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Design and analysis of a sampling probe at high temperature under a CO_2 atmosphere susceptible to oxidative damage. Part 2: Optimization of operation

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Abstract*—This paper propose to continue with the simulations for optimizing operation of a sampling probe at high temperatures and CO_2-rich environment, at which samples are susceptible to deterioration by contact with oxygen from air. The synergy of the Computational Fluid Dynamics- Design of Experiments-Response Surface modelling(CFD-DOE-RS) tools, allowed the optimization of the operation of the sampling device for cement industry and verifies a cooling time long enough to prevent contamination of the specimen in contact with air to maintain itscrystallographic structure. The selection of materials for the construction of the device must resist heat transfer rate and abrasive erosion occasioned for friction between the micro particles specimens that moves at high velocity in the internal walls of the device proposed.

***Index Terms*—Bernoulli, cement, CFD, sampling probe, oxidative damage.**

I. INTRODUCTION

Any industry requires the use of devices for process control and quality assurance. In cement industry, the extraction of samples at high temperatures and inert atmospheres turns the extraction process into a complex activity by the potential degradation of the specimen in contact with oxygen from air. Xue [1] performed the analysis of a jet type pump; Yimer [2] through Computational Fluid Dynamics (CFD) software, which principle of operation is based on the Venturi effect [3]. This effect is widely used in the automotive, aviation and flow measurement industry [4]-[7] and many researchers have modeled this phenomenon by finite volume element [8]-[13]. In cement industry it has been used for the design and optimization of calciners [14] and to simulate the main transport processes in rotary kilns [15]; there are also patents focused on sampling systems for combustion gases from the rotary kiln. Some patents deal with volatile gases, chlorine and sulfur compounds, and the removal of lead from the sample [16]-[20].

This paper proposes to continue with the simulation for optimizing the operation of a cement clinker sampling probe at high temperatures and CO_2-rich environments which may alter the characteristics of the sample.

II. METHODS

A. Background and Methodology optimizing operating parameters.

In Fig. 1 the configuration of the sampling probe is fully detailed. A computational finite volume CFD Fluent ANSYS 15.0 package was used for this study. To verify the operation, the diffusive behavior of gases flowing into the proposed device was modelled using the Reynolds Stress Model turbulence model, based on nonlinear Navier-Stokes differential equations, which describe the motion of fluids [21]. Operating conditions were considered as follows: steady state, $g = -9.81\ ms^{-2}$ and a boundary condition at the entrance of the particles at the extraction point in the cyclone of 2.3 kPa.

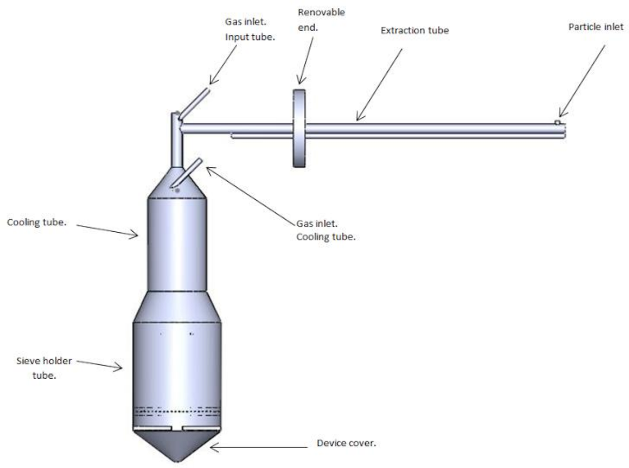

Fig. 1 Isometric view and CFD simulation inside a cyclone process in cement industry

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To obtain the boundary conditions for the simulation of the probe, a simulation of the conditions of the internal flows in the cyclone during the manufacturing process of clinker was done. The same CFD software was used (Fig. 2) for this task. A preliminary CO_2 injection pressure of 10 atmospheres was defined for both extraction and cooling pivot tubes in the device.

