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PNEUMATIC CONVEYOR DYNAMIC MODELS FOR A PULVERIZED COAL PLANT[1]

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Abstract

This article describes new advanced non-linear dynamic models for pulverized coal injection (PCI) plant into blast furnaces. A complete new approach for modelling is developed for the actual state-of-art PCI injection station. These models take into account all the physical dynamic laws and pneumatic conveyor variables allied to a modern updated digital control system (DCS). The models were constructed to operate in real time for the same DCS that controls the industrial PCI plant. Process validations include pressure and modern mass flow meter specially designed to check the models. New verification variables allowed by these equipments shows the functionality of the dynamic model-based, thermal, pressure profile and the particle velocity models. The models can be used mainly to improve coal flow stability control by means of modern control strategies and to prevent clogging lance caused by low coal particle speed and high solid to gas ratio.

Key words: Dynamic models; Coal injection; Blast furnace.

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1 INTRODUCTION

The pulverized coal injection system (PCI) of Brazilian National Steel Company (CSN) in Volta Redonda – RJ – Brazil was supplied and commissioned by Claudius Peters in 1997. It receives two kinds of raw coal with granulometry up to 70 mm, grinds and dries to a granulometry of up to 0.9 mm and humidity less than 1 % with the help of a hot gas generator. The main fan sucks grinding gases through bag filters and the pulverized coal is precipitated into fine coal silos.
The fine coal silos are kept inert by a continuous nitrogen flow and have automatic outlet valves that fill the injection vessels with approximately 12 t of fine coal. Gravity draws the fine coal down where it is filtered by a vibrating screen before filling the coal injection vessel. Each pulverized coal injection stations has two pressure coal injection vessels working in parallel like twins. Those vessels run originally in four different phases (Coal Filling, Pressurization, Injection and Venting) in order to guarantee coal flow continuity to the blast furnace (BF). While one vessel is injecting fine coal to the BF, the complementary vessel prepares for the next injection phase.
The Blast Furnace 2 (BF2) produces about 4,200 tons of hot metal daily and has one pulverized coal injection station. The Blast Furnace 3 (BF3) produces about 10,200 tons of hot metal daily and has two injection stations, one being for odd-route injection into the odd tuyeres and the other station for even- route injection into the even tuyeres. Each injection station has a minimum capacity of 10 t/h and maximum capacity of 50 t/h, totalling 100 t/h for the entire BF3 system.
After pressurization, the fine coal is transported inside a main pipeline up to the distributor located near the BF. The distributor then spreads the main coal flow to the individual lances of each BF tuyere. There, the pulverized coal is injected into the furnace to reduce hot metal and burns at the raceway. Injected coal replaces the coke fuel loaded by the BF top, which makes the top equipments less used allowing cost reduction, higher productivity and quality for the hot metal due the improved fuel and BF fast temperature control.
The better the coal flow stability in the main conveyor pipeline the better will be the coal combustion in the blast furnace raceway. The aim of this article is to provide a complete set of dynamic models that will supply potential solutions for modern control design for coal flow.

2 PULVERIZED COAL INJECTION STATION DESCRIPTION

The pulverized coal injection stations main equipments includes fine silo outlet valves, vibrating screens, 25 m^3 injection vessels with fluidization nozzles at the cone bottom, expansion bellows, automatic shut-off valves, plate, venting and dosing valves known as special valves for PCI. There are basically four closed loop controls for each station in actual industry design:

- A - Transportation nitrogen flow;
- B - Fluidization nitrogen flow;
- C - Vessel pressure constant control;
- D - Pulverized coal flow control.

The measurement of the pulverized coal flow in the main pipeline is estimated from the variation of coal injection vessels weight by seconds with a moving average filter [1]. A

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classic Proportional-Integral-Derivative (PID) controller commands the dosing valve located in the outlet of the injection vessel as a function of the difference between the BF coal flow demand and the measured coal flow.

