{aligned} \tag{12}$$

For a $dz$ of the VC and simplifying

$$W_B\frac{\partial Y}{\partial z} + w_D a_S = \rho_B S_V \frac{\partial Y}{\partial t} + \frac{\partial Y}{\partial z}\frac{\partial m_B}{\partial t} \tag{13}$$

$$\begin{aligned} W_B\frac{\partial i_g}{\partial z} + \dot{q}_{jv}a_j + \dot{q}_{tv}a_t - \dot{q}_{vs}a_S + w_D h_{Av} a_S \\ = \rho_B S_V \frac{\partial i_g}{\partial t} + \frac{\partial i_g}{\partial z}\frac{\partial m_B}{\partial t} \end{aligned} \tag{14}$$

$S_V$ is the cross section of vapor and $\rho_B$ is the density of dry air.

### 5) *Saturated steam $VC_3$*

Inside the tubes and jacket there is a two-phase system of saturated vapor and saturated liquid that are mixed and changing state continuously, because of the dynamics of the system it is difficult to independently assign the parameters of the phases, so it is assumed a uniform mixture of the two phases (liquid and gaseous) for to apply the theory of single-phase system.

The mass and energy balance equations can be obtained to model the mass ratio of saturated vapor and saturated liquid in the system and then calculate the outline of temperature in z and t, but it must be determined whether the friction factor in the fluids are representative, to find the depression.

The evaluation of the equations of [6] in the system, reject the equations that modelling it, because the depression of the saturated steam generated by the friction in the walls to this biphasic fluid is almost 0, therefore it is considered constant temperature of the tubes and jacket along of the dryer. So it is only necessary the dependence between temperature and saturated pressure (Antoine's equation)

$$\ln P_{sat} = 11.759 - \frac{3878}{T_{sat} - 43.289} \tag{15}$$

## *B. Heat and mass transfer coefficients*

It is important to determine each of the coefficients (8), (9), (13) and (14) to determine the rate of energy $\dot{q}$ and mass transfer $w_D$ in each of the VC*s*.

$$\begin{aligned} \dot{q}_{jv} = j_{jv}\Delta T_{jv};\, \dot{q}_{tv} = j_{tv}\Delta T_{tv};\, \dot{q}_{vs} = j_{vs}\Delta T_{vs}; \\ \dot{q}_{jts} = j_{jts}\Delta T_{jts} \wedge w_D = k_Y \Delta Y \end{aligned} \tag{16}$$

$j$ is the heat transfer coefficient and $k_Y$ is the mass transfer coefficient to the gas phase.

### 1) *Coefficient of heat transfer by convection between jacket and vapor*

During the drying process a volume of vapor is produced inside the dryer, the vapor is located in a closed space subjected to an extractor that creates depression in the outlet control valve of the vapor. The difference of pressure creates a flow of vapor in countercurrent to the meal creating the heat transfer by forced external convection. The interior of the jacket will be considered as a smooth tube of large diameter, the average values of $Re$ and $Pr$ are analyzed, determine to be a turbulent flow the vapor. The equations in [7] are used to calculate $Nu_j$ and obtain the value

$$j_{jv} = \frac{Nu_j k_v}{D_j} \tag{17}$$

### 2) *Coefficient of heat transfer by convection between tube and vapor*

The tubes are continuously rotating in the interior where is evenly distributed. To find the real value of $j_{tv}$ is complex, so it is assumed that the vapor only has 2 components, the radial component (Figure *4*) and the longitudinal component

$$v_{promt} = \sqrt{v_{prom}^2 + v_{max}^2} \tag{18}$$

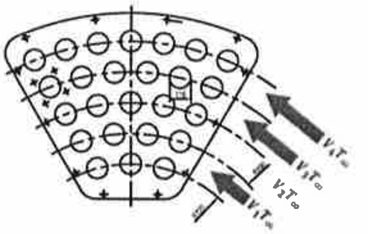

Figure 4 Radial direction of the fluid in the tube bank

$v_{prom}$ is the longitudinal velocity of the vapor and $v_{max}$ is the component perpendicular to the tubes of minimum area that produces the maximum speed [8] which is produced by an infinite bundle of tubes; with this resultant component is used to calculate of $Nu_t$ and obtain the value

