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A computational Code for Sand Erosion Prediction in Elbows and Tees: An Improvement to the Direct Impingement Model to Account for Temperature Dependence

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ABSTRACT

Pipes and fittings erosion is the main consequence of sand production and transportation with oil and gas. To avoid sand erosion, sand production should either be avoided or minimized by applying a sand control technique, or sand is allowed to be produced and a sand management technique is used to avoid sand erosion. The decision of applying either sand control or sand management is normally based on technical and economical considerations. Although sand control has the advantage of minimizing sand production, sand management is the proper decision in many situations due to the high cost of the sand control job and the time spent in workover.

When sand management is applied, flow parameters must be managed to avoid the consequences of sand flow. The safe operations limits of flow velocity must be defined. The high limit of the velocity is referred to as erosional velocity, above which sand erosion is likely to take place. The lower limit is the sand settlement velocity, below which sand settles and accumulates at the bottom of the pipe.

When sand erosion is expected to occur, erosion rate is to be predicted at different sand fluxes and for different fluids parameters and target materials. An optimum process with appropriate material used may be selected to minimize wear to a pipe component. Different models are

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applied to sand erosion predictions but every model suits a specific fluid, geometry, material, and range of data.

A computational package with graphical user interface has been developed by implementing two models using the Visual Basic Programming Language (VB 6) as an attempt to provide a comprehensive sand erosion prediction tool. The first model is an empirical correlation used to predict sand erosion rate in four geometries. In this model sand particles velocity is assumed to be identical to the flowstream velocity. This assumption makes the model not applicable to liquid flow in which particle velocity is different than flow stream velocity. The second model is a semi-empirical model which solves the shortcoming of the empirical model by, first, predicting the sand particles velocity, and then, substituting it into a sand erosion prediction model.

This paper discusses the two models and describes their implementation. The paper, in addition, proposed an improvement to the direct impingement model to account for temperature effects on particles velocity and erosion rate. By this improvement, we believe that more accurate results will be obtained when dealing with crude oils.

Keywords: sand erosion, salama model, direct impingement model

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1. INTRODUCTION

Sand is mostly expected to be produced with oil and gas whenever one of the following conditions is encountered (Salama, 2000; Fajaer et al., 1992):

i. Low strength formations (<2000 pasi)

ii. Water breakthrough

iii. Low pressure (reservoir pressure depletion)

iv. High lateral tectonics

Depending on the amount of produced solids, the severity of solids production problem ranges from a minor problem (few grams per cubic meter) to a complete filling of the tubing. Although the problem can occur in coal and chalk reservoirs, it is most likely to occur in sand reservoirs, hence sand production is the terminology usually used (Fajaer et al., 1992).

In addition to sand produced from the production formations, other particulates come from drilling fluids, completion, or sand control packs may enhance sand erosion (Oyeneyin M.B., Peden J.M., Hossieni Ali, Ren G., 1995)

Two methods are used to prevent sand production and solve the problems arisen by. The first method is sand control by which sand production is avoided or minimized to an acceptable level. The second method is sand management which allows sand production but avoids its consequences by the monitoring and controlling of well pressures, fluid rates and sand influx (Tronvol J. et al., 2001)

One of the main consequences of sand production with oil and gas is wear and erosion of the sub-surface components and surface facilities. The erosion frequently takes place at components that cause flow disturbances such as elbows, tees, and valves (Salama, 2000). N A Barton

(Barton N. A., 2003) has arranged the components where erosion takes place according to erosion vulnerability in six ranks from chokes as the most vulnerable component to straight pipes as the least vulnerable component.

The erosion in a ductile material takes a form of the material removal due to localized plastic strain and fatigue, whereas; in brittle materials surface cracking and chipping takes place as a result of particles impingement (Oyeneyin M.B., Peden J.M., Hossieni Ali, Ren G., 1995).

The ultimate effect on a component may takes the form of wall thinning which may progress gradually to cause total failure of the component. Many problems may result from the component failure such as the costs due to the component replacement, the production loss due to leakage and process shutdown, and the environmental pollution.

The factors which affect the sand erosion, in general, can be grouped into three groups. The first group is the parameters that are related to fluid flow such as velocity and fluid properties. The second group is the parameters that are related to sand flow such as sand flow rate and particles characteristics. And the third group is the parameters that are related to the target component such as material hardness and geometry.

To evaluate the erosion rate for a specific material, experimental investigations can be carried out in a measurement device such as jet impingement or lab-scale flow loops. The experimental results can be formulated as empirical correlations for future application as prediction tools. The main shortcoming of the empirical correlations is its ignorance of sand particles tracking along the flowstream. To solve this problem semi-empirical or computational fluid dynamics (CFD) models can be used. In the semi-empirical models the sand velocity is first tracked preceding its substitution to the model. In the CFD model the solution accuracy is further promoted by employing flow and turbulence solutions.

In this work, selected empirical and semi-empirical models have been employed to the visual basic (VB 6) programming language to develop an easy-to-use, accurate, and flexible friendly-user-interface package for sand erosion prediction in elbows and tees. The paper discusses the employed models and their implementations along with the package results and validations.

Nomenclature

c	constant in API equation for erosional velocity.
D	Pipe diameter [m]
d, d_p	Particle size [m]
ER	Erosion rate [mm/year]
G	API gravity
h	penetration rate [kg/kg]
L	The equivalent stagnation length [m]
P	Hardness parameter [psi]
Re_o	Particles Reynolds number.
S_m	Constant account for geometry in Salama model.
SG	Specific gravity.
T	Temperature [^{o}F].
V_e	Erosional Velocity [m/s].
V_g	Gas velocity [m/s].
V_l	Liquid Velocity [m/s].
V_p	Particle velocity [m/s]
Vm	Mixture velocity [m/s].
W	Sand production rate [kg/s]
ρ_m	Mixture density [kg/m^3]
ρ_f	Fluid density [kg/m^3]
ρ_p	Particle density [kg/m^3].
μ_f	Fluid viscosity Ps.s
Ø	The dimensionless mass ratio.

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2. BACKGROUND

In general, three methods have been proposed for sand erosion prediction in a flow process. The first method is the prediction of erosion rate for a component (most probably elbow or tee) by using the fluid velocity (no particles or bubbles tracking). This method is commonly based on simple empirical correlations that predict erosional velocity (the velocity above which erosion occurs) and erosion rate and it is more applicable to gas flow where the dispersed phase (particles or bubbles) is almost following the fluid mean velocity. The erosional velocity V_e is widely predicted using the American Petroleum Institute Recommended Practice (API RP 14 E) equation

$$V_e = \frac{c}{\sqrt{\rho}} \qquad (1)$$

Where C is constant, its value as proposed by API RP 14 E is 100 for continuous service and 125 for intermittent service and ρ is density.