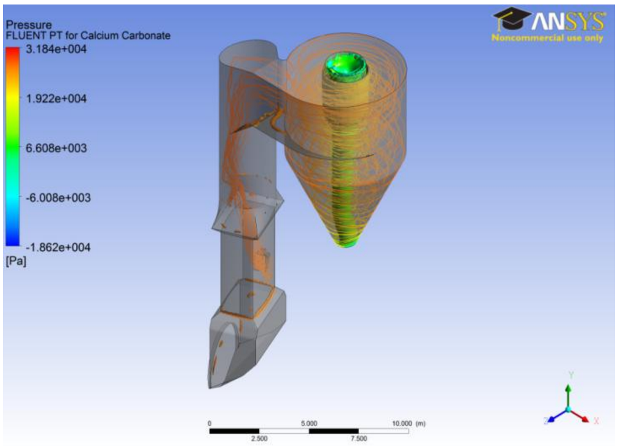

Fig. 2Isometric view from CFD simulation inside a cyclone process in cement industry

B. *Fast cooling principle*

The device captures particles at high temperatures in a non-oxidizing atmosphere and retains the crystal phases arrangement in its original condition. By having a diameter between 1 to 90 microns, the captured particles propitiate a concentrated system condition, which establishes a rapid temperature change when subjected to a fluid environment, since it satisfies the Biot number condition.

$$H = \frac{hL}{k} < 0.1$$

This is also true in practice for raw material powder in cement industry preheaters, where temperature may increase from room temperature to 1123 K in 2.8 s. In this way the cooling of the captured particles is possible.

The final configuration of the probe is under registration number mx/a/2014/002336 Mexican patent (Fig. 1).

III. RESULTS AND DISCUSSION

A. *Description of current sampling conditions and case study*

For the optimization of the device performance, the Rosin Rammler (RR) distribution model for particles in the range of the sample under study was used (Fig. 2, Fig. 3). For the analysis of the actual particle size distribution at the laboratory, a CILAS 1180 L was used. Its operation conforms to ASTM C430.

The simulation tool is alternated with the Design of Experiments (DOE) and the Response Surface (RS) modelling*i)* to minimize calculation costs and *ii)* to optimize the operation of the proposed device. The DOE method allows to analyze experimental data and build empirical models to obtain the more approximate representation of the physical situation, generating the values of the variables to be optimized. The RS methodology can be defined as a method to build global approximations to the behavior of the system on the calculated results at different points in the design space [22].

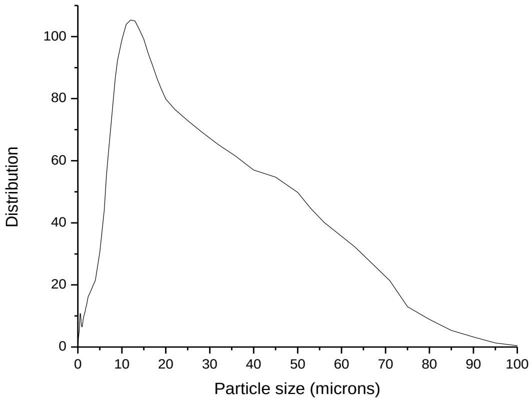

Fig. 3. Particle size distribution within the cyclone, obtained with CILAS 1180 L.

The parameters to optimize were the gases injection angles (extraction and cooling tubes) as well as the injection pressures (Fig. 4) which values are reported in DOE Table I.

To obtain the maximum velocity at the extraction entrancetube, a negative pressure in the x-axis direction will be generated by the Bernoulli effect, i.e. to increase the suction of the samples. The optimum value obtained was -850.69 ms^{-1}, calculated on the highlighted surface in red in Fig. 5. Using this value in Table I, a pivot angle of the extraction tube of 21.479º is obtained with a pressure of 0.874GPa, and a cooling pivot angle of 28.521° with a pressure of 0.2268GPa.

Figure 6 shows the RS generated by DOE simulation (Table I), which relates the injection angles of CO_2, P9-AG1 and P10-AG2, with the extraction velocity in the specified area (Fig. 5). Fig. 7 shows the relationship between the pressures of both pivots (P18-p1, P19-p2) and the temperature at the output of the device. It can be confirmed that at the magnitudes of the pressures selected as optimal, a minimum level of temperature is obtained at the outlet of the device. Fig. 8 also shows the relationship between the injection pressures on the pivots and the extraction velocity.