3 INITIAL CONSIDERATIONS

The pulverized coal injection vessel can be model as if it were a pressurised tank, where the principles of mass conservation and the ideal gas law can be used. However, neither the vessel nor the four control valves have a linear behaviour easy to be modelled. The vessel in the injection phase receives nitrogen flow from the pressure control and fluidisation flow lines according to set-points required by the BF. Dynamic responses of the loop controls and processes also depend on pneumatic flow set-points.
Taking into Claudius Peters' improvements, which changed the injection process significantly along the years since 1997, the dynamic models adds new considerations into Birk´s model [1] since there are new variables and controllers, such as the fluidization flow at cone base of the injection vessel in a modern pulverized coal injection system. Other available variables of the injection system were added to create news models aiming the final coal temperature, particle velocity and a pressure drop profile along the bi-phase (Solid/Gas) stepped pneumatic conveyor pipelines. Available instrumentation in the CSN´s PCI facility has been updated making them more useful and credible to validate the models and to improved new future control strategies.
The PCI plant is all controlled by a Yokogawa DCS Centum CS system. Besides, a modern instrument advised by Birk [1] was added to validate the models. All four controlling valves curves were added into the dynamic models for pneumatic conveyor behaviour control and for the coal flow control stability.
For a complete full dynamic modelling, others new process variables and constants were introduced and considered in this work. However, these special conditions of contour modelling and the variables described previously were not used in the models of Birk [1] and [2] because the Claudius Peters PCI was not as developed in 1993 as it is at CSN (2011). Besides that, process and models incorporates instrumentation added:

- A – Coal and nitrogen temperature characteristics from the supplied net;
- B – Pneumatic conveyor flow set-points and parameters;
- C – Dosing and control valves characteristic curves;
- D – Speed and coal density through the stepped pipelines
- E – Blast Furnace blow pressure;
- F – Pressure drop in the line due to the pneumatic transport

4 MODEL FOR INJECTION VESSEL

Figure 1 illustrates a new schematic drawing for modelling the pressurized coal injection vessel, the primary focus of this article. The modelling is from the injection phase in real time by the DCS and showed in an operator screen monitor:

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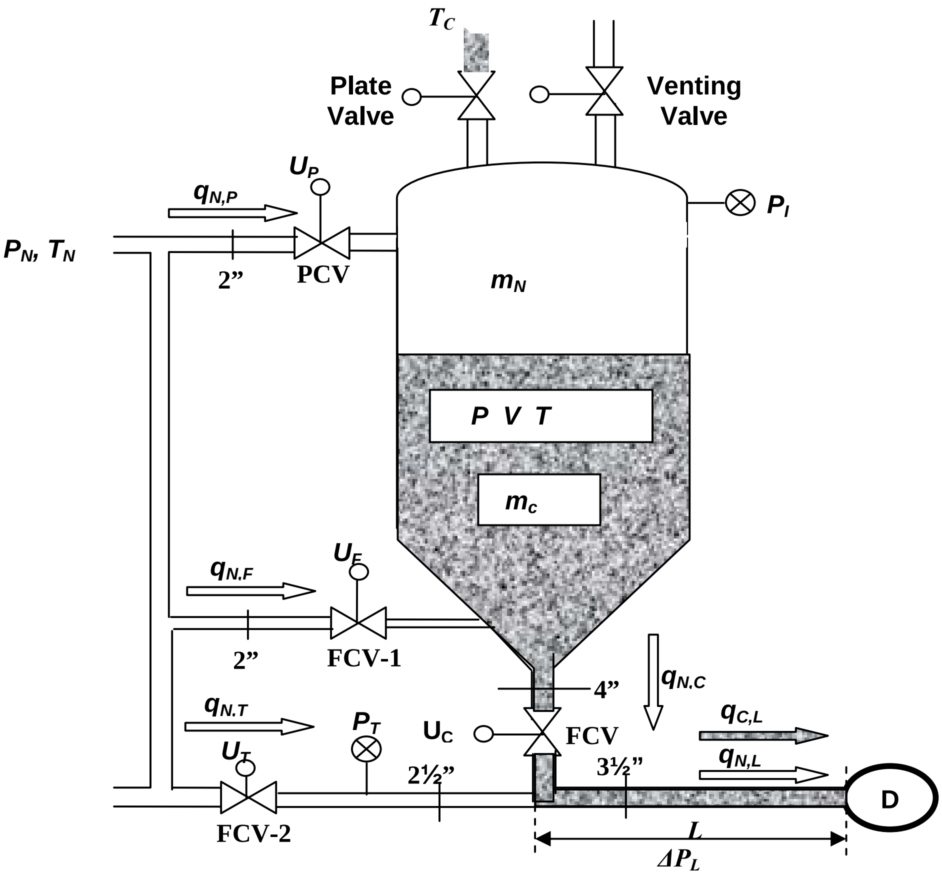