Many researchers and investigators questioned the accuracy of equation1 on grounds of neglecting of other important factors such as particles size and shapes, component geometries and fluid viscosity. Therefore many attempts have been made to enhance the accuracy and extend the applicability of RP 14 E equation. Salama and Venkatesh proposed the following model for penetration rate prediction in elbows and tees (Salama M. M. and Venkatesh E. S., 1983).

$$h = 93000 \frac{WV^2}{PD^2} \qquad (2)$$

Where h is the penetration rate (mpy), W is sand production rate (bbl/month), V is the fluid flow velocity (ft/s), P is the hardness parameter (psi), and D is the pipe diameter (inch). This equation has been further reduced and rearranged by Salama and Venkatesh by using P value of 1.55X105 for steel and assuming an allowable penetration rate of 10 mpy. Their efforts result in the following equation for erosional velocity.

$$V_e = \frac{4D}{\sqrt{W}} \qquad (3)$$

The shortcomings of Salama and Venkatesh model (equation 2) are its neglecting of sand particle size and shape and its inapplicability to two-phase (liquid-gas) flow. Salama (Salama, 2000) incorporated the effect of two-phase mixture density and particle size into equation 2 and proposed the following equation.

$$ER = \frac{1}{S_m} \frac{WV_m^2 d}{D^2 \rho_m} \qquad (4)$$

Where ER is the erosion rate (mm/year), W is the sand production rate kg/day, d is particle diameter (micron), D is the pipe internal diameter (mm), and V_m and ρ_m are mixture velocity (m/s) and density (kg/m3). S_m In equation (4) is a geometry-dependant constant given in table 1. Equation 4 has been created through numerous of tests that carried out using water and nitrogen gas. Since water and gas viscosity is almost constant, so no viscosity parameter is included in the equation. Salama, however, expected that higher viscosity will result in reduction of erosion rate (Salama, 2000).

The second method is the prediction of sand erosion using simplified particles trajectory equations (the direct impingement model). This is a mechanistic model developed by Erosion/Corrosion research center (E/CRC) in University of Tulsa to predict the penetration rate of direct impingement of elbows and tees. The direct impingement model can predict the

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penetration rate after determining the direct impact velocity, erosion ratio, and erosion rate. The data required for the direct impingement model are those relating to the component (geometry and size), flow (velocity, density and viscosity), and particle (density, size, and shape). To account for the particle trajectory along flow stream the concept of equivalent stagnation length has been introduced. The concept of equivalent stagnation length can be explained by the same way of the equivalent length used to predict local pressure loss in fittings, in that, different components geometries have different equivalent stagnation lengths.

The third method is the use of computational fluid dynamics (CFD) models to simulate erosion generated by sand particles. Using the CFD model, sand erosion calculation is performed subsequent to flow solution (using conservation equations and turbulence models) and sand tracking (using Eulerian or Lagrangian method).

In this paper the first and second methods are utilized to develop a computational code for sand erosion prediction in elbows and tees.

3. THE MODELS IMPLIMENTATION

A computational code for sand erosion prediction has been developed by employing Salama model and the direct impingement model into the visual basic programming language (VB 6). These two models are selected in order to make it applicable to wide span of fluids, geometries, and materials. Salama model is simple and requires fewer input data than direct impingement model, but it is not applicable to liquid flow because no account is taken of particles trajectory along the flowstream. In addition to its accounts to particles motion, direct impingement model furthermore accounts for the particle shape (angularity) and target material hardness.

Therefore, by the combination of the two models in one package it is possible to choose the suitable model according to the available data, the flow medium, and the desired output.

SALAMA MODEL

Salama empirical correlation for multi-phase flow (equation 4) has been employed for sand erosion prediction in elbows and tees containing a single phase or a high gas liquid ratio two-phase flow. For the two-phase flow, the mixture density is calculated using the following equation:

$$\rho_m = \frac{\rho_g V_g + \rho_l V_l}{V_g + V_l} \qquad (5)$$

Fig 1 shows the flowchart of this model illustrating the calculations procedure and the graphical user interface of the model along with output examples.

DIRECT IMPINGEMENT MODEL

The direct impingement model relates the erosion rates of complex geometries such as elbows and tees to erosion rate occurring in direct (normal) impingement (Mclaury B. S., 1996). The main attribute of this model is its account to particles trajectory along flow stream. This attribute makes it more suitable for liquid and low gas-oil-ratio flows than Salama model. The particles trajectory is achieved using a computational fluid dynamics based equation of particles motion. The equation of particle motion can be written in differential form as follows (Mclaury B. S., 1996):

$$\frac{dV_p}{dx} = 0.75\left(\frac{1}{d_p}\right)\left(\frac{\rho_f}{\rho_p}\right)\left[\frac{0.5(V_f - V_p)\left|V_f - V_p\right|}{V_p} + \frac{24\mu_f (V_f - V_p)}{V_p \rho_f d_p}\right] \qquad (6)$$

Based on the above equation, three dimensionless terms have been proposed by the Erosion/Corrosion Research Center (ECRC), University of Tulsa to predict the impingement velocity on a tee or elbow surface (Mclaury B. S., 1996, Shirazi et al., 1995, Mclaury and Shirazi, 1999). The first term is called the dimensionless impact velocity defined as the ratio of

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impact velocity to flow stream velocity. The second dimensionless term is the particle Reynolds number based on the flow stream velocity. And the third dimensionless term is called the mass ratio defined as the ratio of the mass of fluid to the mass of particles.

Prior to impingement, a particle is assumed to penetrate a specific distance called stagnation zone. The length of this zone, so-called equivalent stagnation length, can be determined graphically or calculated using the following equations (Mclaury B. S., 1996):

For elbow:

$$\frac{L}{L_0} = 1 - 1.27\tan^{-1}(1.01D^{-1.89}) + D^{0.129} \qquad (7)$$

L_0 =1.18 inches

For Tee

$$\frac{L}{L_0} = 1.35 - 1.32\tan^{-1}(1.01D^{-2.96}) + D^{0.247} \qquad (8)$$

L_0 =1.06 inches

The equivalent stagnation length is used to calculate the mass ratio using the following equation:

$$\phi = \left(\frac{L}{d_p}\right)\left(\frac{\rho_f}{\rho_p}\right) \qquad (9)$$

The particle Reynolds number is calculated using the following equation:

$$\mathrm{Re}_o = \frac{V_f d_p \rho_f}{\mu_f} \qquad (10)$$

A graph relating the three dimensionless terms can be used to determine the dimensionless impact velocity from which the impact velocity can be obtained by multiplying it with the fluid velocity, i. e.

$$V_p = \left(\frac{V_p}{V_f}\right)V_f \qquad (11)$$

The particle velocity is then substituted to the following equation to predict the sand penetration rate (mass/mass), which can be converted to erosion rate (depth/time).

$$h = F_M F_s F_P F_{r/D} \frac{W V_l^{1.73}}{D^2} \qquad (12)$$

Where F_S, F_M and F_P are empirical factors to account for sand sharpness (angularity), the material hardness, and penetration, respectively. Their values for different sand sharpness and material can be determined from tables in (Shirazi et al., 1995) and (Mclaury and Shirazi, 1999)

$F_{r/D}$ is a factor to account for the elbow curvature and can be obtained from the following empirical equation:

$$F_{r/D} = \exp\left[-\left[\frac{0.1\rho_f^{0.4}\mu_f^{0.65}}{d_p^{0.3}} + 0.015\rho_f^{0.25} + 0.12\right]\left(\frac{r}{D} - C_{std}\right)\right] \qquad (13)$$

For two-phase flow mixture density can be calculated using equation 4 and mixture viscosity can be calculated using the following equation:

$$\mu_m = \frac{\mu_g V_g + \mu_l V_l}{V_g + V_l} \qquad (14)$$

The flowchart and the graphical user interface along with output examples are illustrated in fig 2.