$$j_{tv} = \frac{Nu_t\, k_v}{D_t} \tag{19}$$

#### 3) *Coefficient of convective heat transfer between vapor and solids*

The rotating cylinder with the paddles raises the wet particles that are inner the perimeter, the particles falls creating spherical particle curtains throughout the dryer, this causes the area of heat transfer by convection to increase to dry faster and uniform. In order to calculate the rate of fall of the solids in a turbulent fluid, it is considered that the trajectory of the solids is only affected by gravity and resistance to the movement of the vapor towards the surface of the solid. So the limit speed $v_p$ that gets the particles by their apparent weight submerged in the vapor

$$v_p = \left(\frac{4}{3}\frac{d_p g}{C_D}\frac{\rho_s - \rho_v}{\rho_v}\right)^{1/2} \tag{20}$$

determine the value of $Nu_s$ [9] and since the particles behave as unitary spheres, it is possible to obtain

$$j_{vs} = \frac{Nu_s\, k_v}{d_p} \tag{21}$$

#### 4) *Coefficient of heat transfer by conduction between jacket, tubes and solids*

Part of the solid particles is in direct contact with the paddles, tubes and the lower part of the cylinder, which are in steady state at time intervals, even when the system is rotating. The value of $j_{Jts}$ is found in [10] considering that the particles are spherical, stationary and the diameter of the particles are much smaller than the diameter of the pipes and jacket $d_p \ll D_t < D_J$; it is calculated for the particle layer that is in contact with the surfaces, finding the coefficient of heat transfer by instantaneous local convection, considering that the particles expand during the drying process, the coefficient is calculated as a function of the porosity $\varepsilon$

$$j_{Jts} = 3.55\frac{k_v Pr^{1/3}}{(\varepsilon^{-1/3} - 1)d_p} \tag{22}$$

#### 5) *Mass transfer coefficient*

##### a) *The constant drying rate period*

The particles are immersed in turbulent fluids, making it impossible to accurately determine by mathematical calculations the flow conditions, for that reason these conditions rely on experimental calculations which must meet certain conditions and ranges for the properties of the fluid. In this zone it is considered that each particles is covered by water up the critical humidity$X_{cr}$, so is used the general case of the Chilton-Colburn [7]

$$k_Y = \frac{j_{vs}}{c_A \rho_v}\left(\frac{D_{eff}}{\alpha}\right)^{2/3} \tag{23}$$

The effective diffusion of moisture is the physical phenomena is the representation of mass transfer, to the particles of fish meal it has the form of Arrhenius.

$$D_{eff} = D_0 exp\left(-\frac{E_a}{N_R T}\right) \tag{24}$$

As there are no specific values for this material, the values are from estimated the active energy $E_a$, considering the phenomena of diffusion strongly linked to the Arrhenius constant $D_0$ and these values depend moisture [11]; the evaluation of experimental data [11], [12], [13] and [14] is calculated

$$D_{eff} = (-4 + 150X)x10^{-5} exp\left(-\frac{35.2 + 5.5X}{N_R T}\right) \tag{25}$$

##### b) *The decreasing drying rate period*

To find the characteristic curve drying is used as base the value of characteristic moisture $\Phi$

$$\Phi = \frac{\bar{X} - X^*}{X_{cr} - X^*} \tag{26}$$

$X_{cr}$ is the critical moisture content, it is invariable and independent of any internal or external condition. There are studied models that best model the case [15], but for its simplicity is used

$$w_D = k_Y \Phi \Delta Y \tag{27}$$

### C. *Flow and speed of vapor*

The vapor inside the dryer does not have a uniform movement because there are solids that create depressions and turn the vapor into a turbulent fluid, but the predominant depression is the one created by the extractor regulated by a valve in the outlet of the vapor. The vapor velocity is calculated from the volume of the vapor-gas mixture per unit mass at pressure $P_t$ and temperature $T_v$

$$V_H = m_B\left(\frac{1}{M_G} + \frac{Y}{M_W}\right)\frac{T_v R}{P_t} \tag{28}$$

Related to a wet volume differential

$$v_{prom} = \frac{W_B}{S_v}\left(\frac{1}{M_G} + \frac{Y}{M_W}\right)\frac{T_v R}{P_t} \tag{29}$$

$M_G, M_W$ are the molar mass of dry air and water. The vapor flow $F_v$ at the outlet is almost saturated or saturated, so the output flow can be formulated from the depression created by the value for a saturated steam (Figure 5).