Figure 1 - Advanced coal injection vessel model

5 NOMENCLATURE AND TYPICAL PROCESS VALUES

The nomenclature for the dynamic models contains all the variables, pneumatic conveyor parameters, and constants used to model the vessel´s injection phase. All PCI plants normally have similar parameters, variables and constants. The nomenclature uses part of Birk´s model nomenclature [1] plus the variables obtained from the new models described ahead.

- a - Dosing valve restriction area = 63 mm;
- A - Section cross of a stepped conveyor pipeline bore;
- d - Main conveyor pipeline internal diameter= 83 mm;
- L - Pneumatic conveyor pipeline length =150 m;
- M - Total mass inside the vessel (t);
- m_c - Coal mass inside the vessel (t);
- m_n - Nitrogen mass inside the vessel (t);
- P_I - Injection vessel pressure (Bar)
- P_T - Transportation nitrogen pressure (Bar);
- P_N - Pressure of the nitrogen buffer tanks =17 Bar;
- N - Number of injection lances in operation;
- ΔP_L - Pressure drop throughout the conveyor pipeline (Bar);

ISSN 2176-3135

- P_D - Pressure before the coal distributor (Bar);
- P_{BF} - Blast furnace 3 main bustle pressure = 4.2 (Bar);
- $F_{N,P}$ - Nitrogen flow trough pressure control valve;
- $F_{N,C}$ - Nitrogen flow trough dosing control valve;
- ΔP_{FCV} - Pressure drop trough the dosing valve (Bar);
- $F_{N,F}$- Nitrogen flow trough fluidization control valve;
- $F_{N,T}$- Nitrogen transportation flow behind the injector;
- $q_{N,P}$- Nitrogen mass flow through pressure control valve;
- $q_{N,C}$ - Nitrogen mass flow through dosing valve;
- $q_{N,F}$- Nitrogen mass flow through fluidization control;
- $q_{N,T}$- Nitrogen mass flow through transportation valve;
- $q_{N,L}$- Nitrogen mass flow through main conveyor pipeline;
- $q_{C,L}$- Coal mass flow through dosing valve in the main line;
- μ - Admensional Coal/Nitrogen ratio [1];
- D_F - Two-phase flow density in the main pipeline (kg/m^3);
- C - Coal velocity trough the stepped pipelines (m/s);
- ρ_N - Nitrogen density at process conditions (kg/m^3);
- ρ_C - Coal density = 610 kg/m^3;
- T_C - Coal temperature inside the vessel = 50 ºC;
- T_N - Nitrogen temperature from compressors = 25 ºC;
- T_F - Final two-phase (coal/nitrogen) flow temperature (ºC);
- U_C - Control signal to dosing valve;
- U_F - Control signal to fluidization flow control valve;
- U_P - Control signal to pressure control valve;
- U_T - Control signal to transportation flow control valve;
- V - Vessel volume = 25 m^3;
- P_{MAX} - Vessel maximum pressure (12 Bars);
- P_{MIN} - Vessel minimum pressure (9 Bars);
- F_{MAX} - Maximum fluidisation flow (900 Nm^3/h);
- F_{MIN} - Minimum fluidisation flow (300 Nm^3/h);
- V_{MAX} - Maximum transportation flow (1200 Nm^3/h);
- V_{MIN} - Minimum transportation flow (600 Nm^3/h);
- C_{MAX} - Coal injection maximum flow (50 t/h);
- C_{MIN} - Coal injection minimum flow (10 t/h);
- C_{REQ} - Required coal flow injection into blast furnace (t/h).