Proposed improvement to the direct impingement model: The temperature-dependence erosion rate

During production and transportation of crude oils, the rheological properties of the crude are highly affected by temperature. Since particles velocity depends on the particles Reynolds number which is a function of the fluids viscosity, the particles velocity at any temperature is proposed to be predicted based on the particles Reynolds number at that temperature. Particles

Reynolds number at any temperature T can be calculated using the following formula (The effect of temperature on density is neglected):

$$\mathrm{Re}_o(T) = \frac{V_o d_p \rho_f}{\mu_f(T)} \qquad (15)$$

The viscosity at the temperature T can be calculated using Beggs and Robinson (Arnold and Stewart, 1999) correlations as follows:

$$\mu(T) = 10^{y(T)^{-1.165}} - 1 \qquad (16)$$

Where

$$y(T) = 10^{3.0324-0.02023G}$$

$\mu(T)$ is the viscosity (CP) at temperature T (oF)

G is the API gravity which can be obtained from the following correlation

$$G = \frac{141.5 - 131.5SG}{SG}$$

SG is the crude specific gravity.

4. RESULTS AND DISCUSSION

THE EFFECTS OF FLOW VELOCITY

The relationship between sand erosion and flow velocity has been proposed quantitatively by many investigators. For carbon steel the relationship is in the form $ER \propto V^n$ where V is the particle velocity and the value of the exponent n ranges from 1 to 3. Typical proposed n values for carbon steel are 1.73 (Shirazi et al., 1995), 2.6 (Haugen et al., 1995) and 2.0 (Salama, 2000). In Salama model sand particles velocity is assumed to be identical to the fluid velocity. So the

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fluid velocity can be used to calculate sand erosion. In direct impingement, however, a simplified computational fluid dynamics equation is used to track the particles within the stagnation zone to acquire the exact values of the particles velocities on the target surface. Figures 3 and 4 illustrate examples of the direct impingement model output showing the variation of sand erosion with the particle velocity.

THE EFFECTS OF PIPE DIAMETER

Figures 5 and 6 illustrate examples of the direct impingement model output showing the variation of sand erosion with internal diameter. It is clear from the two figures that the erosion rate is markedly affected by the pipe size. The erosion rate can be mitigated by increasing the pipe diameter. This fact is emphasized by figures 7 and 8 which show the variation of erosion rate with velocity for different pipe diameters. It is clearly shown that above diameter of 137.5 mm (5.5 in.), the erosion rate can be ignored for the same process as compared with the erosion rate of diameter of 25 mm (1 in.).

THE EFFECTS OF SAND PRODUCTION RATE

Both Salama model and direct impingement model assume a linear proportional relationship between sand erosion and sand production rate in kg/s. in fact, the linear relationship is only valid for low sand concentration. Salama proposes a critical concentration of 500 ppm above which the linear relationship will no longer be valid and the effects will increase (1). Fig 9 shows the variation of erosion rate with sand production rate and fig 10 shows the variation of erosion rate with velocity for different sand flow rates. The sand flow rate units in the curves are in Ft^3/year.

RESULTS OF THE TEMPERATURE DEPENDANCE MODIFICATION

Input data in table 2 is used to predict the Reynolds number and erosion rate for an elbow at different temperatures.

The results are shown in figures 11 to 13. Figure 13 shows a clear increase of the erosion rate with temperature. The erosion rate values, however, are very low due to the low velocity of the crude oil.

5. THE VALIDATION OF THE CODE

The code results have been validated using published measured data [Salama, 2000, Shirazi et al., 1995]. Good agreement has been found between the code results and the published data as shown in tables 3 and 4 and figures 14 and 15.

6. CONCLUSION

A computational code has been developed for sand erosion in elbows and tees. The new attributions of this code are the applicability to wide span of fluids type and flow conditions, the easy-to-use, the high calculation speed, and the ability to be installed and run in any computer regardless of the availability of the computer language used for the development. The combination of empirical and semi-empirical models used for sand erosion makes the code applicable to gas flow, multi-phase flow, and liquid flow with consideration of all parameters that are believed to affect erosion rates. The direct impingement model used to develop the code has been improved to account for temperature effects on particles velocity and erosion rate for crude oils.

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Table 1: The geometry-dependant constant in Salama Model

Geometry	Elbow (1.5 and 5D	Seamless and cast elbows (1.5 to 3.25 D)	Plugged tee (gas-liquid)	Plugged tee (gas flow)
S_m	5.5	33	68	1379

Table 2: The input data of temperature-dependence erosion rate

parameter	Unit	Value
Sand production rate	Kg/s	0.000886
Fluid velocity	m/s	1
Fluid density	Kg/m^3	800
Pipe diameter	mm	50.8
Particle size	Micron (10^{-6} m)	300
Sand density	Kg/m^3	2650

Table 3: The validation of the code results (Salama model) using published data

V_l m/s	V_g m/s	ρ_m kg/m^3	d sand micron	D pipe mm	Bend radius *Dpipe	ER measured mm/kg	ER predicted
1	30	34.48	150	49	5	5.52E-04	8.83E-04
5.8	20	226.59	150	49	1.5	5.19E-05	9.16E-05
6.2	9	413.5	250	26.5	5	1.8E-04	9.93-05
0.5	34.3	24.1	250	26.5	5	7.2E-03	8.98E-03
0.7	52	23	250	26.5	5	1.33E-02	2.15E-02

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Table 4: The validation of the code results (Direct Impingement model) using published data

V m/s	Sand rate kg/s	ρ_m kg/m^3	Viscosity pa.s	d sand micron	D pipe mm	Bend radius	Sand shape	Brinnel No.	ER measured Mil/year	ER predicted Mil/year
24.4	0.000886	1.2015	0.0000182	300	50.8	5	angular	109	17802	14745
9.14	0.0008801	1.2015	0.0000182	300	50.8	5	angular	109	2330	2712
12.2	0.000881	1.2015	0.0000182	300	50.8	5	angular	109	4160	4474
15.24	0.000875	1.2015	0.0000182	300	50.8	5	angular	109	8160	6530
18.29	0.0008797	1.2015	0.0000182	300	50.8	5	angular	109	9990	9016
21.34	0.000878	1.2015	0.0000182	300	50.8	5	angular	109	13300	11729
27.44	0.000886	1.2015	0.0000182	300	50.8	5	angular	109	19800	18384
30.49	0.000881	1.2015	0.0000182	300	50.8	5	angular	109	22300	21936
21.34	0.0194	1.2015	0.0000182	300	50.8	5	angular	109	107000	256062

