Design, Development and Analysis of a Versatile Screw Feeder Based Powder Dispenser For Dispensing of The Heterogenous Zirconium Molybdate Powder

KEYWORDS: screw feeder based powder dispenser, hopper, independent variables, dependent variable, dimensional analysis, graphical method, mathematical model, MEF,MSE, hopper side slope angle.

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ABSTRACT *A screw feeder based powder dispenser for handling heterogeneous zirconium Molybdate (Zr-Mo) powder was designed with a stirrer as flow promotion device. Since the Zr-Mo powder is bone dry and free flowing, in the design improvement, stirrer was removed by selecting appropriate hopper angle by studying the properties of the Zr-Mo powder. Improved prototype was fabricated and put to actual use. In order to get exact idea about the behavior of the powder dispenser, mathematical modeling using dimensional analysis and graphical method has been done. Total 11 independent terms first were reduced to eight and further to four. In order to get exact mathematical model, four independent terms further converted to one by forming various combinations and their behaviour was plotted on graph. Mathematical model has been generated by using graphical method in the form of the mathematical equation. Finally predicted mean square error (MSE) and efficiency of the model (MEF) has been calculated. Poor MEF has been observed which may be due to several reasons like error in material properties obtained by using non-standard instruments, influence of powder dispenser etc.*

INTRODUCTION

The variable dispensing capacity screw feeder based powder dispenser (VDCSFPD) is used for dispensing of the radioactive Zr-Mo powder into the glass column (GC) in the TCGP facility of BRIT. For satisfying the demand of the customers for specific Zr-Mo powder, this dispenser is developed. It is been fitted with a hopper with a stirrer to break the stagnant mass of the powder to be dispensed stops flowing due to formation of the arch or the rat hole. Failure to flow occurs mainly due to moisture content and the favourable particle size in addition to the geometry of the hopper. But since the existing volumetric dispenser fitted with ultra high molecular weight polyethylene (UHMWPE) hopper (36° hopper angle) never used any kind of flow promotion device and Zr-Mo powder is basically free flowing (proved by tests on Zr-Mo powder) and so in case of VDCSFPD, chances of no-flow condition shall not occur. With the objective of removing the stirrer from the hopper and to get highest achievable flow using the conical hopper, experiments were conducted to select the most desired angle of the side wall slope (ϕ_s) of the hopper (fig.1). The angle ϕ_s of the hopper was decided by using the property of the angle of repose of the powder. By using the methodology of experiments, the hopper having ϕ_s = 50° has been selected over the hopper with stirrer. Selection was based on the factors like maximum flow rate through the established screw feeder, minimum retention of the powder in the hopper. Further, characterization of screw feeder with the 50° hopper was done by experimentation only and it has been found that irrespective of the powder bulk density, the flow rate remains constant ~0.3g/s as compared to the delivery rate of 0.21g/s in the old design with stirrer. This was done by changing the hopper design while screw feeder geometry remained unchanged [1,2].

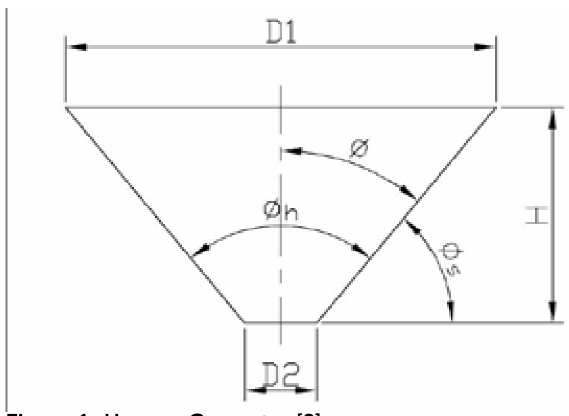

Figure 1: Hopper Geometry [2]

In order to get exact idea about the behavior of the powder dispenser mainly the flow rate with respect to the variables on which the flow rate depends, mathematical modeling of the hopper using dimensional analysis and graphical method has been done. Total 11 independent terms first were reduced to eight and further to four. In order to get exact idea about the dispensing process, four independent terms have been further converted to one by forming various combinations using multiplication and division and the product values of the various combinations was plotted on graph paper. By using the general equation of the line, mathematical model has been formed by using graphical method in the form of the mathematical equation. Finally efficiency of the model has been calculated. This paper discusses the process of design and analysis of the powder dispenser.

ABOUT THE SCREW FEEDER BASED POWDER DISPENSER[1,2]:

In BRIT at Vashi, Navi Mumbai, the radioactive Zr-Mo gel powder is filled in the GC using a fixed volume dispenser.

As the demand for this powder increased, users preferred denomination as per their requirement thus converting the demand into user specific. At production management level, need of converting the process specific dispenser into user specific one generated specification of the desired dispenser which will have advantage over the existing machines. With the objective of designing a machine which will be able to dispense powder in small volumes (between 0.2 to 0.6 gm/sec.) to control the powder discharge so that production team will be able to deliver the powder as desired by the user, a general approach to the design of the powder dispenser was followed, under the influence of the constraints imposed by the existing facility. This approach involved

1. Market survey:
in this study of at least 8 successful concepts was done. Based on the desired characteristics most appropriate one i.e. the screw feeder based powder dispenser was selected.

2. Designing of the screw feeder based powder dispenser and fabricating the desired powder dispenser-
while designing the dispenser, knowledge of powder properties is must. Since the powder is unique in nature, no published data was available. Since the powder of interest is having special characteristics, the design of the dispenser was not possible without knowing the minimum desired properties of the Zr-Mo powder like bulk density, angle of repose, shear strength, coefficient of friction etc. In order to overcome these constrain and since the Zr-Mo powder is radioactive in nature, it was tested by developing required testing machines. Machines for testing the powder were designed based on the design and purpose of the standard machines available in the market for testing the powders. Tests on the available Zr-Mo powder were conducted inside the approved shielded and sealed tong box. Tests unfolded the powder properties like angle of repose, bulk density, internal angle of friction, coefficient of friction between the powder and the hopper material like stainless steel, UHMWPE, powder shear stress etc. Using these properties and the general design principles, machine was designed with components like screw feeder, hopper with stirrer, geared DC motor (fig.2). Designed machine was fabricated and tested. Testing of the machines was done to know the behavior of the machine i.e. the flow rate with respect to the powder bulk density. It has given the delivery rate of 0.21g/s which will help in controlling the mass of the powder dispensed in the glass column or tube by controlling it using the timer. Machine has been commissioned and is in use. Most of the constraints in developing the desired powder dispenser have been satisfied.

VDCSFPD has been fitted with a hopper with a stirrer to break the stagnant mass of the powder to be dispensed stops flowing due to formation of the arch or the rat hole. Failure to flow occurs mainly due to moisture content and the favourable particle size in addition to the geometry of the hopper. But since the existing volumetric dispenser fitted with ultra high molecular weight polyethylene (UHMWPE) hopper (36° hopper angle) never used any kind of flow promotion device, Zr-Mo powder is free flowing (further proved by tests on Zr-Mo powder) and so in case of VDCSFPD chances of no-flow condition never occur. With the objective of removing the stirrer from the hopper and to get highest achievable flow using the conical hopper, experiments were conducted to select the most desired angle of the side wall slope (ϕ_s) of the hopper from amongst the ϕ_s = 36°, 38°, 40°, 41°, 44°, 47°, 51°, 55°, 56°, 63° (refer table-1 for flow rate of the powder through hoppers having different ϕ_s). The hopper having ϕ_s =50° side slope angle has been selected over the hopper with stirrer. Selection was based on the factors like maximum flow rate through the established screw feeder, minimum retention of the powder in the hopper. Further, characterization of screw feeder with the 50° hopper was done by experimentation only and it has been found that irrespective of the powder bulk density, the flow rate remains constant ~0.3g/s (fig.3).