6 NON LINEAR PHYSICAL MODEL

Figure 2 shows the physical model of the coal injection vessel is an ordinary pressurised tank filled with coal and nitrogen. The mass balance dynamic model with the interaction to pneumatic conveyor process can be seen ahead:

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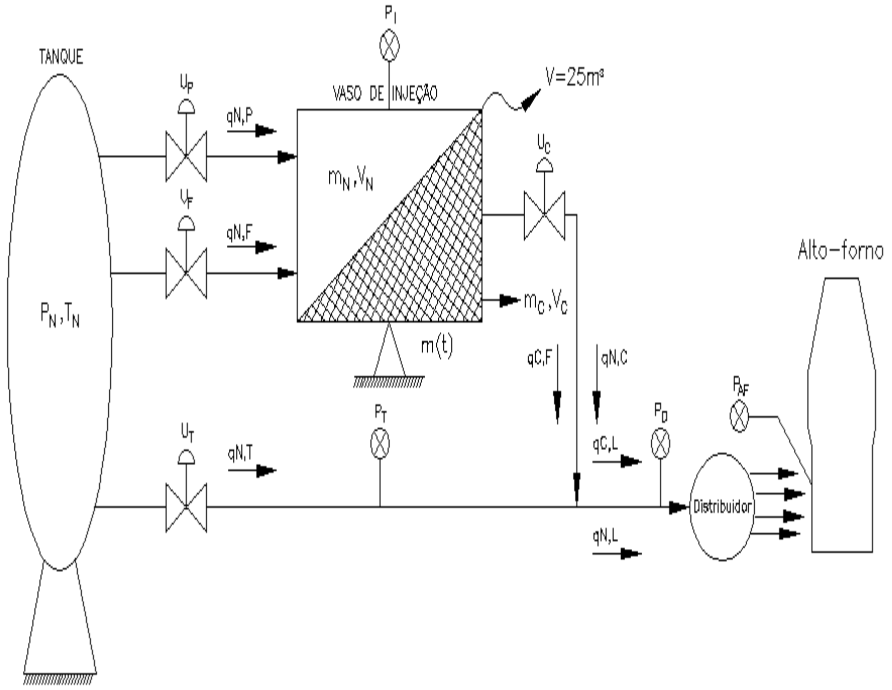

Figure 2 - Advanced Non Linear coal injection vessel model

The entrance signs in the dynamic model are: UP, UF, UT, and UC. The exits are: pressure in the vessel (PI) mass or weight of current coal in the vessel (mc) and the flow of the exit coal, qC,F, nitrogen and coal temperatures.
The temperature changes in the vessel are small, so that the temperature T is almost constant along the time. In this new advanced model, the temperatures of the coal and nitrogen are not constant and are used as entrance variables of the model.
For that, a resulting temperature of the mixture of nitrogen and coal has to be calculated and inserted as variable of entrance of the model that becomes 4x4 dimensions. The high temperature of the coal (90ºC) and the mass relation (about 500 times more coal than nitrogen) makes the nitrogen density (25ºC) decreases after its entrance in the vessel, due to gas expansion. Coal densities, final two-phase temperature, coal speed and others important pneumatic conveyor variables and calculated parameters were included in order to obtain new others models.
The pressure and coal particle speed profiles through the stepped pipelines, the main pipeline density flow, the estimated final coal temperature and the specific nitrogen consumption are the new dynamic models implemented in a real time in the DCS system. In general, mass flow through the three vessel control valves can be described as Eq. (1), (2) and (3) bellow:

$$\dot{m}_P = k_{N1} \cdot g_{PCV_p}(p_N, p_I).g_{PCV_u}(u_P) \quad (1)$$

$$\dot{m}_F = k_{N2} \cdot g_{FCV1_p}(p_N, p_I).g_{FCV1_u}(u_F) \quad (2)$$

$$\dot{m}_C = k_C \cdot g_{FCV2}(p_I, p_T).g_{FCV2_u}(u_C) \quad (3)$$

ISSN 2176-3135

Where: $g_{PCV_p}(p_N, p_I).g_{PCV_u}(u_P)$ (4)

It is the non-linear function of the pressure control valve, (PCV).