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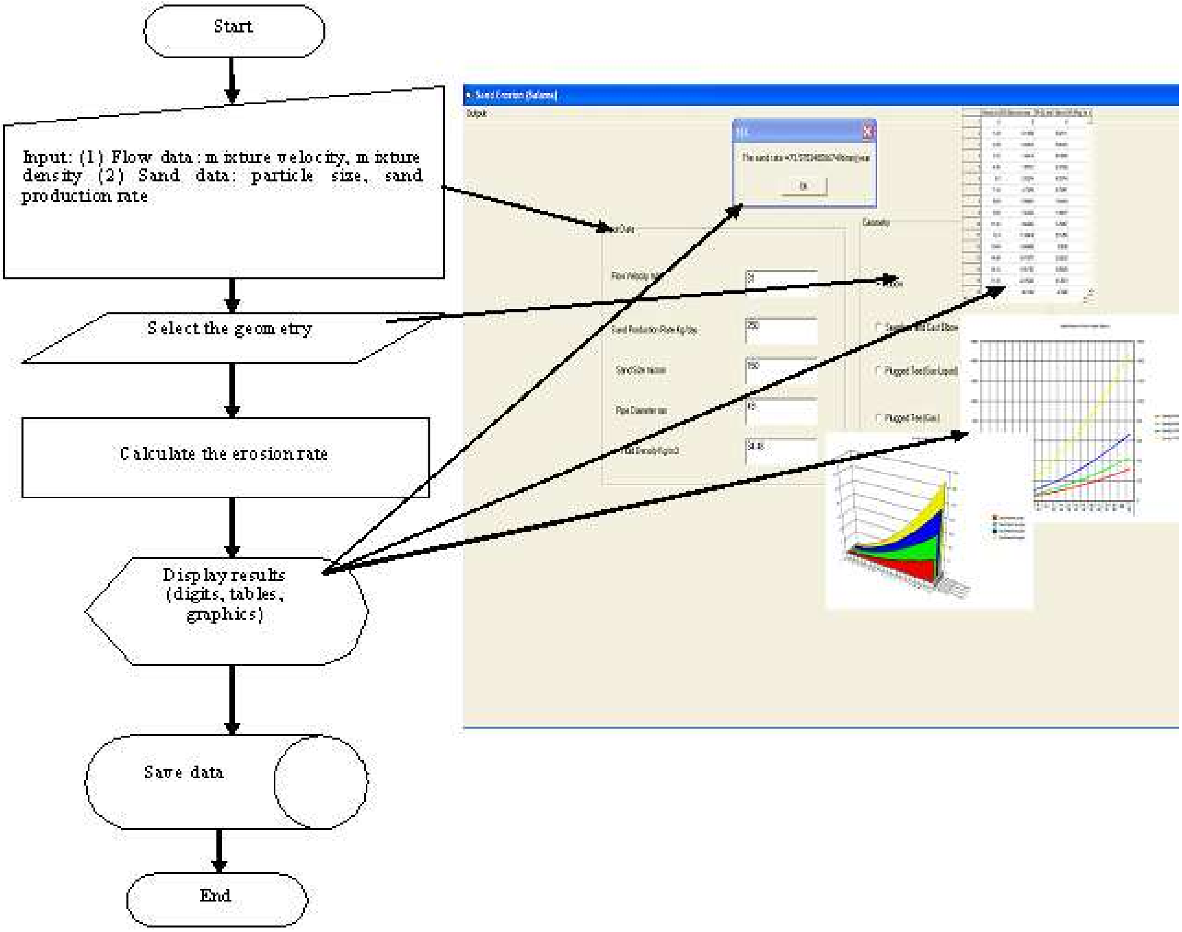

Fig 1: The GUI and flow chart of Salama model

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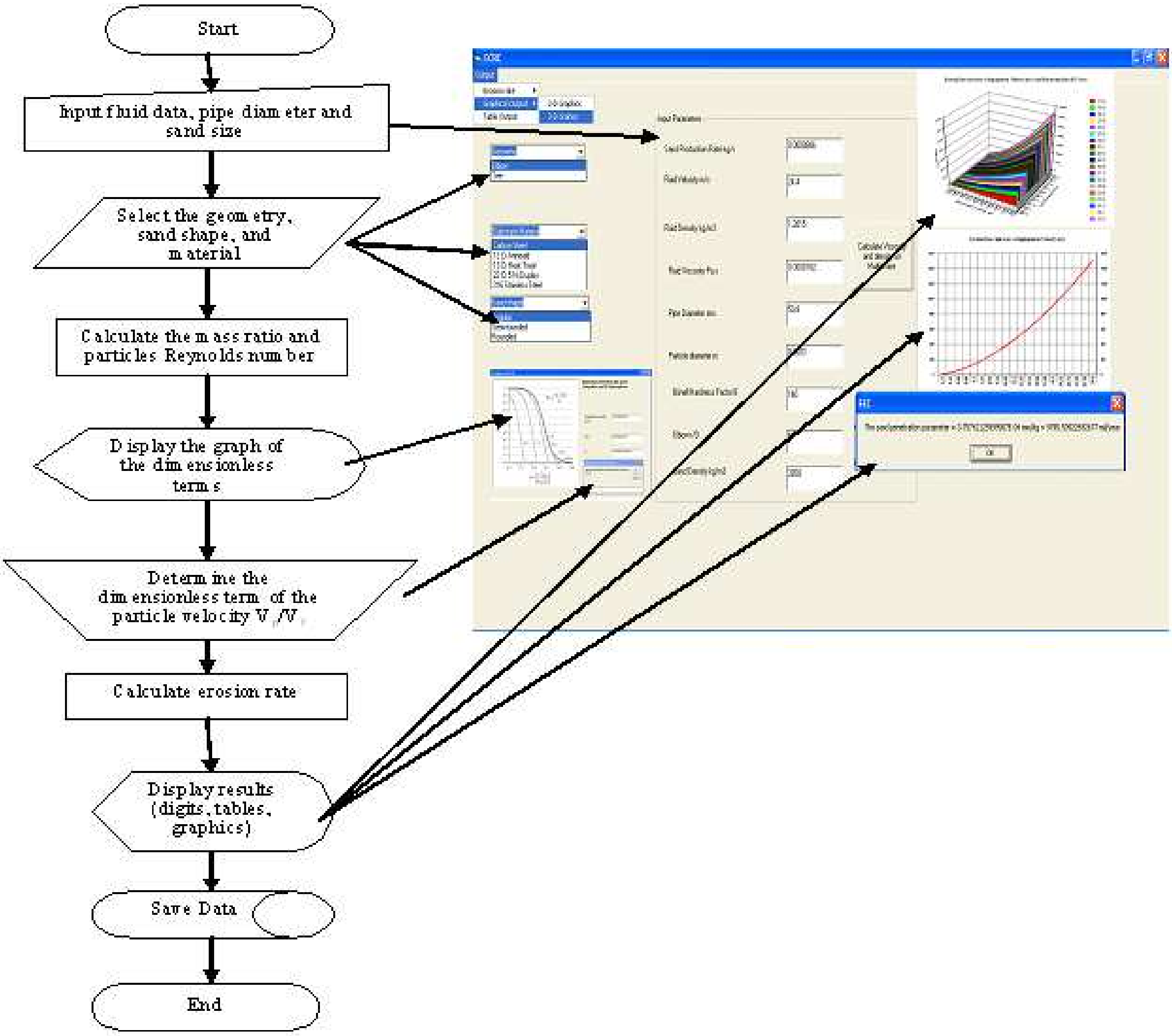