ANALYSIS OF VDCSFPD:
For analysis of the developed machine, it was decided to model the process of dispensing of the powder, with the objective of maximizing the flow rate through the powder dispenser. For this two approaches have been considered namely the experimental approach and the mathematical modeling approach.

In the experimental approach, the experimentation involves designing and fabrication of the hoppers, conducting experiments by using various powder samples etc. This approach is costly as hoppers need to be fabricated every time a variable is changed. Even powder produced is in limited quantity, and most important it is radioactive in nature, not advisable to handle frequently. These constraints add to the complexity. Therefore it was decided to use mathematical modeling approach particularly using Buckingham Pi theorem.

Figure 2: Powder dispenser with stirrer[1]

Figure3: Powder dispenser without stirrer[2]

Zr-Mo is basically a pharmaceutical preparation and for similitude B Mazumder, R Rajan, et. al.[7] studied the gravity flow characteristics of various pharmaceutical granules through static conical hoppers of different cone angles. They found that the mass flow rate depends on properties of granules and cone angles when environmental conditions such as temperature and relative humidity are kept within a fixed range. They made the granules with active pharmaceutical ingredients as per Indian pharmacopoeia with other additives like binders and diluents. Lubricants were added with the granules to observe their effects on mass flow rate. Magnesium stearate and colloidal silicon dioxide of different proportions were used as lubricants after granulation. Following new dimensionally analyzed equation was developed in this study to predict flow rate of the granules.

$Q.(\mu)^{-0.6}/(d_s.\mu.\rho_p/\rho)=0.15.\{d_s)^3.(\rho_p)^2.g\cos\theta/\mu^2\}^{0.45}.(d_o/d_s)^{1.1}$ ……..(1)

The developed equation agreed well with the experimental data with a percentage deviation of ±10%. But the powders, to compare, are different in properties and so characteristic equation (no.1) cannot be used directly.

1. Mathematical Modeling[10,12]:
In case of modeling approach, the process of flow of the powder through the hopper can be defined in equation 2 as

$Q = f\,[D1, D2, D_p, H, g, \mu_a, \mu_i, \mu_{ps}, \rho_a, \rho_p]$ …(2)

The independent and a dependent variables are defined as:

Independent (total 10) - D1(smaller dispensing hopper diameter or orifice diameter), D2(larger diameter of the hopper), H(material head), g(acceleration due to gravity), D_p(powder particle diameter), μ_a (air viscosity), μ_{ps} (co-efficient of friction between the hopper material and powder), μ_i (powder's internal co-efficient of friction), ρ_a (air density), ρ_p (powder bulk density)

Dependent (total 1 only): Q(mass flow rate of powder)

As a step towards getting a mathematical model, dimensional analysis is performed as explained in next section.

2. Dimensional analysis [10]:
Table-2 shows the dimensions of the variables and Observation of the independent variables found that repeating variables are D1, ρ_a, g. On performing the analysis on the variables, it is found that

$\pi_1 = D2 / D1$

$\pi_2 = D_P / D1$

$\pi_3 = H / D1$

$\pi_4 = \mu_{ps}$

$\pi_5 = \mu_i$

$\pi_6 = \rho_p\ \rho_a$

$\pi_7 = \mu_a\ D1^{1.5}\ \rho_a\ \ g^{0.5}$

$\pi_{01} = Q\ D1^{2.5}\ \rho_a\ \ g^{0.5}$

The relation between dependent and independent terms can be written as

$\Pi_{01} = [\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6, \Pi_7]$

$Q\ D1^{2.5}\ \rho_a\ \ g^{0.5} = [D2 / D1, H / D1, D_P / D1, \mu_{ps}, \mu_i, \rho_{p/}\ \rho_a, \mu_a\ D1^{1.5}\ \rho_a\ \ g^{0.5}]$ ………..(3)

Therefore, number of variables reduced to 8 from 11.

To reduce the no. of variable, rearranging the terms in 3 again by combining the geometrical and material property variables,

$Q\ D1^{2.5}\ \rho_a\ \ g^{0.5} = f\ (\Pi'_1, \Pi'_2, \Pi'_3, \Pi'_4)$ **…..(4)**

$\Pi'_1 = (D2 / D1)x\ (H / D1)\ x\ (D_P / D1) = (D2\ H\ D_P)/ D1$

$\Pi'_2 = \mu_{ps}\ x\ \mu_i$

$\Pi'_3 = \rho_{p/}\ \rho_a$

$\Pi'_4 = \mu_{a/}\ D1^{1.5}\ \rho_a\ \ g^{0.5}$

3. Model formation and analysis:
For mathematical modeling of the process, as a part of the process, calculation of the product of the variables has been done (table -3). In this case, calculation was done using the standard as well experimentally determined values as mentioned below[2]:

D1= 13mm= 0.013 m;

Dp = 0.003mm;

H= 0.034m ;

$g = 9.81\ m/s^2$;

$\mu_a = 1.8 \times 10^{-5}$

$\mu_i = 0.949$

$\mu_{ps} = 0.502$

$\rho_a = 1.2\ Kg/m^3$

$\rho_p = 1.32$ or 1.4 or 1.355 g/cc

3.1 Mathematical modeling-reduction of variables:
In order to get the mathematical model of the flow rate of the dispensing process for the powder dispenser, further reduction of the independent Pi terms has been done by studying the various combinations of the same.

Accordingly, following combinations were considered in first attempt:

$\Pi'_1 \times \Pi'_4$

Π'_1 / Π'_4

$\Pi'_2 \times \Pi'_3$

Π'_2 / Π'_3

Using the available values for the case under study, values were tabulated and graphs were plotted. After studying the graphs, it was found that no specific relation can

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be arrived at due to the complex nature of the dispensing process and graphs were not defining the process to the extent desired. Also since the first four combinations were not including all the Pi prime terms, these could not yield any result. Therefore it was decided to consider all possible combinations of the Pi terms as mentioned below which includes all Pi terms and therefore we get following combinations,

$\Pi'_1 \times \Pi'_2 \times \Pi'_3 \times \Pi'_4$

$(\Pi'_2 \times \Pi'_3) / (\Pi'_4 \times \Pi'_1)$

$(\Pi'_1 \times \Pi'_2) / (\Pi'_3 \times \Pi'_4)$

$(\Pi'_1 \times \Pi'_4) / (\Pi'_2 \times \Pi'_3)$

$(\Pi'_1 \times \Pi'_3) / (\Pi'_2 \times \Pi'_4)$

$(\Pi'_4 \times \Pi'_2) / (\Pi'_1 \times \Pi'_3)$

$(\Pi'_1 \times \Pi'_2 \times \Pi'_3) / \Pi'_4$

$(\Pi'_4 \times \Pi'_2 \times \Pi'_3) / \Pi'_1$

$(\Pi'_1 \times \Pi'_4 \times \Pi'_3) / \Pi'_2$

$(\Pi'_1 \times \Pi'_2 \times \Pi'_4) / \Pi'_3$

$\Pi'_4 / (\Pi'_2 \times \Pi'_3 \times \Pi'_1)$

$\Pi'_3 / (\Pi'_2 \times \Pi'_1 \times \Pi'_4)$

$\Pi'_2 / (\Pi'_1 \times \Pi'_3 \times \Pi'_4)$

$\Pi'_1 / (\Pi'_2 \times \Pi'_3 \times \Pi'_4)$

Using the values of the prime Pi terms, product of the various combinations was plotted and analyzed for solving the problem of the mathematical model by using the curve fitting method.