$$g_{FCV1_p}(p_N, p_I).g_{FCV1_u}(u_F) \qquad (5)$$

It is the non-linear function of the fluidisation control valve, (FCV1).

$$g_{FCV}(p_T, p).g_{FCV_u}(u_C) \qquad (6)$$

It is the non-linear function of the dosing control valve, (FCV). Those functions depend on the valves design. In the CSN´s PCI design, the PCV and FCV1 are equal in size and Cv. Therefore, they have got the same characteristics curve:

$$g_{PCV_p}(p_N, p_I) = g_{FCV1_p}(p_N, p_I)$$

Especially for CSN´s coal injection station, it is possible to infer the nitrogen flow through the PCV via the fluidisation flow meter, as shown ahead. Usually, the original Claudius Peters coal injection station does not have flow measurement for the vessel control pressure line. In the mass balance vessel, this flow through PCV is added to the fluidisation flow in the vessel cone base. These two flows influence in the vessel injection pressure and have to be calculated and considered in this advanced model.
As seen in the process illustration model, it is not only the pulverized coal that goes through the dosing valve, FCV. There is also a nitrogen flow due the pneumatic conveyor. Therefore, a second nitrogen flow must be defined. In the basic model developed by [2], it was assumed that this flow should be zero.
The mass balance and its derivation along the time are:

$$m = m_P + m_F - m_C \qquad (7)$$

$$\dot{m} = \dot{m}_P + \dot{m}_F - \dot{m}_C \qquad (8)$$

For an ideal gas, the nitrogen mass is added in Eq. (9):

$$p \cdot V_N = (m_P + m_F)R_N T \qquad (9)$$

As seen, the N_2 temperature rises up from 25 to 75 ºC when going inside the vessel. Therefore, if the coal temperature variation can be despised but the gas temperature cannot:

$$\frac{\partial T}{\partial t} \neq 0 .$$

The balance mass derivation plus the temperature changed can be expressed as Eq. (10) below:

$$\dot{p} \cdot V_N + p \cdot \dot{V}_N = (\dot{m}_P + \dot{m}_F)R_N T + (m_P + m_F)R_N \dot{T} \quad (10)$$

Equation (11) introduces the constant volume balance:

$$V_N = V - V_C = V - \frac{m_C}{\rho_C} \qquad (11)$$

ISSN 2176-3135

The coal volume loss or coal mass along is the same to the replacement entrance nitrogen flow through the PCV added with to the fluidisation flow through FCV1, as in Eq. (12):

$$\dot{V}_N = -\frac{\dot{m}_C}{\rho_C} \qquad (12)$$

For coal flow in the main conveyor pipeline, the value can be obtained by the derived of the vessel weight along the time, discounting the replacement of nitrogen and assuming that there is not nitrogen vessel leakage. This physical phenomenon is essential for the correct coal flow measurement in the main conveyor pipeline to the blast furnace and was not foreseen in the model of [1] and [2]. This is the main dynamic innovation in the coal station models for the corrected biphasic flow throughout the steeped pipeline until the injection lance.

The nitrogen that enters in the vessel is used to keep its pressure constant. Therefore, almost all the nitrogen flow that enters into the vessel goes out via the dosing valve if there is no leakage in the plate and venting valves or elsewhere.

$$q_{N,P}(t)+q_{N,F}(t)=\frac{dm_n}{dt}=\frac{dm_P}{dt}+\frac{dm_F}{dt}+\frac{1}{\rho_C}\frac{dm_C}{dt} \qquad (13)$$

The only nitrogen flow remained inside the vessel is equal to N2 volume used to replace of coal volume injected. Assuming that there is no leakage and the vessel pressure is kept constant during the whole injection phase, the nitrogen mass trough dosing valve can be estimated as in Equation (14):

$$q_{N,C}(t)=q_{N,P}(t)+q_{N,F}(t)-\frac{1}{\rho_C}\frac{dm_c}{dt} \qquad (14)$$

However, of course, the weighing system does not know the difference between coal and nitrogen and flow measurement does not really measures the real coal flow. So, the coal flow in the main line has to be correct, as in Equation (15):

$$q_{C,L}(t)=\frac{dm}{dt}=\frac{dm_C}{dt}-\frac{dm_n}{dt} \qquad (15)$$

Applying the continuity equation, finally, the N2 flow through the mail coal pipeline can be obtained by Eq. (16):

$$q_{N,L}(t)=q_{N,C}(t)+q_{N,T}(t) \qquad (16)$$

For the pressure, the Equation (17) can be describes as:

$$\dot{p}\cdot V_N=(\dot{m}_P+\dot{m}_F)R_N T+(m_P+m_F)R_N \dot{T}-p\cdot\dot{V}_N \quad (17)$$