Fig 2: The GUI and flow chart of Direct Impingement model

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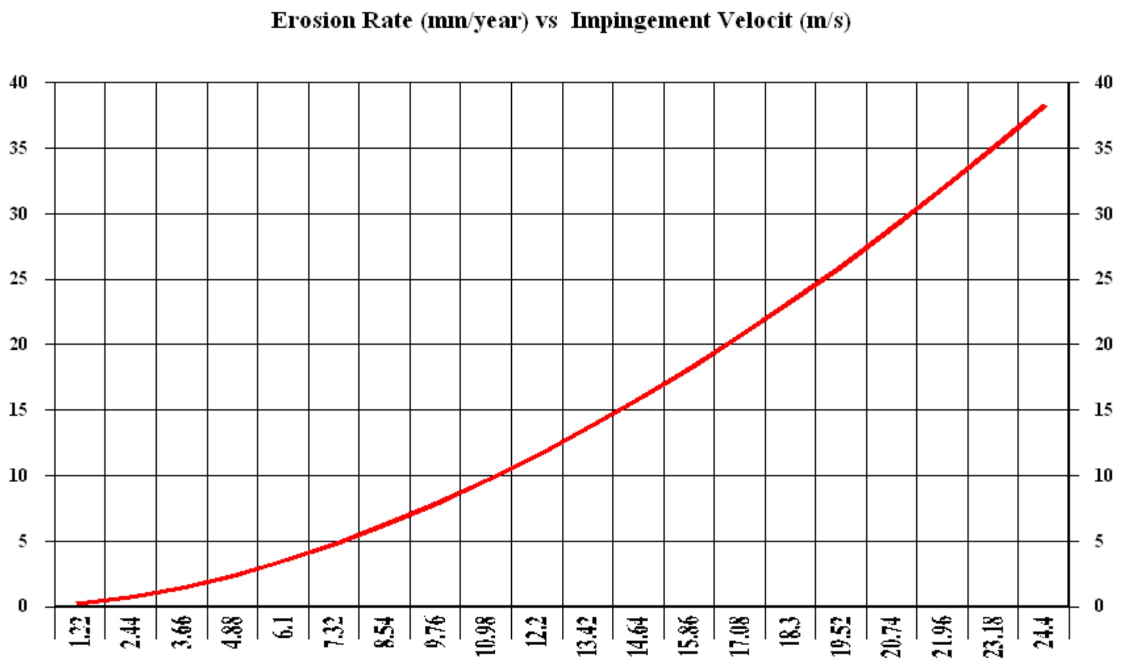

Fig 3: the variation of erosion rate (mm/year) with particles velocity (m/s)

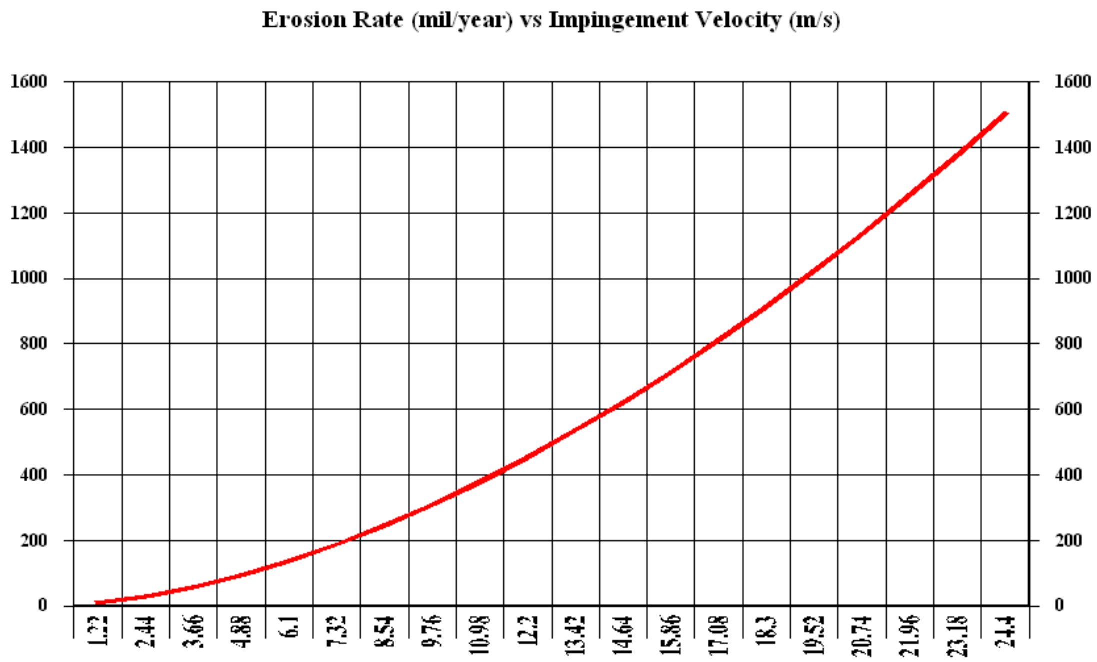

Fig 4: the variation of erosion rate (mil/year) with particles velocity (m/s)

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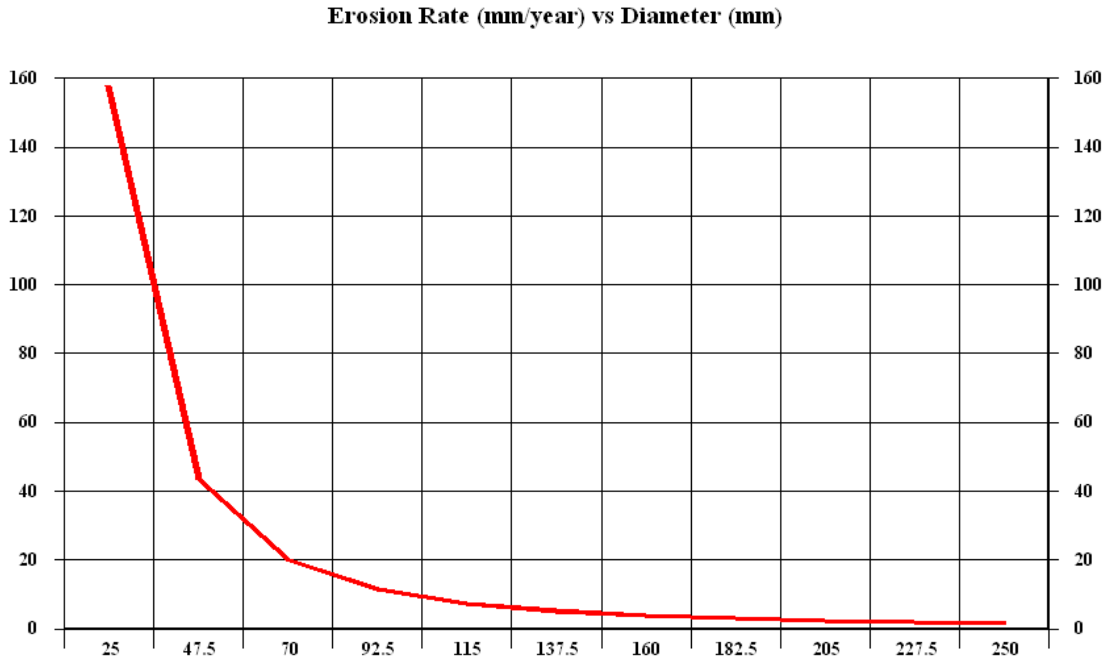