$$F_v = \%S.K_x\sqrt{\Delta p_v(p_1 + p_2)} \tag{30}$$

$\%S$ is the percentage of opening of the valve

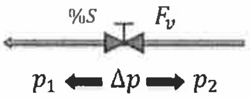

Figure 5. Depression of the valve at the vapor outlet

### D. *Heat transfer area*

#### *1) Surface of jacket and tubes*

The constant movement of the dryer causes the solids to disperse throughout its interior, but the most significant area in contact is the bottom of the dryer (Figure 6) where the solids are accumulates and in partial contact with the internal part of the jacket and the surface of tubes that are immersed in the solids, and that is the reason why it is necessary to know the volumetric fraction $fr$ of the solids in the dryer

$$fr = \frac{4}{3\pi}\tau^3 \tag{31}$$

To calculate the area of submerged tubes use the arrow $rf$ formed by the arc of the jacket

$$rf = \frac{\mathrm{D}_j}{2}(1 - \cos\tau) \tag{32}$$

With these values, the area in contact per unit length of jacket $a_j$, tubes $a_t$ and paddles $a_p$ is calculated

$$a_j = \mathrm{D}_j.\pi + a_p \wedge a_t = \mathrm{N}_t\,\mathrm{D}_t\,\pi \tag{33}$$

for convection and conduction

$$a_{j1} = \frac{\mathrm{D}_j}{2}(\pi + \tau) + \frac{\tau}{\pi}a_p + \frac{\tau - \pi}{4\pi}a_p \wedge a_{t1} = \mathrm{N}_t\mathrm{D}_t\,\pi \tag{34}$$

$$a_{t2} = a_t - a_{t1} \wedge a_{j2} = a_j - a_{j1} \tag{35}$$

The value of $\mathrm{N}_t$ is in function of $fr$.

#### *2) Surface of the solids*

The granules of meal are irregular particles whose dimension is a function of the sphericity factor φ, which relates the average equivalent diameter $d_{pe}$ and the diameter of the particle $d_p$

$$d_{pe} = \varphi\, d_p \tag{36}$$

The sphericity factor is correlated as

$$\varphi = \frac{1}{1.101 + 414 d_p} \tag{37}$$

The specific surface area of the particles is determined by the ratio of surface area to particle volume

$$a_v = \frac{6}{d_{pe}} \tag{38}$$

Therefore, the surface area of the particles per unit length of the dryer

$$a_S = a_v\, S\, fr \tag{39}$$

$S$ is the area of the cross section of the dryer.

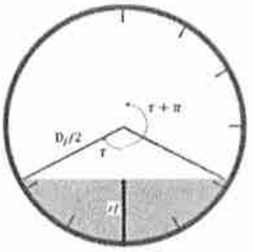

Figure 6. Cross section of dryer

## IV. SIMULATION AND RESULT

The model is used to identify along time $t$ and space $z$ the measures of: temperature of the fishmeal $T_s$, temperature of the vapor $T_v$, moisture of the fishmeal on dry basis $X$, absolute humidity of the vapor $Y$, fishmeal mass $m_S X$, vapor mass $m_B Y$, fishmeal speed $L/\tau$, vapor speed $v_{prom}$. It is plotted with respect to the excitation signals of the operational variables: input flow of the fishmeal $F_{s_{in}}X_{in}$, initial moisture of the fishmeal on dry basis $X_{in}$, initial temperature of the fishmeal $T_{in}$, saturated steam pressure $P_{sat}$ and percentage of opening of the valve $\%S$.

The sampled data from a rotary dryer from Diamante S.A. fishmeal factory in Peru is used as a basis for the simulation in this paper. The dryer of $L = 21.7m$ has 2 stages $L_1 = 4.1m$ and $L_2 = 16.6m$, with a $\tau_r = 2700\,s$, considering the constant speed of fishmeal estimated in $v_s = 0.00794\,m/s$. Inside the dryer the numbers of concentric tubes, $\mathrm{N}_t$, 150; the outside diameter of the tubes, $\mathrm{D}_t = 0.127\,m$; internal diameter of the jacket, $\mathrm{D}_j = 3.356\,m$; total area of pallets, $a_p = 20\,m^2$; particle diameter, $d_p = 2\,mm$; critical humidity, $X_{cr} = 0.25$; moisture in equilibrium, $X^* = 0.02$; porosity, $\varepsilon = 0.2$.