Finally, the derived pressure along the time can be calculated as in Equation (18):

$$\dot{p}=\frac{(\dot{m}_P+\dot{m}_F)R_N T+(m_P+m_F)R_N \dot{T}-p.\dot{V}_N}{V-\frac{m_C}{\rho_C}} \quad (18)$$

ISSN 2176-3135

The non-linear dynamic space state model 4x4 for the injection process can be defined as:

- x = [**p**, **m_c** , **m_N** , **q**]^T as vector state;
- y = [**p**, **c, d, q**]^T as output vector;
- u = [**u_P, u_F, u_T, u_C**] ^{T} as input vector;

The state matrixes are:

$$u(t) = \begin{bmatrix} U_P(t) \\ U_F(t) \\ U_T(t) \\ U_C(t) \end{bmatrix}; \dot{x}(t) = \begin{bmatrix} \dot{p}(t) \\ \dot{m}_C(t) \\ \dot{q}(t) \\ \dot{n}(t) \end{bmatrix}; y(t) = \begin{bmatrix} p(t) \\ m_C(t) \\ q(t) \\ n(t) \end{bmatrix}$$

7 CONTROL VALVES CHARACTERISTCS

In [1], these valve functions were not known. In this article, the characteristic curves of the valve PCV and FCV1 were raised from the suppliers and introduced in the model with theirs new characteristics. According to [3], the flow through a valve is equivalent to Equation (19) below:

$$Q = C_V f(x)\sqrt{\Delta P} \qquad (19)$$

Where:

- C_V = valve flow capacity;
- f(x) =valve opening;
- ΔP = differential pressure across the valve;
- x= MV%/100% = output controller signal;

Fluidisation flow control valve (FCV1) and pressurization control valve (PCV) are equal in dimensions (DN50) and both equal in flow capacity (same CV). They also have got the same characteristic curve of equal percentage (=%) according to [3] with the same slope (α=16). Eq. (20) shows:

$$f(x) = \alpha^{x-1} \qquad (20)$$

The N_2 flow thought PCV (Q') can be estimated from the actual fluidization flow, as shown in Equation (21):

$$Q' = C_V f(x)\sqrt{\Delta P} \qquad (21)$$

Both valves have the same characteristics curves (CV) and are applied in the same (ΔP). Thus, the relation (22) is:

$$\frac{Q}{Q'} = \frac{f(x)}{f(x')} = \frac{\alpha^{u-1}}{\alpha^{u'-1}} \qquad (22)$$

Finally, the flow qN,P is calculated in the DCS as Eq. (23):

$$q_{N,P} = q_{N,F}\frac{\alpha^{U_P-1}}{\alpha^{U_F-1}} \qquad (23)$$

The FCV dosing valve is a special Claudius Peters valve design and its characteristic curve was risen up by means of math model in AutoCad using an intersection of two circles. The results shows that the special Claudius Peters dosing valve has got a linear

ISSN 2176-3135

characteristic for any value of opening above 32%. Therefore, the manipulated variable controller to dosing valve should be low limited in 32%, and no high limit. However, as can be seen in Eq. (19), the linear behaviour of the area does not mean a lineal coherence between the opening and the mass flow through the valve.