Fig 5: The variation of erosion rate (mm/year) with diameter

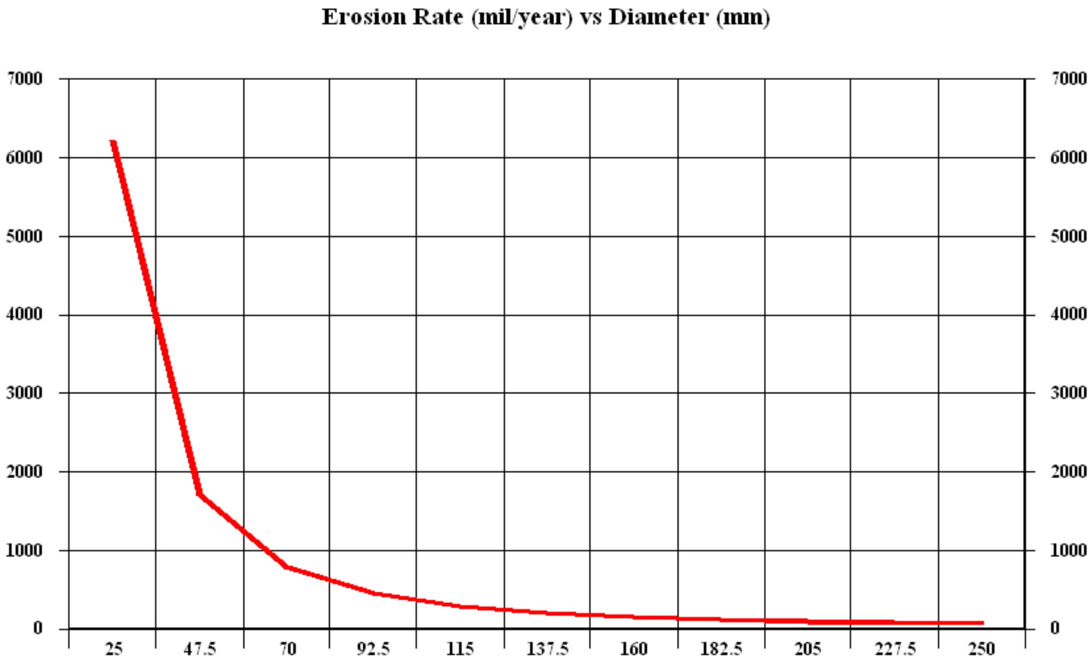

Fig 6: The variation of erosion rate (mil/year) with diameter

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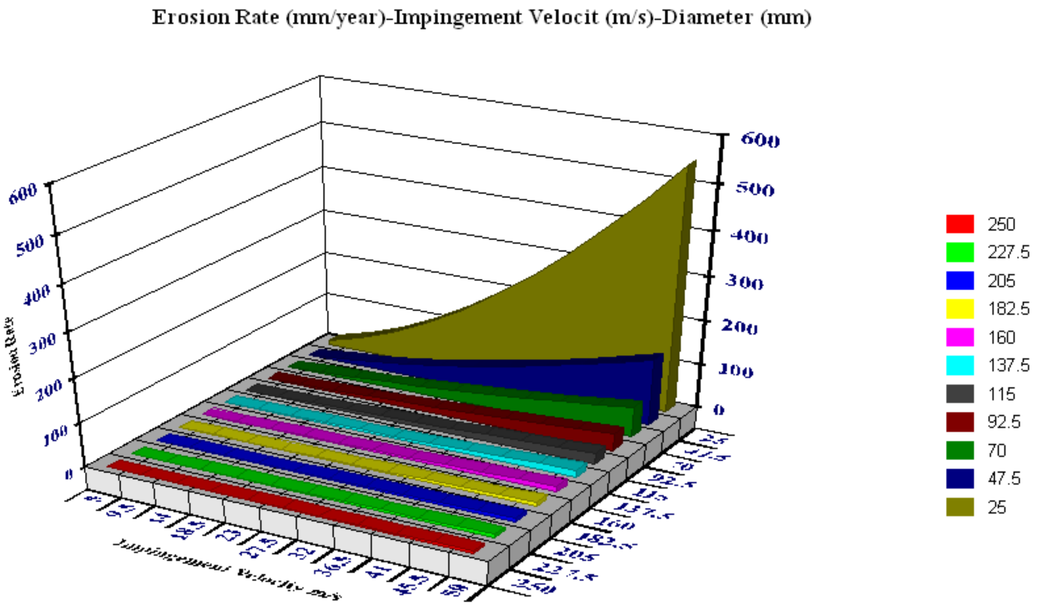

Fig 7: The variation of erosion rate (mm/year) with particles velocity (m/s) for different diameters (mm)

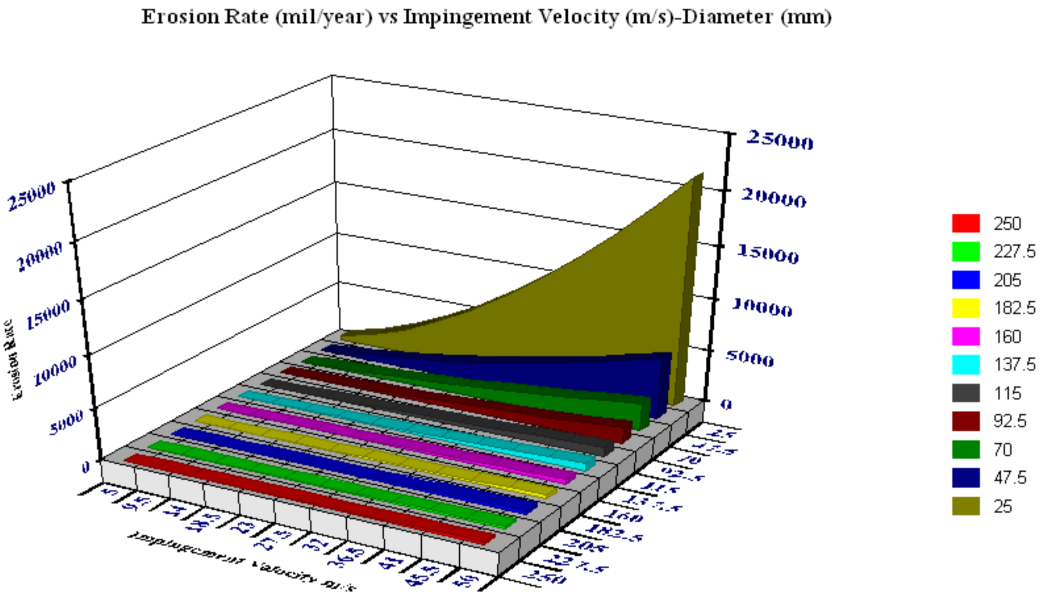

Fig 8: The variation of erosion rate (mil/year) with particles velocity (m/s) for different diameters (mm)