3.2 Curve fitting method [8,11]:
In order to select the most suitable combination for modeling by curve fitting method, product of the Pi term values were plotted (Xcal Vs Zexp). This is specifically done to avoid complications in modeling approach. It was specifically done as the powder flow process is comparatively a simple process and so the plotted characteristic graph. In other words the characteristic graph shall be simple with one or two curves. As the number of curves increases, complication in mathematical modeling increases, generating undesirable equations and data. Therefore , it was decided to avoid those combinations in which the curve drawn are intersecting each other and curves which are not covering the maximum points. Fig 4 and 5 shows the graph plotted using the values obtained from combination of the prime Pi terms. In case of plot in fig.4 and 5, the curve drawn will be intersecting thus shows the complication. In case of plot in fig.6, distinctive curves can be plotted and thus selected for analysis. On studying similar plots for various other combinations of Π', it was decided select those cases in which smooth curves can be drawn and the drawn curve can generate an equation of the model. Accordingly, it was decided to reject following combinations on the basis of non-feasibility and complexity

$\Pi'_4 / (\Pi'_2 \times \Pi'_3 \times \Pi'_1)$

$\Pi'_3 / (\Pi'_2 \times \Pi'_1 \times \Pi'_4)$

$\Pi'_2 / (\Pi'_1 \times \Pi'_3 \times \Pi'_4)$

$(\Pi'_1 \times \Pi'_4 \times \Pi'_3) / \Pi'_2$

$(\Pi'_1 \times \Pi'_2 \times \Pi'_3) / \Pi'_4$

$\Pi'_1 \times \Pi'_2 \times \Pi'_3 \times \Pi'_4$

$(\Pi'_1 \times \Pi'_3) / (\Pi'_2 \times \Pi'_4)$

And thus short listing following combinations for mathematical modeling using curve fitting method. Figure 7 to 22 shows the plot of the product values of the various combinations on the graph paper alongwith the plot on the log graph paper shows the line obtained from the equation 5.

$\Pi'_1 / (\Pi'_2 \times \Pi'_3 \times \Pi'_4)$ (see fig. 7 and 8)

$(\Pi'_4 \times \Pi'_2) / (\Pi'_1 \times \Pi'_3)$ (see fig. 9 and 10)

$(\Pi'_4 \times \Pi'_2 \times \Pi'_3) / \Pi'_1$(see fig. 11, 12 and 13)

$(\Pi'_1 \times \Pi'_2 \times \Pi'_4) / \Pi'_3$(see fig. 14 and 15)

$(\Pi'_2 \times \Pi'_3) / (\Pi'_4 \times \Pi'_1)$ (see fig. 16, 17 and 18)

$(\Pi'_1 \times \Pi'_2) / (\Pi'_3 \times \Pi'_4)$ (see fig. 19 and 20)

$(\Pi'_1 \times \Pi'_4) / (\Pi'_2 \times \Pi'_3)$ (see fig. 21 and 22)

Theory of curve fitting method:

Plotting X vs Z on log graph paper and drawing a line. Theory behind it is explained by equation- 5

$Z = K X^N$

$\text{Log}(Z) = \text{Log}(K) + N.\text{Log}(X)$ .....(5)

i.e.

$Y = C + mX$ -----equation of the line

For modeling of the process using this method, graph has been plotted for the values obtained from various combinations of the Π'_1, Π'_2, Π'_3, Π'_4 (on X -axis) against the Z values (on Y-axis) (table-4). Then a smooth curve is drawn such that it covers most of the points on the graph. After studying the graphs it is found that in most of the cases the curves drawn intersect each other thus creating an area of complexity where number of lines can be drawn is more and lines intersects each other. Therefore such complex cases were not considered for further studying for generating a model equation using Log graph paper. Few selected simple plots were considered for mathematical modeling. In the graph where it was possible to draw an average curve, the characteristic curve was drawn to simplify the process of modeling. Figures show the blue colour curve as an average curve. Following section explains the mathematical modeling done:

A). For **$((\Pi'_1 \times \Pi'_2 \times \Pi'_4) / \Pi'_3)$ (fig. 14, 15)**

Over the variation in X over 6.85 to 10.47, the model is

$Z = (18) \times (X.10^{-10})^{-0.5509}$

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$Z= [(18) \times ((D2)\ (H)\ (D_P) \times (\mu_{ps}) \times (\mu_i) \times (\mu_a)) / (((D1^{2.5} \times \rho_a^2 \times g^{0.5} \times \rho_p)\ 10^{-10})^{-0.5509})]$

$Q/D1^{2.5}\ \rho_a\ g^{0.5} = (18) \times [((D2)\ (H)\ (D_P)\ (\mu_{ps})\ (\mu_i)\ (\mu_a)) / ((((D1^{2.5})\ (\rho_a^2)\ (g^{0.5})\ (\rho_p))\ 10^{-10})^{-0.5509})]$ ....(6)

B). for **$(\Pi'_2 \times \Pi'_3) / (\Pi'_4 \times \Pi'_1)$ (fig. 16, 17,18)**

In this case it found that two curves can be drawn namely curve –A and curve-B

Case b1: For curve-A

Over the variation in X over 2.163 to 3.306, the model is

$Z= 3.1[(X).(10^8)]^{0.6349}$

$Q/ D1^{2.5}\ \rho_a\ g^{0.5} = 3.1[((\mu_{ps} \times \mu_i \times \rho_p \times D1^{2.5} \times g^{0.5}) / (D2 . H . D_P . \mu_a))\ (10^8)]^{0.6349}$ **....(7)**

Case b2: For curve B

Over the variation in X over 3.278 to 6.06, the model is

$Z= 8.8[(X).(10^8)]^{(-0.2594)}$

$Q/ D1^{2.5}\ \rho_a\ g^{0.5} = 8.8[((\mu_{ps} \times \mu_i \times \rho_p \times D1^{2.5} \times g^{0.5}) / (D2 . H . D_P . \mu_a))\ (10^8)]^{(-0.2594)}$ **....(8)**

C). for **$(\Pi'_4 \times \Pi'_2) / (\Pi'_1 \times \Pi'_3)$ (fig. 9, 10)**

$X= (\mu_a \times \mu_{ps} \times \mu_i) / (D2 . H . D_P\ \rho_p\ D1^{0.5}\ g^{0.5})$

Over the variation in X over 1.245 to 2.05

$Z = 4.5\ (X\ (10^{-3}))^{0.3714}$ is the model.

$Q/ D1^{2.5}\ \rho_a\ g^{0.5} = 4.5\ ((\mu_a \times \mu_{ps} \times \mu_i) / (D2 . H . D_P\ \rho_p\ D1^{0.5}\ g^{0.5})\ (10^{-3}))^{0.3714}$ **....(9)**

D). for **$(\Pi'_4 \times \Pi'_2 \times \Pi'_3)/ \Pi'_1$ (fig. 11, 12, 13)**

$X = [(\mu_{ps} \times \mu_i \times \rho_p \times \mu_a)] / [\rho_a^2 \times D1^{0.5}\ g^{0.5} \times (D2 . H . D_P)]\ (10^2)$

Case d1: Curve –A

Over the variation in X over 22.5 to 34.605

$Z= 1.2\ [X\ (10^2)]^{0.4804}$ is the model

$Q/ D1^{2.5}\ \rho_a\ g^{0.5} = 1.2\ [[(\mu_{ps} \times \mu_i \times \rho_p \times \mu_a)] / [\rho_a^2 \times D1^{0.5}\ g^{0.5} \times (D2 . H . D_P)]\ (10^2)]^{0.4804}$ **....(10)**

Case d2: Curve –B

over the variation in X over 27 to 63.42

$Z = 7.4\ [X\ (10^2)]^{-0.0671}$

$Q/ D1^{2.5}\ \rho_a\ g^{0.5} = 7.4\ [[(\mu_{ps} \times \mu_i \times \rho_p \times \mu_a)] / [\rho_a^2 \times D1^{0.5}\ g^{0.5} \times (D2 . H . D_P)]\ (10^2)]^{-0.0671}$ **..(11)**

is the model.