8 PNEUMATIC CONVERYOR MODELS

The pneumatic conveyor variables influence on the non-linear model and must be determined. The pneumatic variables basically depend on the blast furnace Pulverized Coal flow request (PR rate) and are already configured in the DCS. They were configured according to the Claudius Peters PCI functional description and its process variables are used as inputs to the real-time DCS model. The injection pressure set-point is linear and proportional to the coal flow requested by the blast furnace, (24):

$$P_I = P_{Mín} + \frac{P_{Máx} - P_{Mín}}{C_{Máx} - C_{Mín}}(C_{REQU} - C_{Máx}) \quad (24)$$

The fluidisation nitrogen flow is also linear as in Eq. (25):

$$F_{N,F} = F_{Mín} + \frac{F_{Máx} - F_{Mín}}{C_{Máx} - C_{Mín}}(C_{REQU} - C_{Máx}) \quad (25)$$

Transportation nitrogen flow is inversely linear to the BF coal flow set-point request and follows Equation (26):

$$F_{N,T} = V_{Mín} + \frac{V_{Máx} - V_{Mín}}{C_{Máx} - C_{Mín}}(C_{Máx} - C_{REQU}) \quad (26)$$

The N2 mass flows can be obtained from the process variable volumetric flow measurements multiplied by the N_2 density at NTP. The main parameters are the solid/gas relation (μ) and the density flow in the main coal pipeline. They are used as reference points to decrease the coal injection lance clogging probability.
Basically, the probability of lance clogging depends on a combination of many variables. Among them, there are:

- A – Granulometry out of size (super gross) (2% > 300μm);
- B – Low particle velocity (C<2m/s) mainly in the coal lance;
- C – High relation solid/gas ratio (μ,> 30);

The relation solid/gas ratio,μ, can be depicted as in Eq. (27):

$$\mu = \frac{KgCoal}{KgNitrogen} = \frac{q_{C,L}}{q_{N,L}} \quad (27)$$

The two-phase flow density in the conveyor pipeline is (28):

$$D_F = \frac{kgCoal + kgN_2}{VolCoal + VolN_2} = \frac{\mu + 1}{\frac{\mu}{\rho_C} + \frac{P_0 T_F Z}{\rho_N P_I T_0}} \quad (28)$$

Where:

- P_0, T_0 = Temperature and pressure at NTP conditions;
- Z= N_2 compressibility factor = 0.9998

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According to [4], if the velocity falls down then 2 m/s, the risk of coal injection lance clogging increases enormously. The flow to be considered is a two-phase flow with coal and nitrogen together. As the conveyor line is stepped the velocity throughout the stepped lines is Equation (29):

$$C = \frac{Q}{A} = \frac{q_{C,L} + q_{N,L}}{A} \qquad (29)$$

These two important parameters are used to make the validation of the pneumatic conveyor flows once Densflow also measures velocity and density directly.
The sketch of the stepped pneumatic conveyor pipelines with bents and lengths must be raised before the ΔP model. However, like the thermal model, the dynamic of the ΔP is much lower than the pressure, speed, density and flow controls. They are used just for pneumatic modelling and not for control purposes. The drop pressure profile model through the pneumatic conveyor pipelines can be calculated on-line in real time using Darcy's Equation (30).

$$\Delta P = \left(\frac{4f}{L} + \sum k \right) + \rho_C \frac{C^2}{2} \qquad (30)$$

Where:

- f = fiction coefficient of the pipelines (main and branches);
- k = drop pressure trough the 90º and 45º bents;

9 MODEL VALIDATION

To validate the models, it was inserted a pressure transmitter behind the distributor and a new modern cross relation instrument with a tube sensor installed in the main coal pipeline.
The Figure 3 shows the dynamic Pneumatic conveyor model for single and double coal lance schedule 160 in a real time calculated by the DCS. It can be seen that the speed for double coal lance when using schedule 160 goes dangerously under 2 m/s, which allows or increase the probability of the double coal lance clogging although the excess of conveyor nitrogen.