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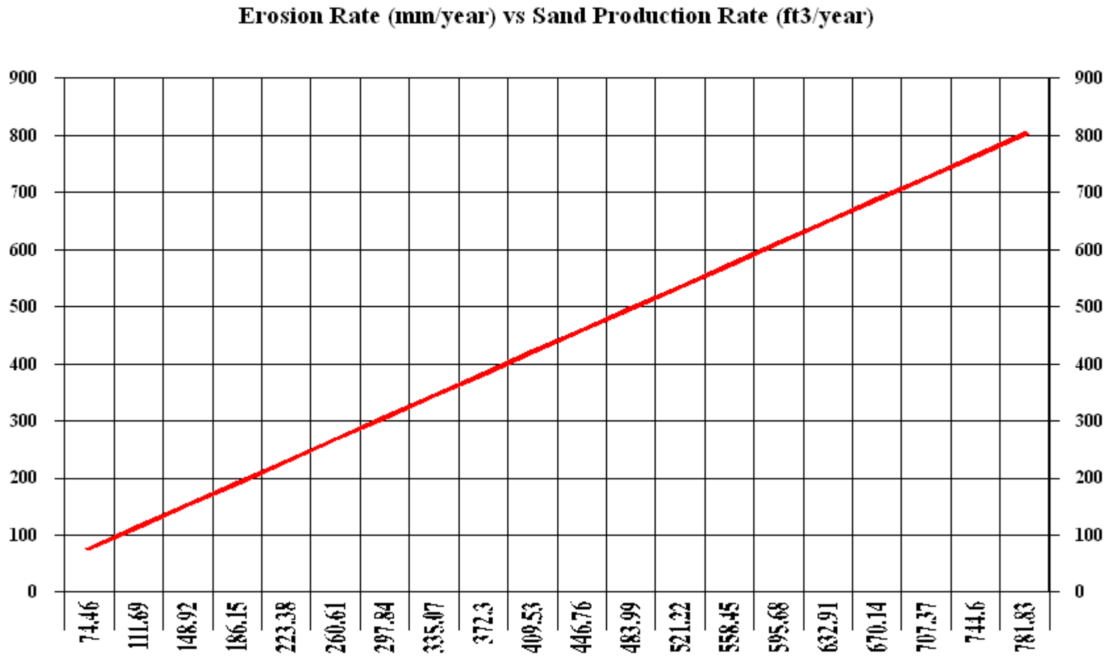

Fig 9: The variation of erosion rate (mil/year) with sand rates (ft^3/year)

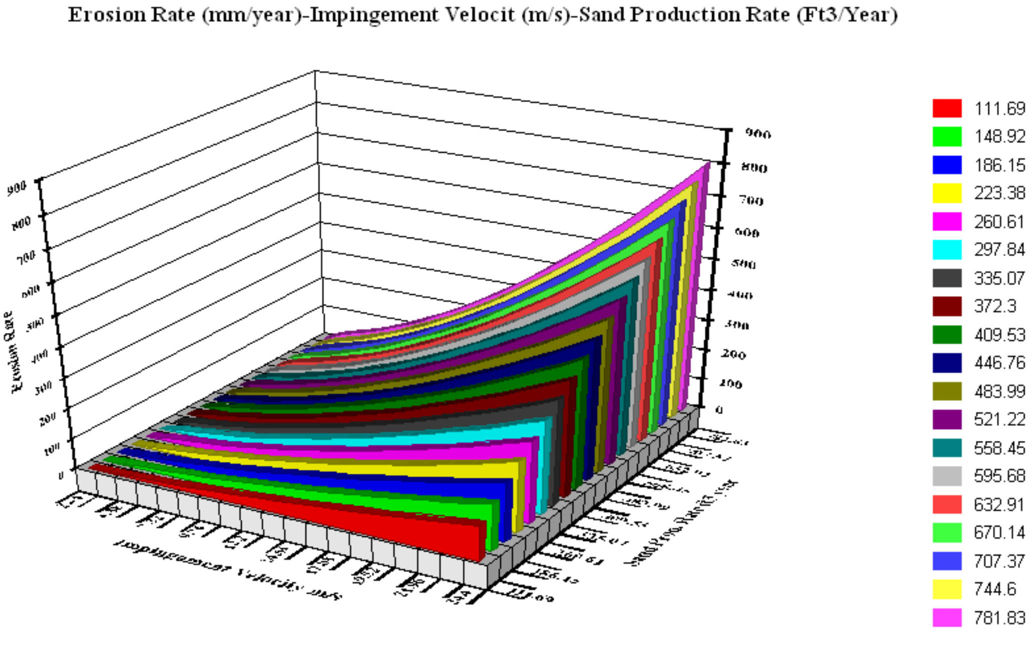

Fig 10: The variation of erosion rate (mil/year) with particles velocity (m/s) for sand rates (ft^3/year)

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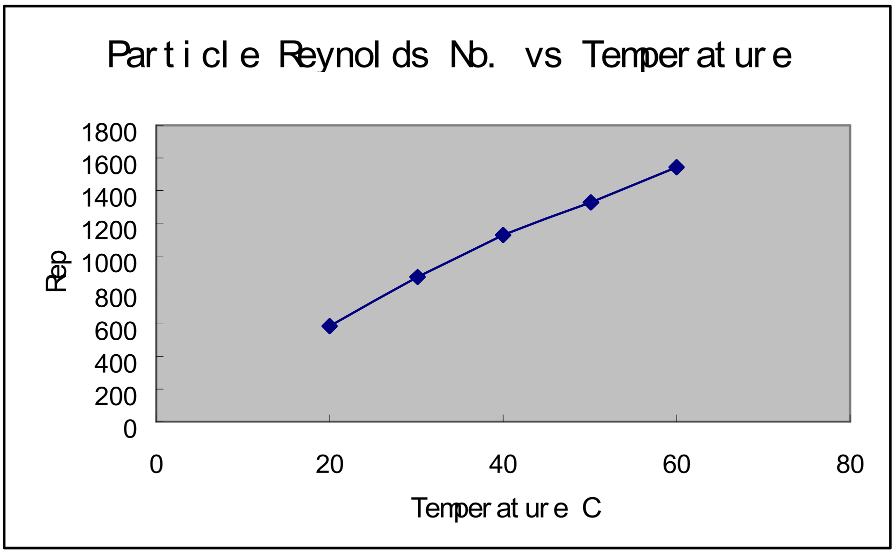

Fig 11: The variation of particles Reynolds number with temperature.