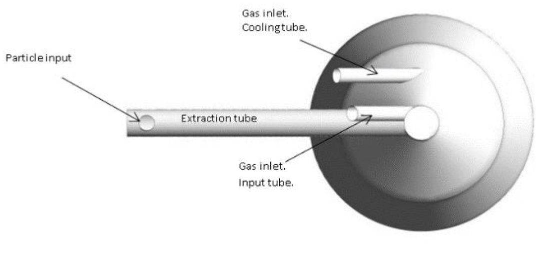

Fig. 4 Lateral view extraction probe

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Table IDOE.

P9-AG1	P10-AG2	P18-P1 (GPa)	P19- P2 (GPa)	P12-Tempout (K)	P15-vel 1 (ms^{-1})
25	25	90900	5.5045e+05	294.8	-82.467
25	25	5.5045e+05	5.5045e+05	322.32	-346.17
20	25	5.5045e+05	5.5045e+05	300.9	-433.85
30	25	5.5045e+05	5.5045e+05	297.39	-228.15
25	25	5.5045e+05	5.5045e+05	294.58	-342.47
25	30	5.5045e+05	5.5045e+05	300.29	-336.89
25	25	1.01e+05	5.5045e+05	333.6	-698.34
25	25	5.5045e+05	90900	291.34	-374.34
25	25	5.5045e+05	1.01e+05	325	-336.04
21.479	21.479	2.2683e+05	2.2683e+05	297.95	-192.24
28.521	21.479	2.2683e+05	2.2683e+05	299.85	-139.86
21.479	28.521	2.2683e+05	2.2683e+05	314.6	-198.57
28.521	28.521	2.2683e+05	2.2683e+05	302.84	-140.87
21.479	21.479	8.7407e+05	2.2683e+05	335.88	-763.53
28.521	21.479	8.7407e+05	2.2683e+05	343.06	-510.74
21.479	**28.521**	**8.7407e+05**	**2.2683e+05**	**335.58**	**-850.69**
28.521	28.521	8.7407e+05	2.2683e+05	340.94	-530.81
21.479	21.479	2.2683e+05	8.7407e+05	334.31	-170.58
28.521	21.479	2.2683e+05	8.7407e+05	335	-128.45
21.479	28.521	2.2683e+05	8.7407e+05	335.16	-176.63
28.521	28.521	2.2683e+05	8.7407e+05	333.17	-131.37
21.479	21.479	8.7407e+05	8.7407e+05	336.8	-753.54
28.521	21.479	8.7407e+05	8.7407e+05	347.12	-493.89
21.479	28.521	8.7407e+05	8.7407e+05	334.65	-833.11
28.521	28.521	8.7407e+05	8.7407e+05	344.99	-517.1

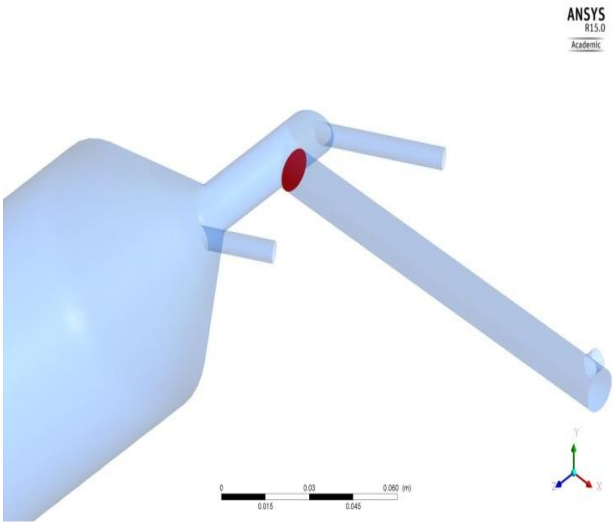

Fig. 5. Isometric probe (in red) where the surface taken as a reference for the calculation of gas velocity extraction

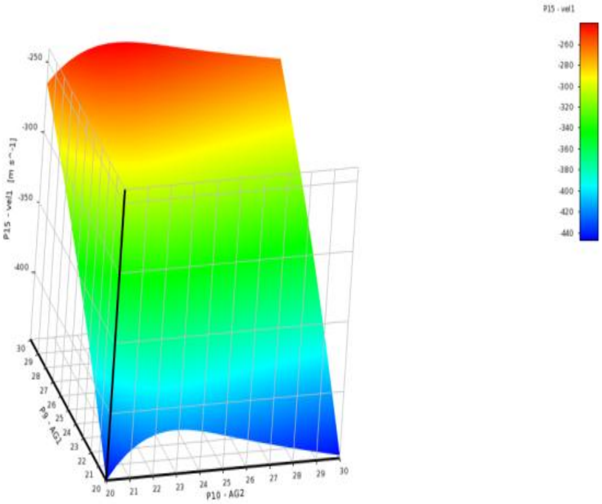

Fig. 6. 3D graph of injection angle of cooling tube (P10-AG2), injection angle of extraction tube (P9-AG1) respect to velocity extraction (P15-vel1)