E). for **$\Pi'_1 / (\Pi'_2 \times \Pi'_3 \times \Pi'_4)$ (fig. 7, 8)**

Over the variation in X over 2.89 to 4.42

$Z = 9.6\ [X\ (10^{-4})]^{-0.3956}$

$X= (D2 . H . D_P . \rho_a^2\ D1^{0.5}\ g^{0.5}) / \ \mu_{ps} \times \mu_i \times \rho_p \times \mu_a$

$Q/ D1^{2.5}\ \rho_a\ g^{0.5} = (9.6)[((D2 . H . D_P . \rho_a^2\ D1^{0.5}\ g^{0.5}) / (\mu_{ps} \times \mu_i \times \rho_p \times \mu_a))\ (10^{-4})]^{-0.3956}$ **....(12)**

is the model

F). for **$(\Pi'_1 \times \Pi'_2)/ (\Pi'_3 \times \Pi'_4)$ (fig. 19, 20)**

$X = [(\rho_a^2 . D2 . H . D_P\ \mu_{ps} . \mu_i .\ D1^{0.5}\ g^{0.5}) / (\rho_p . \mu_a)]$

Over the variation in X over 6.54 to 10 , the model is

$Z = 15\ [X\ (10^{-5})]^{-0.4455}$

$Q/ D1^{2.5}\ \rho_a\ g^{0.5} = 15[[(\rho_a^2 . D2 . H . D_P\ \mu_{ps} . \mu_i .\ D1^{0.5}\ g^{0.5}) / (\rho_p . \mu_a)]\ (10^{-5})]^{-0.4455}$ **....(13)**

G). for $(\Pi'_1 \times \Pi'_4)/ (\Pi'_2 \times \Pi'_3)$ (fig. 21, 22)

$X = [(D2 . H . D_P . \mu_a\ \rho_a) / (D1^{2.5}\ \rho_a\ g^{0.5}\ \mu_{ps} . \mu_i . \rho_p)]$

Over the variation in X over (26×10^{-10}) to (46.2×10^{-10}) the model is

$Z = 9.2\ [X\ (10^{-10})]^{-0.1328}$

$Q/ D1^{2.5}\ \rho_a\ g^{0.5} = 9.2\ [[(D2 . H . D_P . \mu_a\ \rho_a) / (D1^{2.5}\ \rho_a\ g^{0.5}\ \mu_{ps} . \mu_i . \rho_p)]\ (10^{-10})]^{-0.1328}$ **....(14)**

ANALYSIS OF THE MODELS [6]

The most convincing way of testing a model is to use it to predict data which has no connection with the data used to estimate model parameters. In this way, we reduce to a minimum our chance of obtaining a spuriously good match between model predictions and data.

The phrase "has no connection with" is an important one. Suppose we were to estimate the parameters of a model by fitting to data collected at a farm over several years. To test the model, we collect more data from the same farm in the following years. What can this tell us about the model? At best, it will suggest that the model gives reliable predictions for that one farm. To justify statements about the use of models over a range of farms, the model must be tested over a selection of farms covering the entire range. What summary statistics should we use to describe the discrepancy between data and model predictions? For predictions *Pi* of observations *Oi*, *i* = 1.....*m*, we might use:

$$\text{Bias}(B) = \frac{1}{n}\Sigma_{i=1}^{n}(P_i - O_i)$$

$$\text{Standard deviation } (SD) = \sqrt{\frac{1}{n}\Sigma_{i=1}^{n}(P_i - O_i - B)^2}$$

$$\text{Prediction mean square error (MSE)} = \frac{1}{n}\Sigma_{i=1}^{n}(P_i - O_i)^2 = SD^2 + B^2$$

MODELING EFFICIENCY [7]

The modeling efficiency statistic (MEF) is interpreted as the proportion of variation explained by the fitted line whereas the MEF statistic is the proportion of variation explained by the line 1 (,...,) *p Y = f X X* . This statistic has been extensively used in hydrology models, but can certainly be used in biological models. Equation shows its calculation; simply, the term Y_i in Equation was replaced by the term 1 (,...,) *pi f X X* in Equation.

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$$MEF=\frac{\left(\sum_{i=1}^{n}(Y_i-\bar{Y})^2-\sum_{i=1}^{n}(Y_i-f(X_1,....X_p)_i)^2\right)}{\sum_{i=1}^{n}(Y_i-\bar{Y})^2}=1-\frac{\sum_{i=1}^{n}(Y_i-f(X_1,....X_p)_i)^2}{\sum_{i=1}^{n}(Y_i-\bar{Y})^2}$$

In a perfect fit, both statistics would result in a value equal to one.

The upper bound of MEF is one and the (theoretical) lower bound of MEF is negative infinity. If MEF is lower than zero, the model-predicted values are worse than the observed mean. The MEF statistic may be used as a good indicator of goodness of fit. For the case of interest, the bias, standard deviation, prediction mean square error and modeling efficiency has been calculated and arranged in table-5.

RESULT AND DISCUSSION:

For designing the versatile powder dispenser, market survey step found to be useful to eliminate the unsuitable mechanisms required for designing the desired powder dispenser. Past experience of designing the powder dispensers also helped in eliminating the unsuitable mechanisms. The screw feeder based powder dispenser needed unknown properties of the Zr-Mo powder to get unfolded to design it. Accordingly, due to limitations related to handling of the radioactive powder, the gadgets were designed to know the least desired properties. Four gadgets were designed and powder properties were found out. Based on the test results, the principle components like hopper, screw dimensions like pitch, diameter, motor rating etc were finalized. The designed machine fabricated for testing the results. The machine achieved a dispensing rate of 0.2g/s. Additionally, the machine delivered more than 99% powder to the destination (<1% fines).

Further work on the improvement of the design of the powder dispenser was done by using the methodology of experiments. It resulted in finalizing an hopper having 50° hopper side slope angle over the hopper with stirrer in first design. Selection was based on the factors like maximum flow rate through the established screw feeder, minimum retention of the powder in the hopper. Further, characterization of screw feeder with the ϕ_s =50° hopper was done by experimentation only and it has been found that irrespective of the powder bulk density, the flow rate remains constant ~0.3g/s.

In order to get exact idea about the behavior of the developed powder dispenser mainly the flow rate with respect to the variables on which the flow rate depends, mathematical modeling of the hopper using dimensional analysis and graphical method has been done. In this analysis, total 11 independent terms first were reduced to eight and further to four. For mathematical modeling, four independent terms have been further converted to one by forming various combinations using multiplication and division and the behavior of the various combinations was plotted on graph paper (correlated by Log). Combinations which were complex for deriving an equation using graphical method using Log graph were removed from the primary list. By using the general equation of the line, mathematical model has been formed by using graphical method in the form of the mathematical equation. While forming the mathematical model, it has been observed that geometric properties influence more that the material (powder, hopper material, air) properties. For example, the ∏'1 (=(D2 . H . D_P)/ D1) term when it is alone in numerator, the curve slope is descending (fig. 7) and when it is alone in denominator, the curve slope is ascending (fig. 11). That is Z is inversely proportional to the hopper geometry. It is observed that for certain range the behavior of the process changes thus leading to change in the characteristic equation. This postulate that governing equation changes with the range of variables.