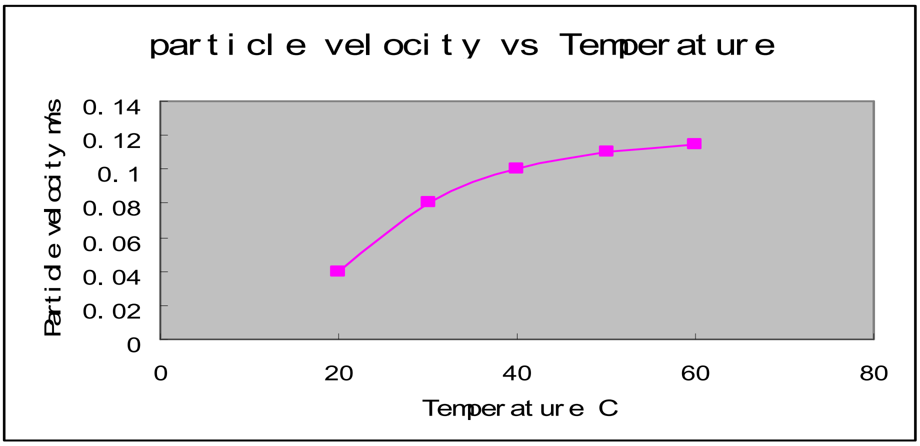

Fig 12: The variation of particles velocity with temperature.

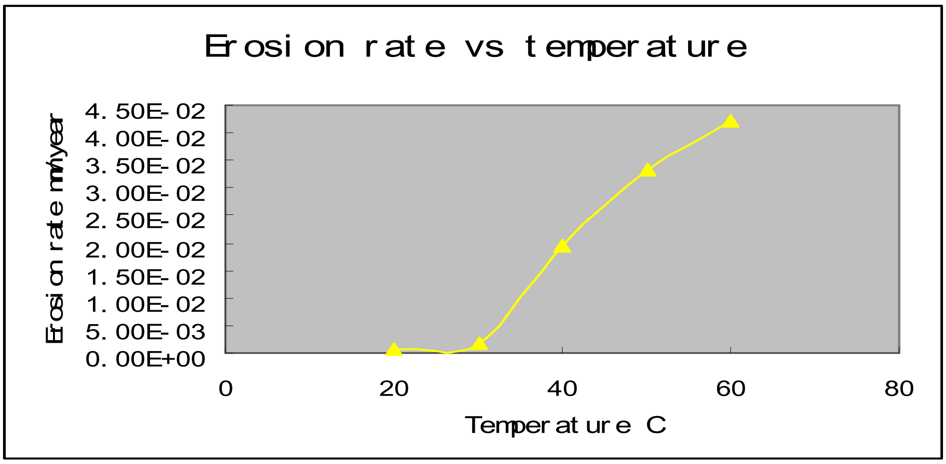

Fig 13: The variation of erosion ratey with temperature.

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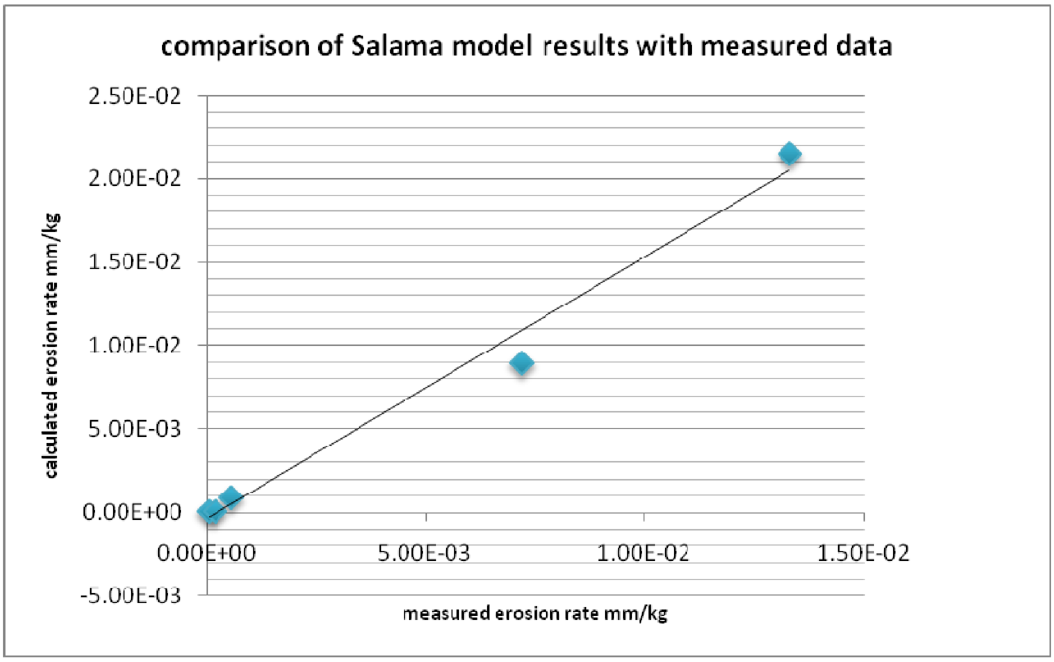

Fig 14: Validation of Salama model

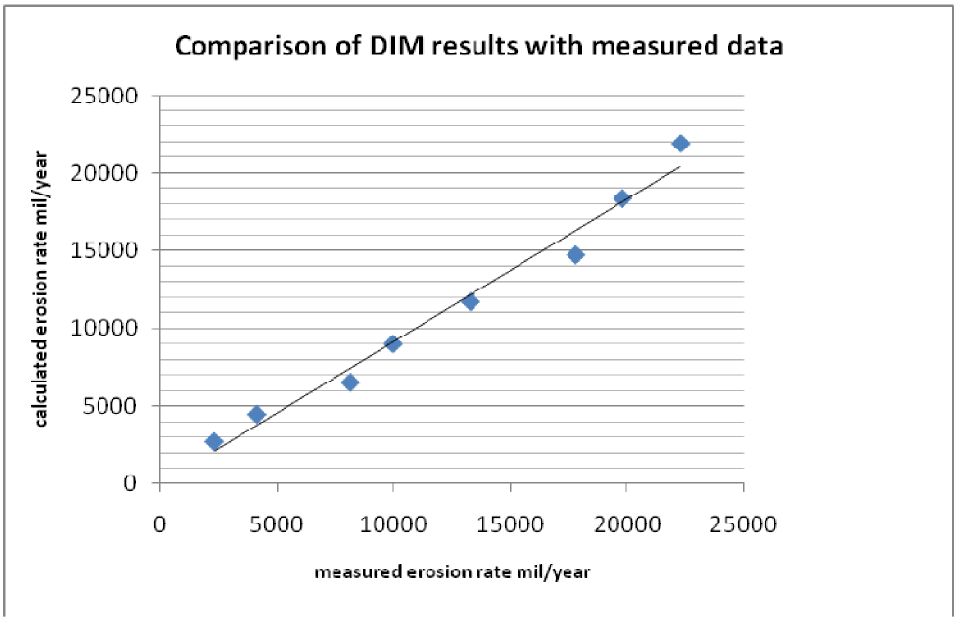

Fig 15: Validation of Direct Impingement model