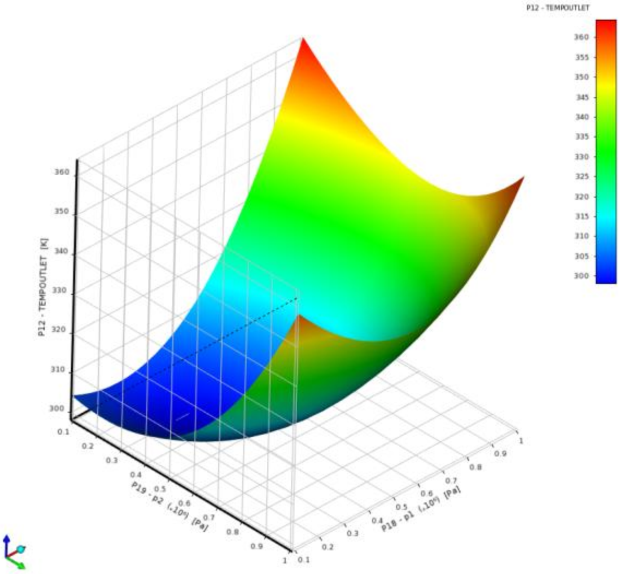

Fig. 7 3D graph of the pressure pivot in cooling tube (P19-p2), the pressure pivot in extraction tube (P18-p1) respect to outlettemperature device (P12-TEMPOUTLET)

Fig. 9 shows an image of the simulation with optimized parameters, including the flow of particles (Lagrange discrete phase model) represented by the RR distribution function, obtained with the experimental analysis with CILAS 1180 L.Fig. 3 also shows that the particles temperature at the entrance of the extraction tube is 1090 K, therefore the temperature at the intersection of the extraction tube and the input tube (Fig. 5) has dropped to 562 K. Moreover, the temperature at the cooling tube exit has dropped to 290°K. In this simulation, 99% of the path of 2220 particles was followed, representing $1x10^{6}$ steps of 0.01m. The mean residence time of these particles was 0.5619 s with a standard deviation of 0.8526 s. These results show that the heat transfer (heat rate) was $-6.176e10^{-15}$ W with a cooling rate of 1423 Ks^{-1}.

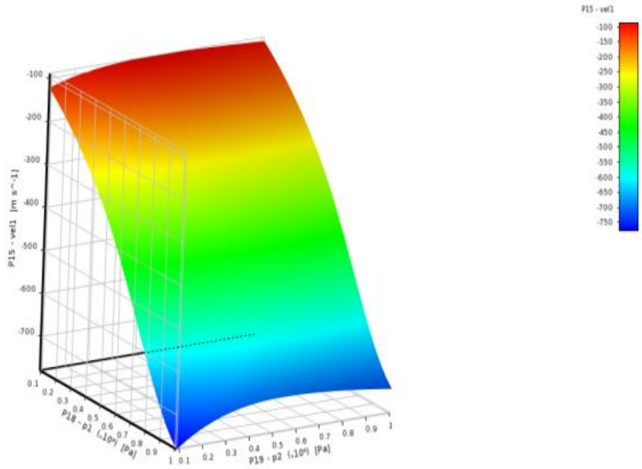

Fig. 8 3Dgraph of pressure pivot incooling tube (P19-p2), pressure pivot in extraction tube (P18-p1) respect tovelocityextraction (P15-vel1).