It is known that the boundary conditions for the design and simulation in the countercurrent type are defined at the opposite ends, so that to solve the EDP is used the orthogonal collocation method, where differential equations are solved by approximating the solution to polynomials are found by the collocation points on the spatial domain and the approximate solution is forced to coincide with the exact one at these points.

$$\dot{x}_{ki}(t) = v\sum_{j=0}^{P}\frac{\partial P_j(s_{ki})}{\partial s}\frac{x_{kj}(t)}{\Delta_k} + F(x_{ki}(t), t), \qquad k = 1, \ldots K \wedge i = 1, \ldots P \tag{40}$$

The simulation uses Radau roots of order 3 as collocation points (P = 3). For the first stage are used 2 elements $K_1 = 2$ and second stage are used 5 elements $K_2 = 5$ for the solution of the equation system. The boundary conditions are established by $T_S(0,t) = T_{S_{in}}$, $X(0,t) = \mathrm{X}_{in}$, $W_S(0,t) = W_{S_{in}}$, $T_v(L,t) = T_{v_L}$, $Y(L,t) = Y_L$.

The values were recalculated in equidistant distances in each stage to have a more uniform response and easier to locate in longitudinal points on the plots of PROOSIS in $T_s$, $T_v$, $X$ and $Y$ (Figure 7 and Figure 9), but in the accumulated mass it should be considered that the value $\delta l$ is not the same in each stage (Figure 10).

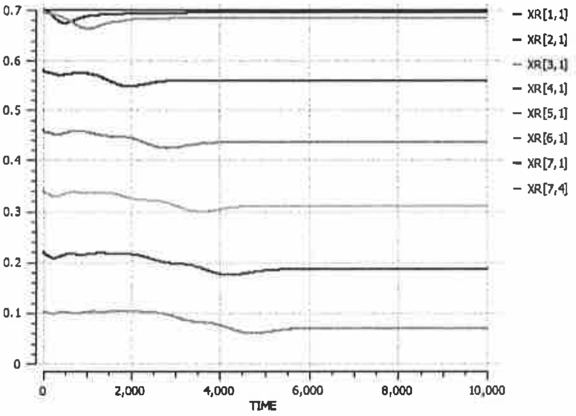

Figure 7. Simulation of some states of moisture of fishmeal - X (PROOSIS)

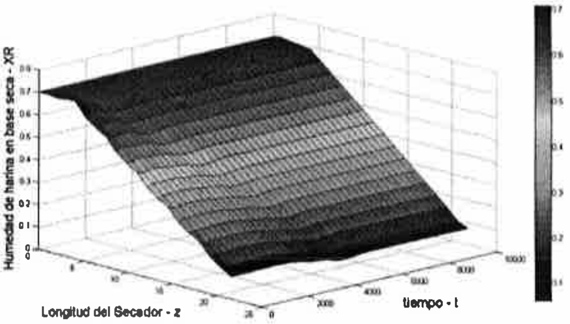

Figure 8. Simulation in the spatio-time of the moisture of the fishmeal - X (MATLAB)

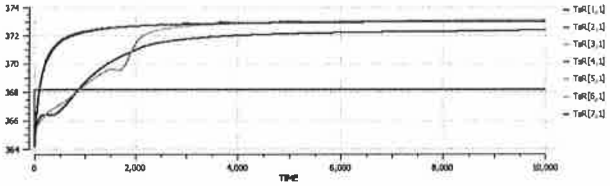

Figure 9. Simulation of some states of temperature of fishmeal - $T_s$ (PROOSIS)

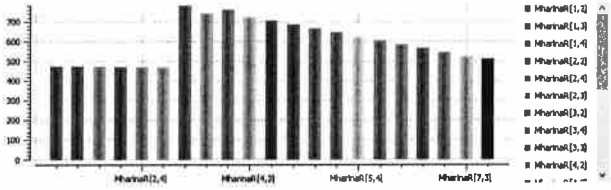

Figure 10. Simulation of the fishmeal mass accumulated in each subelement - $m_S X$ (PROOSIS)

## V. CONCLUSION

The main advantage of modeling in distributed parameters is that you can know the internal dynamics in the dryer and take corrective actions so the fishmeal is not subjected to high temperatures and obtain the desired humidity. Corrective actions can be applied to the model by altering control variables ($P_{sat}$ $y$ $\%S$) which are used for operators in the real dryer. The model allows testing other control variables such as the speed of rotation of the dryer or dry air flow to the dryer.