From the characteristic graphs in fig. 7,9,14, 19, 21 it is found that the bulk density (ρ_p) is influencing the dependent variable (Z) indirect proportionately irrespective of the position of the D1 i.e. orifice diameter of the hopper. When the bulk density (ρ_p) is in the numerator of the mathematical model equation, both ascending and descending curves have been noticed (fig. 11 and 16), thus the corresponding model only gives the idea about the influence of powder bulk density and not the final solution to the problem of modeling of the process.

Based on the experimental values and the model output, modeling efficiency (MEF) has been calculated. In all cases, MEF is negative. This means that the model predicted values are worst than the experimental values. Amongst the several reasons, influence of the powder dispenser limitation, error in calculation of the Zr-Mo properties, deviation between the environmental parameters at the time of experiment and values of the same considered in the mathematical model calculation may have contributed in subzero MEF.

SUMMARY AND CONCLUSIONS

An ergonomically superior, versatile, variable dispensing capacity screw feeder based powder dispenser with a stirrer has been designed and successfully deployed at the Geltech generator facility of the BRIT at Vashi complex. It gave the delivery rate of 0.21g/s (for Zr-Mo powder) which will help in controlling the mass of the powder dispensed in the glass column or tube by controlling it using the timer.

Further, with the objective of removing the stirrer from the hopper and to get highest achievable flow using the conical hopper, experiments were conducted to select the most desired angle of the side wall slope (ϕ_s) of the hopper. By using the methodology of experiments, design and fabrication of the hopper having 50° side slope angle has been selected over the hopper with stirrer. Selection was based on the factors like maximum flow rate through the established screw feeder, minimum retention of the powder in the hopper. Further, characterization of screw feeder with the 50° hopper was done by experimentation only and it has been found that irrespective of the powder bulk density, the flow rate remains constant ~0.3g/s as compared to the delivery rate of 0.21g/s in the old design with stirrer.

Since the powder is heterogeneous, in order to get exact idea about the behavior of the powder dispenser mainly the flow rate with respect to the variable on which the flow rate depends, mathematical modeling using dimensional analysis and graphical method has been done. Total 11 independent terms first were reduced to four. In order to get exact idea about the dispensing process, four independent terms further converted to one by forming various combinations using multiplication and division and the behaviour of the various combinations were plotted on graph paper. By using the general equation of the line, mathematical model has been formed by using graphical method in the form of the mathematical equation. It is found that Z is inversely proportional to the hopper geom-

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etry. It is observed that for certain range the behavior of the process changes thus leading to change in the characteristic equation. This postulate that governing equation changes as the range of variables. Z is influenced by the bulk density more than the geometry of the hopper. It can be concluded that the mathematical models in equation 6, 9, 12, 13 and 14 gives more closer and clear relationship between the dependent and independent variable of the process.

Based on the experimental values and the model output, modeling efficiency (MEF) has been calculated. In all cases, MEF is negative meaning the model predicted values are worst than the experimental values. Amongst the several reasons, influence of the powder dispenser limitation, error in calculation of the Zr-Mo properties, deviation between the environmental parameters at the time of experiment and values of the same considered in the mathematical model calculation may have contributed in sub-zero MEF. Further work on this modeling will be concentrated on achieving the MEF between 0-1 by improving the powder testing methods and machines, using computer program to draw the curve and mean curve etc.

ACKNOWLEDGEMENT

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TABLE -1
FLOW RATE, g/s THROUGH THE HOPPER HAVING DIFFERENT CONE ANGLE FOR DIFFERENT BULK DENSITY Zr-Mo POWDERS

Cone angle in degree	36	38	40	41	44	47	51	55	56	63
Bulk density, g/cc										
1.32	0.37	0.39	0.4	0.407	0.415	0.423	0.402	0.402	0.4	0.4
1.4	0.468	0.485	0.459	0.453	0.402	0.402	0.402	0.395	0.395	0.395
1.355	0.398	0.406	0.423	0.429	0.442	0.448	0.448	0.448	0.451	0.462

TABLE -2 DIMENSIONS OF THE VARIABLES

VARIABLES	DIMENSION
D1	L
D2	L
H	L
D_p	L
μ_a	$ML^{-1}T^{-1}$
ρ_a	ML^{-3}
ρ_p	ML^{-3}
G	LT^{-2}
μ_I	Dimensionless
μ_{ps}	Dimensionless
Q	MT^{-1}

TABLE -3 PRODUCT OF REARRANGED VARIABLES

Sr no.	Diameter D2, mm	$\Pi'_1 = (D2 . H . D_P)/ D1$ (10^{-4})	$\Pi'_2 = \mu_{ps} \times \mu_i$	$\Pi'_3 = \rho_p / \rho_a$ (x 10^3)	$\Pi'_4 = \mu_a / D1^{1.5} \rho_a g^{0.5}$ (10^{-5})	$Q / D1^{2.5} \rho_a g^{0.5}$ (Z)	Bulk density, g/cc
1	95.6	7.5	0.476	1.1	323.5	5.109	1.32
2	94.6	7.42	0.476	1.1	323.5	5.385	1.32
3	94	7.37	0.476	1.1	323.5	5.52	1.32
4	82	6.43	0.476	1.1	323.5	5.62	1.32
5	75	5.884	0.476	1.1	323.5	5.73	1.32
6	69	5.413	0.476	1.1	323.5	5.84	1.32
7	51.6	4.048	0.476	1.1	323.5	5.55	1.32
8	95.6	7.5	0.476	1.667	323.5	6.46	1.4
9	94.6	7.42	0.476	1.667	323.5	6.69	1.4
10	94	7.37	0.476	1.667	323.5	6.33	1.4
11	82	6.43	0.476	1.667	323.5	6.25	1.4
12	75	5.884	0.476	1.667	323.5	5.55	1.4
13	69	5.413	0.476	1.667	323.5	5.55	1.4
14	51.6	4.048	0.476	1.667	323.5	5.55	1.4
15	95.6	7.5	0.476	1.129	323.5	5.49	1.355
16	94.6	7.42	0.476	1.129	323.5	5.6	1.355
17	94	7.37	0.476	1.129	323.5	5.84	1.355
18	82	6.43	0.476	1.129	323.5	5.92	1.355
19	75	5.884	0.476	1.129	323.5	6.103	1.355
20	69	5.413	0.476	1.129	323.5	6.186	1.355
21	51.6	4.048	0.476	1.129	323.5	6.186	1.355