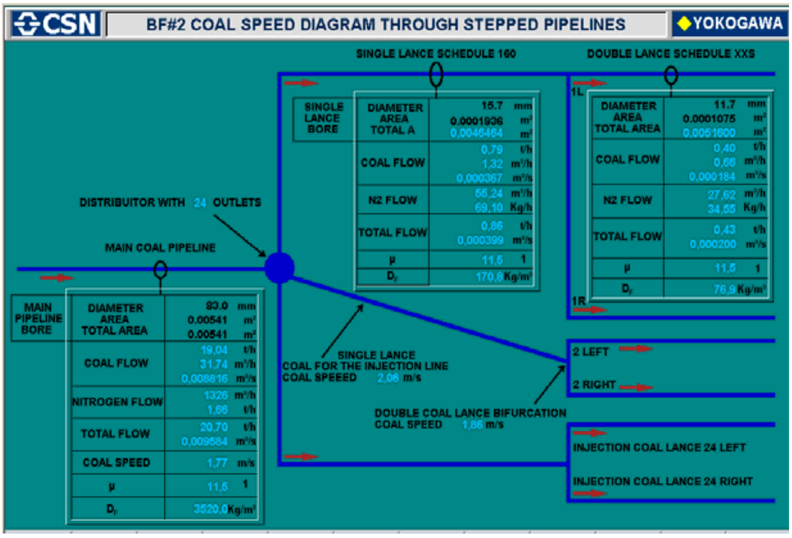

Figure 3 - Dynamic Pneumatic conveyor model for single and double coal lance schedule 160.

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The Figure 4 now shows the dynamic Pneumatic conveyor model for double coal lance schedule XXS in a real time. It can be seen that the speed for double coal lance when using schedule XXS remains safely around 2 m/s avoiding the range from 2 down to 1 m/s where the coal lance clogging probability is greater.
After changing all double coal lances from Schedule 160 to schedule XXS, it was also allowed to decrease the amount of conveyor nitrogen and the aim of double coal lance, which is spread the pulverized coal in the blast furnace race-way was finally reached without wasting too much nitrogen.

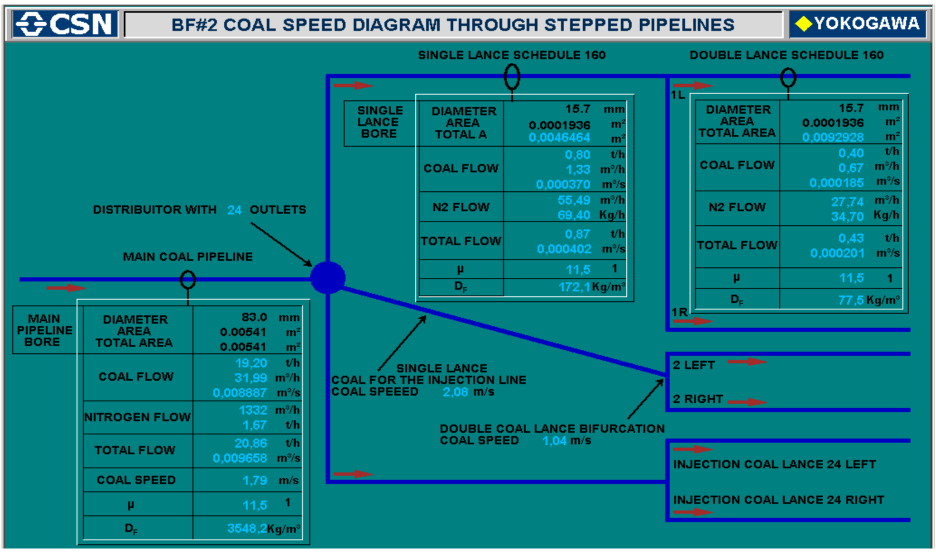

Figure 4 – Dynamic Pneumatic conveyor model for double coal lance schedule XXS.

10 CONCLUSIONS

The advanced dynamic models are essential to develop a new coal flow control using modern control strategies. This method has been used in CSN´s to control coal flow rate in certain cases and also to avoid coal lances clogging by means of calculating the final speed in a pneumatic stepped lines.
The validations for coal flow, drop pressure profile, density and particle speed in the main and stepped lines were successfully carried out.
The model calculations and parameters described are made in a real time using the DCS control. It was also developed a static model just for simulation using EXCEL to compare with the real time DCS values and results.
The control strategies described here for instantaneous coal flow control were industrial tested and implanted at CSN since 2010. They have been used daily with successful.
The velocity model allowed through the stepped lines is used to avoid very low speed when the PC rate is lower than 120 kg/THM. The model guided us towards to a new specification for the double coal lance internal diameter in order to avoid lance clogging.

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