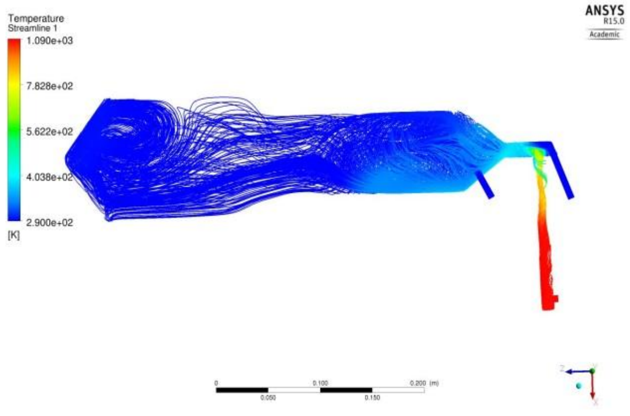

Fig. 93D trace particles from real particle size distribution.

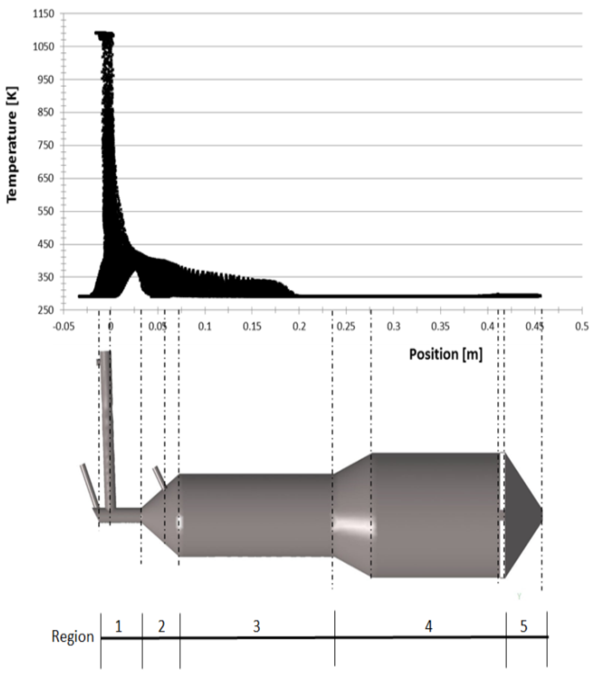

Fig. 10 Temperature behavior in each node and position of the particle within the probe

Fig. 10 shows the temperature behavior representing the values of every node conforming the simulation domain. The figure shows the heat transfer rate of both, the particles and the gas flow. This is true since the energy transfer condition approaches a concentrated system; i.e. the temperature changes are the same on the particle surface and inside the particle.

In regions 1, 2 and 3 a cooling ramp is identified; region 1 shows how the particles and the carrier gas tend to a thermal equilibrium while region 2 shows a conic geometry in which takes place the expansion of the particle-gas system and a second gas injection at room temperature. At this point, a complementary cooling rate to that observed in region 1 is generated. Finally, region 3 shows that the mixture is thermally homogenized. Regions 4 and 5 contribute to the feedback of the low-pressure gases to keep the necessary turbulence of the system allowing the collection of the samples in the sieves.

IV.CONCLUSIONS

Simulation tools and the statistical analysis of the RS values contribute significantly to the design, performance optimization and materials selection for construction devices required to control the current industrial processes.

In this particular study, the synergy of the CFD-DOE-RS tools, has allowed the optimization of the operation of the sampling device in the cement industry.

The response surfaces generated show that *i)*the cooling pivot injection has minimal effect on the extraction and *ii)* the pivotextraction injection has minimal effect on the cooling inside the device.

By this study, an optimized device was obtained. This device increases the flow rateat which the samples are extracted from extreme environments (high temperature and CO_2-rich atmosphere) in cement manufacturing process. The result of this simulation verifies a cooling long time enough to prevent contamination of the specimen by contact with air keeping at the same time, the crystallographic structure of the sample inside the cyclones.The materials for the construction of the device must resist a heat transfer rate of 1423Ks^{-1} and an abrasive wear given the friction between the (micro) particles moving at high velocity and temperature in the internal walls of the device.

V. ACKNOWLEDGMENTS

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The relevant contributions;“Simulation of Flow Field Pattern Influence on the Hydrogen Consumption in A PEMFC” published in 2013 on Journal of New Materials for Electrochemical Systems. “The mathematical modeling of biomethane production and the growth of methanogenic bacteria in batch reactor systems fed with organic municipal solid waste” published in 2009 on Int. J. Global Warming. "A Method to Evaluate the Tensile Strength and Stress–Strain Relationship of Carbon Nanofibers, Carbon Nanotubes, and C-chains" published in 2005 on SMALL.

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