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TABLE -4

Sr. no.	Z Calculated	X						
		$(\Pi'_2 \times \Pi'_3) / (\Pi'_4 \times \Pi'_1)$ (10^8)	$(\Pi'_1 \times \Pi'_2) / (\Pi'_3 \times \Pi'_4)$ (10^{-4})	$(\Pi'_1 \times \Pi'_4) / (\Pi'_2 \times \Pi'_3)$ (10^{-8})	$(\Pi'_4 \times \Pi'_2) / (\Pi'_1 \times \Pi'_3)$ (10^{-3})	$(\Pi'_4 \times \Pi'_2 \times \Pi'_3) / \Pi'_1$ (10^2)	$(\Pi'_1 \times \Pi'_2 \times \Pi'_4) / \Pi'_3$ (10^{-10})	$\Pi'_1 / (\Pi'_2 \times \Pi'_3 \times \Pi'_4)$ (10^{-4})
1	5.109	2.163	1	0.462	1.866	22.588	10.47	4.427
2	5.384	2.181	0.99	0.458	1.88	22.835	10.38	4.379
3	5.52	2.196	0.985	0.455	1.899	22.985	10.31	4.35
4	5.62	2.517	0.8597	0.397	2.177	26.351	9	3.79
5	5.73	2.751	0.786	0.363	2.38	28.8	8.23	3.472
6	5.84	2.99	0.723	0.334	2.586	31.297	7.57	3.195
7	5.55	4	0.541	0.25	3.459	41.854	5.66	2.389
8	6.46	3.278	0.661	0.305	1.231	34.231	6.909	2.921
9	6.69	3.306	0.654	0.302	1.245	34.605	6.85	2.889
10	6.33	3.328	0.65	0.3	1.253	34.832	6.806	2.8709
11	6.25	3.815	0.567	0.262	1.436	39.934	5.93	2.504
12	5.55	4.169	0.519	0.239	1.57	43.646	5.43	2.291
13	5.55	4.531	0.4776	0.22	1.706	47.429	4.99	2.108
14	5.55	6.06	0.357	0.165	2.282	63.428	3.73	1.576
15	5.49	2.22	0.977	0.450	1.818	23.184	10.2	4.313
16	5.6	2.239	0.966	0.446	1.838	23.436	10.11	4.266
17	5.84	2.254	0.960	0.4436	1.8508	23.59	10	4.239
18	5.92	2.583	0.8377	0.387	2.121	27.045	8.76	3.697
19	6.103	2.823	0.766	0.354	2.319	29.559	8.02	3.383
20	6.186	3.069	0.705	0.325	2.52	32.122	7.38	3.113
21	6.186	4.105	0.527	0.243	3.37	42.957	5.518	2.327

TABLE -5

Combination of Π' terms	Derived Mathematical Model	Bias, B	Standard deviation, SD	Predicted mean square error, MSE	Modeling efficiency, MEF
$(\Pi'_1 \times \Pi'_2 \times \Pi'_4) / \Pi'_3$ (10^{-10})	$Z = (18) \times (X.10^{-10})^{-0.5509}$	-1947207	316627.4	3.89E+12	-2.5E+13
$(\Pi'_2 \times \Pi'_3) / (\Pi'_4 \times \Pi'_1)$	For curve-A $Z= 3.1[(X).(10^8)]^{0.6349}$	-766291.29	20898987295	6.08101E+11	-3.93E+12
	For curve B **$Z= 8.8[(X).(10^8)]^{(-0.2594)}$**	5.775726	0.394533	33.51467	-215.542
$(\Pi'_4 \times \Pi'_2 \times \Pi'_3) / \Pi'_1$ (10^2)	For Curve –A **$Z= 1.2 [X (10^2)]^{0.4804}$**	-52.5082	8.151633	2823.555	-18242.3
	For Curve –B **$Z = 7.4 [X (10^2)]^{-0.0671}$**	1.523319	0.421634	2.498275	-15.1416
$(\Pi'_4 \times \Pi'_2) / (\Pi'_1 \times \Pi'_3)$ (10^{-3})	$Z = 4.5 (X (10^{-3}))^{0.3714}$	-40.0242	4.642812	1623.492	-10488.5
$\Pi'_1 / (\Pi'_2 \times \Pi'_3 \times \Pi'_4)$ (10^{-4})	$Z = 9.6 [X (10^{-4})]^{-0.3956}$	-228.985	26.97449	53161.9	-343483
$(\Pi'_1 \times \Pi'_2) / (\Pi'_3 \times \Pi'_4)$ (10^{-5})	$Z = 15 [X (10^{-5})]^{-0.4455}$	-1059.4449	138.6136	1141637	-7376230

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$(\Pi'_1 \times \Pi'_4)/(\Pi'_2 \times \Pi'_3)$ (10^{-10})	$Z = 9.2\,[X\,(10^{-10})]^{-0.1328}$	-117.39631	4.585255	13802.92	-89181.03547

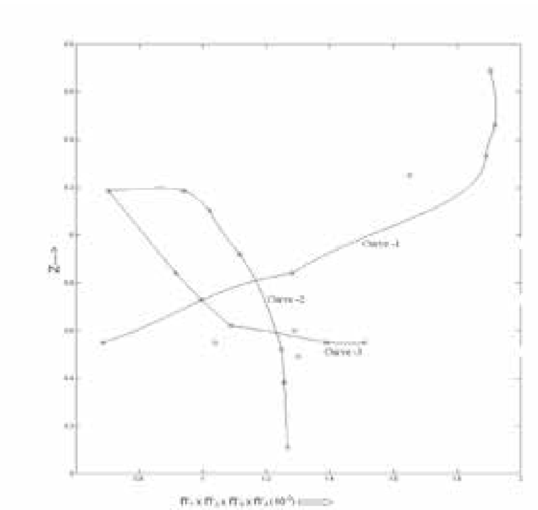

Figure 4: For $(\Pi'_1 \times \Pi'_2 \times \Pi'_3 \times \Pi'_4)$ (10^{-3})

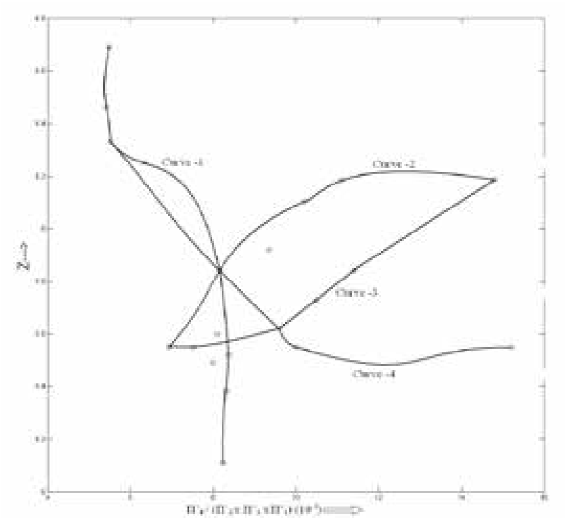

Figure 5: Curve for $\Pi'_4 / (\Pi'_2 \times \Pi'_3 \times \Pi'_1)$

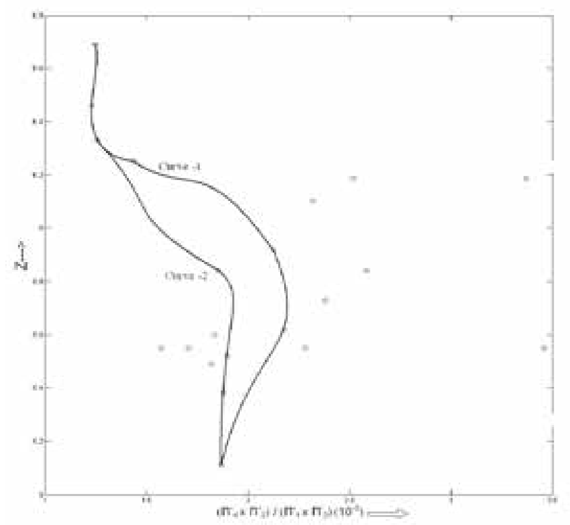

Figure 6: Curve for $(\Pi'_4 \times \Pi'_2) / (\Pi'_1 \times \Pi'_3)$ (10^{-3})