Determine an equation equivalent to the porosity model of fishmeal dependent $X$ y $T_S$ is very important because the area of heat transfer and mass of the particle depends on the porosity as the equivalent model of $D_{eff}$ which was calculated theoretically.

The discretization method by orthogonal collocation reduces the computational weight compared to finite volume method and facilitates the implementation of the coding of the model countercurrent compared to FDM.

The PROOSIS tools facilitate the simulation by giving a quick analysis of the inconsistencies in the model or considerations in the modeling, which can be corrected more quickly. In the plots of the EDP that PROOSIS gives are not easy to interpret the values of the states, being the reason why the data is exported to MATLAB to plot the surface of states in space-time (Figure 8).

## ACKNOWLEDGMENT

The authors are grateful to University of Piura in Peru, University of Valladolid in Spain, Company Diamante S.A. and INNOVATE PERU who provided insight and expertise that greatly assisted the research. This research was supported by INNOVATE PERU through of the project PITEI-3-P-227-167-15.

## REFERENCES

[1] IFFO, "The production of fishmeal and fish oil from Peruvian anchovy".

[2] Departamento de Productos Pesqueros de la subdirección de Internacional de la Oferta Exportable, PROMPERÚ, "Desenvolvimiento del comercio exterior pesquero en el Perú." .

[3] S. Ariyawansa, "The evaluation of functional properties of fish meal," *U. N. Univ. Fish. Train. Programme Proj. Final Sri Lanka*, vol. 125, 2000.

[4] *User Manual PROOSIS 3.7.28*, 2016th ed. España: Empresarios Agrupados.

[5] M. H. Lisboa, M. H. Lisboa, and W. B. Delaiba, "A study of particle motion in rotary dryer," *Braz J Chem Eng*, vol. 24, pp. 365–374.

[6] D. R. H. Beattie and P. B. Whalley, "A simple two-phase frictional pressure drop calculation method," *Int. J. Multiph. Flow*, vol. 8, no. 1, pp. 83–87, 1982.

[7] Y. A. Cengel and A. Ghajar, "Transferencia de calor y masa," *Editor. Editor. McGraw–Hill*, 2007.

[8] W. Khan, J. Culham, and M. Yovanovich, "Convection heat transfer from tube banks in crossflow: Analytical approach," *Int. J. Heat Mass Transf.*, vol. 49, no. 25, pp. 4831–4838, 2006.

[9] S. Whitaker, "Forced convection heat transfer correlations for flow in pipes, past flat plates, single cylinders, single spheres, and for flow in packed beds and tube bundles," *AIChE J.*, vol. 18, no. 2, pp. 361–371, 1972.

[10] J. Wu, X. Li, B. Chen, R. Wang, X. Ma, and L. Gao, "Modeling for heat transfer coefficient in indirect-heating tube rotary dryer," *Trans. Chin. Soc. Agric. Eng.*, vol. 29, no. 14, pp. 53–59, 2013.

[11] N. P. Zogzas, Z. B. Maroulis, and D. Marinos-Kouris, "Moisture diffusivity data compilation in foodstuffs," *Dry. Technol.*, vol. 14, no. 10, pp. 2225–2253, 1996.

[12] N. M. Panagiotou, M. K. Krokida, Z. B. Maroulis, and G. D. Saravacos, "Moisture diffusivity: literature data compilation for foodstuffs," *Int. J. Food Prop.*, vol. 7, no. 2, pp. 273–299, 2004.

[13] C. Suarez, P. Viollaz, and J. Chirife, "Diffusional analysis of air drying of grain sorghum," *Int. J. Food Sci. Technol.*, vol. 15, no. 5, pp. 523–531, 1980.

[14] M. Toujani, L. Hassini, S. Azzouz, and A. Belghith, "Experimental study and mathematical modeling of silverside fish convective drying," *J. Food Process. Preserv.*, vol. 37, no. 5, pp. 930–938, 2013.

[15] A. Hallström and R. Wimmerstedt, "Drying of porous granular materials," *Chem. Eng. Sci.*, vol. 38, no. 9, pp. 1507–1516, 1983.

VB Líder de Proyecto Convenio
N° 099-INNOVATEPERU-PITEI-2016