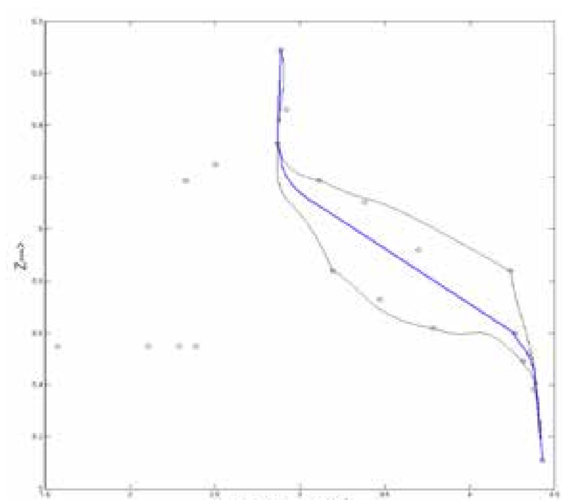

Figure 7: Mean curve for $\Pi'_1 / (\Pi'_2 \times \Pi'_3 \times \Pi'_4)$

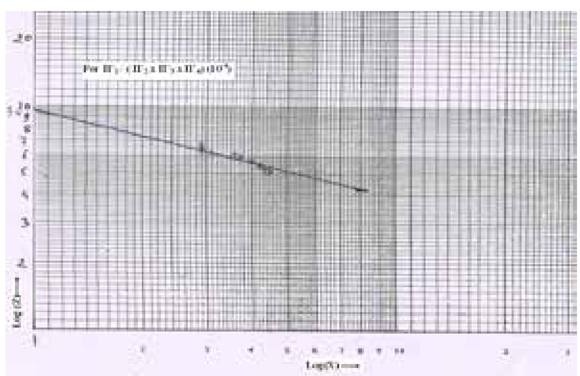

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Figure 8: Plot on Logarithmic scale for $\Pi'_1 / (\Pi'_2 \times \Pi'_3 \times \Pi'_4)$

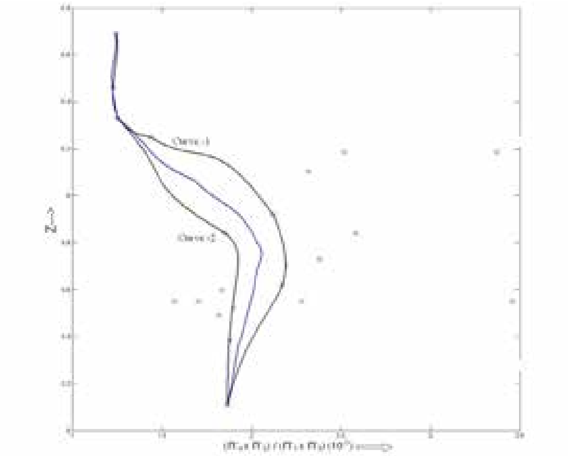

Figure 9: Mean curve for $(\Pi'_4 \times \Pi'_2) / (\Pi'_1 \times \Pi'_3)$

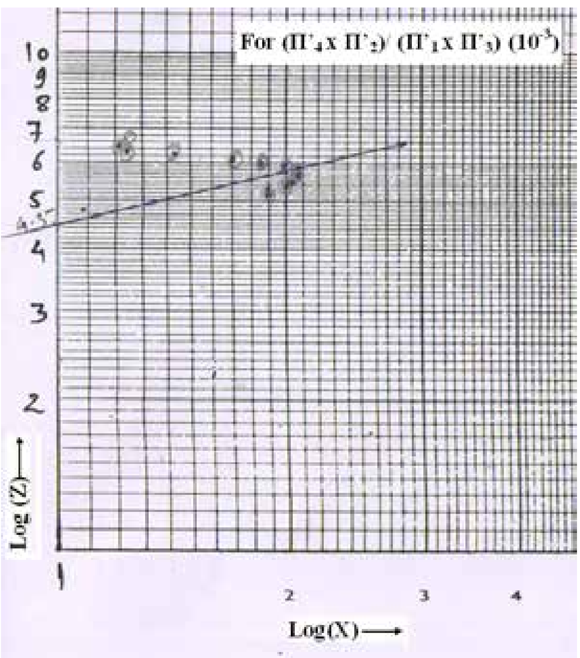

Figure 10: Plot on Logarithmic scale for $(\Pi'_4 \times \Pi'_2) / (\Pi'_1 \times \Pi'_3)$

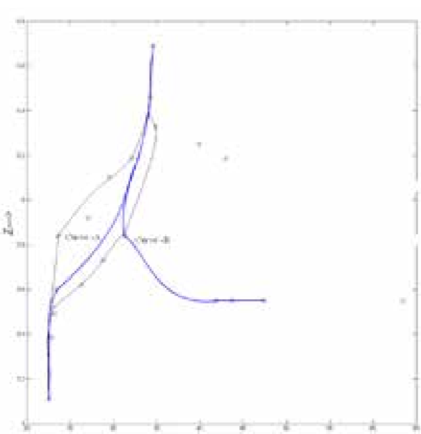

Figure 11: Mean curve for $(\Pi'_4 \times \Pi'_2 \times \Pi'_3)/ \Pi'_1$

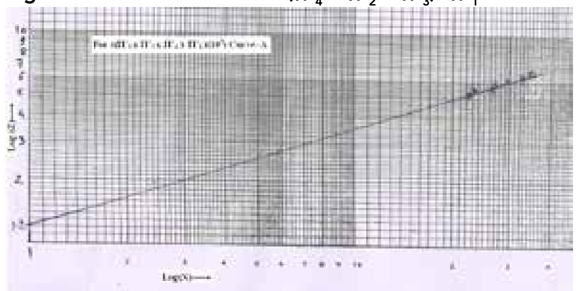

Figure 12: Plot on Logarithmic scale for $(\Pi'_4 \times \Pi'_2 \times \Pi'_3)/ \Pi'_1$, curve –A

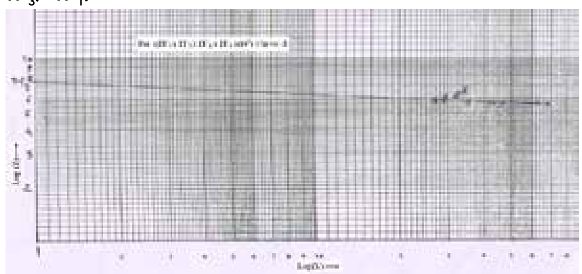

Figure 13: Plot on Logarithmic scale for $(\Pi'_4 \times \Pi'_2 \times \Pi'_3)/ \Pi'_1$, curve –B

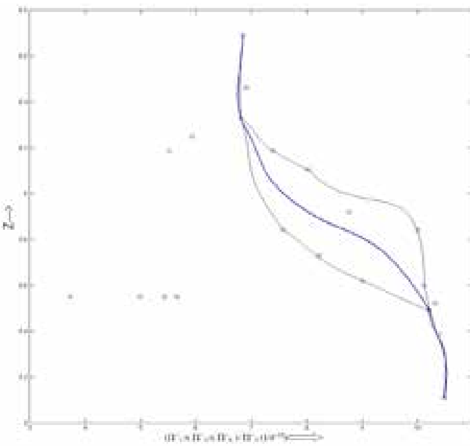

Figure 14: Mean Curve for $(\Pi'_1 \times \Pi'_2 \times \Pi'_4)/ \Pi'_3$

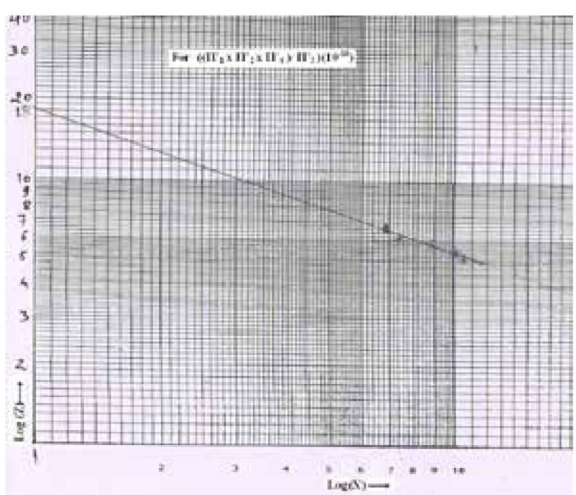

Figure 15: Plot on Logarithmic scale for $(\Pi'_1 \times \Pi'_2 \times \Pi'_4)/ \Pi'_3$

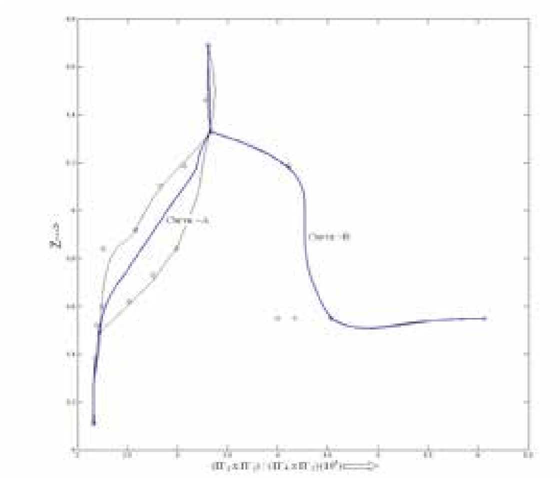

Figure 16: Mean Curve for $(\Pi'_2 \times \Pi'_3) / (\Pi'_4 \times \Pi'_1)$

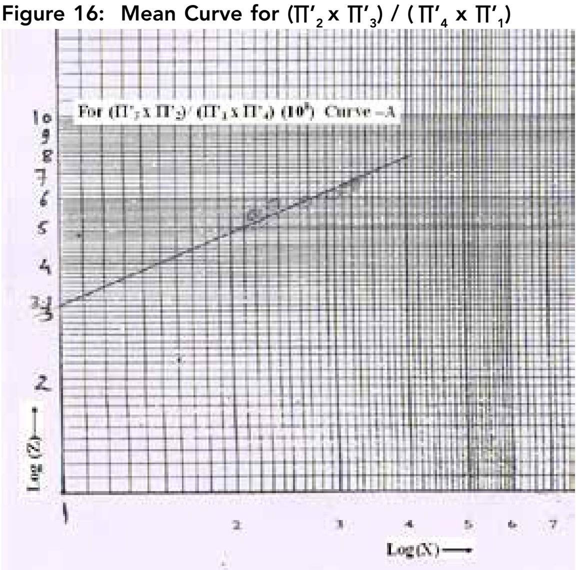

Figure 17: Plot on Logarithmic scale for $(\Pi'_2 \times \Pi'_3) / (\Pi'_4 \times \Pi'_1)$ curve-A

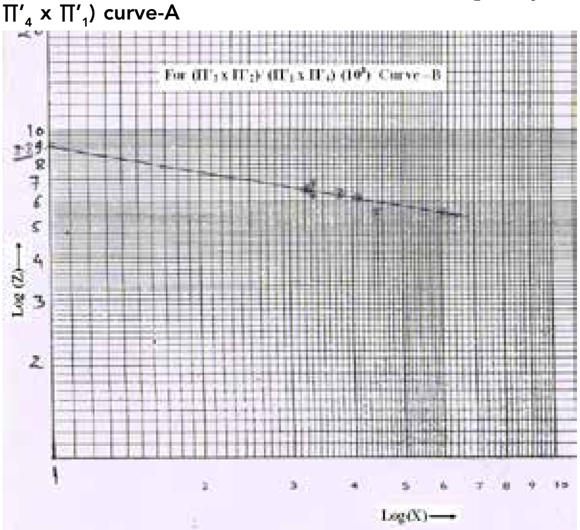

Figure 18: Plot on Logarithmic scale for $(\Pi'_2 \times \Pi'_3) / (\Pi'_4 \times \Pi'_1)$ curve-B

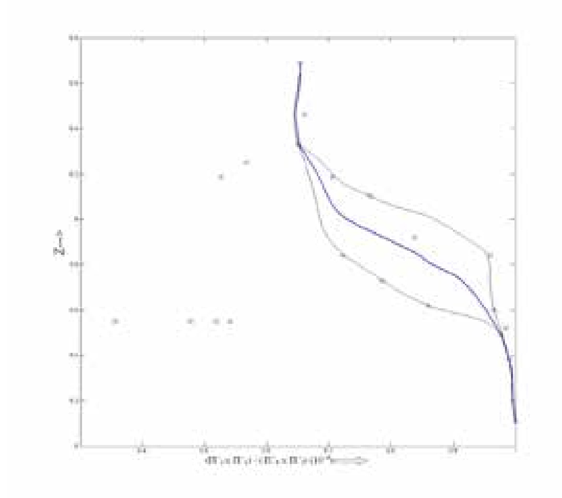

Figure 19: Mean Curve for $(\Pi'_1 \times \Pi'_2) / (\Pi'_3 \times \Pi'_4)$

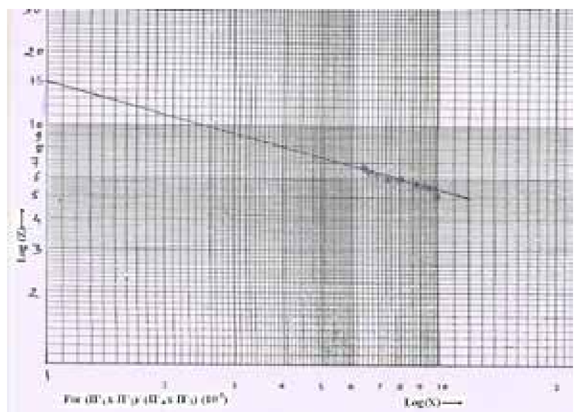

Figure 20: Plot on Logarithmic scale for $(\Pi'_1 \times \Pi'_2) / (\Pi'_3 \times \Pi'_4)$

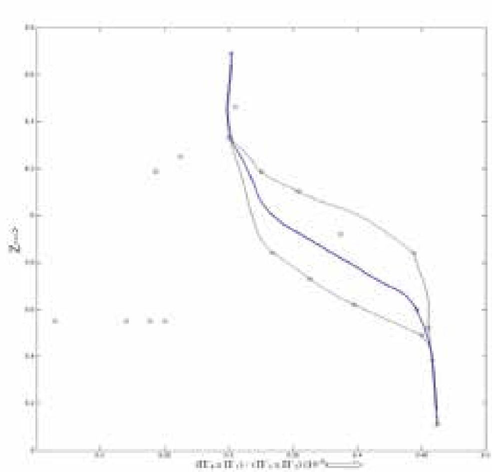

Figure 21: Mean Curve for $(\Pi'_1 \times \Pi'_4) / (\Pi'_2 \times \Pi'_3)$

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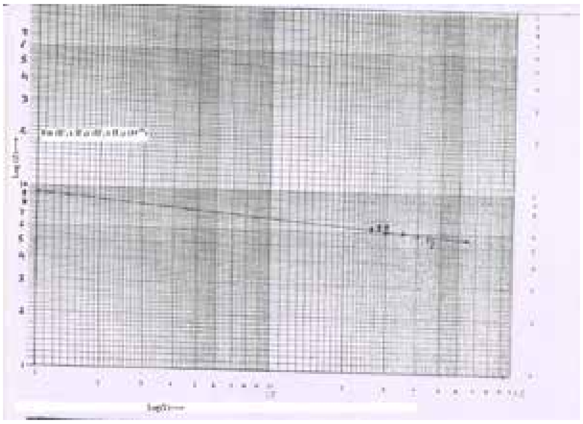

Figure 22: Plot on Logarithmic scale for (Π'_1 x Π'_4)/(Π'_2 x Π'_3)

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