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Enhancement of Uniformity of Solid Particles in Spouted Bed Using Stochastic Optimization

Ghanim.M. Alwan
Chemical Engineering Dept., University of Technology, Baghdad, Iraq

Abstract

Performance of gas-solid spouted bed benefit from solids uniformity structure (UI).Therefore, the focus of this work is to maximize UI across the bed based on process variables. Hence, UI is to be considered as the objective of the optimization process .Three selected process variables are affecting the objective function. These decision variables are: gas velocity, particle density and particle diameter. Steady-state solids concentration measurements were carried out in a narrow 3-inch cylindrical spouted bed made of Plexiglas that used 60° conical shape base. Radial concentration of particles (glass and steel beads) at various bed heights and different flow patterns were measured using sophisticated optical probes. Stochastic Genetic Algorithm (GA) has been found better than deterministic search for study mutation of process variables of the non-linear bed. Spouted bed behaved as hybrid system. Global GA could provide confirmed data and selected best operating conditions. Optimization technique would guide the experimental work and reduce the risk and cost of operation. Optimum results could improve operating of the bed at high-performance and stable conditions. Maximum uniformity has been found at high-density, small size of solid beads and low gas velocity. Density of solids has been effective variable on UI.Velocity of gas and diameter of solid particles has been observed more sensitive decision variables with UI mutations. Uniformity of solid particles would enhance hydrodynamic parameters, heat and mass transfer in the bed because of improving of hold-up and voids distributions of solids. The results of the optimization have been compared with the experimental data using sophisticated optical probe and Computed Tomography technique.

Key Words: Genetic algorithm*;* Spouted bed*;* Solids*;* Stochastic optimization*;* Uniformity.

Introduction

Gas-solid spouted beds are either cylindrical bed with cone base or the whole bed is in a cone shape where the gas enters as a jet. The gas forms a spout region that carries the solids upward in a diluted phase that forms a fountain at the top of the bed where the solids fall down and move downward in the annular region. Among several configurations typical of gas-solids fluidization, spouted beds have demonstrated to be characterized by a number of advantages, namely a reduced pressure drop, a relatively lower gas flow rate, the possibility of handling particles coarser than the ones treated by bubbling fluidized beds.

Additionally, significant segregation is prevented by the peculiar hydraulic structure. Spouted bed can be realized by replacing the perforated plate distributor typical of a standard fluidized bed with a sample orifice, whose profile helps the solids circulation and voids stagnant zones.

When the gas flow rate is large enough, the spout reaches the bed surface and forms a "fountain" of particles in the free board (Fig.1). After falling on the bed surface, the solids continue their downward travel in the "annulus" surrounding the spout and reach different depths before being recaptured into the spout [1] and [2].

A spouted bed is a special case of fluidization. It is an effective means of contacting gas with coarse solid particles. There is increasing a application of spouted such as; coating, desulfurization, CO_2 capture, combustion and gasification of coal and biomass [3].The spouted bed is a kind of high performance reactor for fluid-solid particles reaction, also it is a hybrid fluid-solid contacting system [4]. It is better to develop the design of the spouted bed to enhance uniformity of the products resulting from the chemical or physical treatment due to the elimination of the back mixing .Uniformity of solid particles enhances the mass and heat transfer in addition improves the conversion of the reactants in the spouted bed [5].

Many non-linear mathematical equations of chemical processes are either not differentiable or need a lot of difficult mathematical treatment for differentiating. Therefore, stochastic sampling methods have been found better than deterministic algorithms for optimize such functions. Genetic Algorithm (GA) search from a population of points, not a single point. Hence GAs are said to be suitable global optimization techniques for hybrid non-linear systems.

Motivation and Objective

The present work is a part of scale-up methodology in the Multiphase and Multi-scale processes Laboratory (MMPL) of Chemical and Biological Engineering Department, Missouri University of Science and Technology, USA.Uniformity index of solids (UI) could improve performance of the spouted bed. Enhancement of UI is depending on process variables. The present work focuses on study of effect of the selected decision variables (gas velocity, solid's density and solid's diameter) on UI across the bed.

Steady-state measurements are carried out at different operating conditions. The objective is to maximize UI. Stochastic GA is global search for non-linear hybrid bed .Optimal results will guide the decision makers to select the best operating conditions. This will reduce the risk of experimental runs and cost for operating and design.

Optimum results will be confirmed by using sophistical optical probes and Computed Tomography technique (CT).

Material and Methods

1- Experimental set-u

The experimental set-up was designed and constructed in the best way to collect the data as explained in Figs.(1and2) .The cylindrical spouted bed is made of Plexiglas. The bed is (3 inches in diameter and 36 inches in height) on which 20 holes (0.5 inch in diameter) are perforated-vertically.

At the bottom of the bed, there is a 60° cone-shaped base with height of 3-inch.The Plexiglas spouting nozzle has diameter of 0.25-inch locates in the center of the conical base. The spouted gas is air supplied from the air compressor and the airflow rate is controlled by pressure regulator and measured by flow-meter (Fig. 1). The solid particles used are steel and glass beads have good reflective properties (not black) with different sizes and properties as shown in Table(1).Holes are drilled at vertical intervals of (1.86 inch) along the column wall in which the optical probes are placed at different radiant locations: 1.5, 1.25, 1.0, 0.75, 0.5, and 0.25-inch. The spouted bed was divided to three positions: position 1 with head of 7.5-inch, while positions 2 and 3 have heads of 5.5 and 3.5 inches respectively above the conical-base.

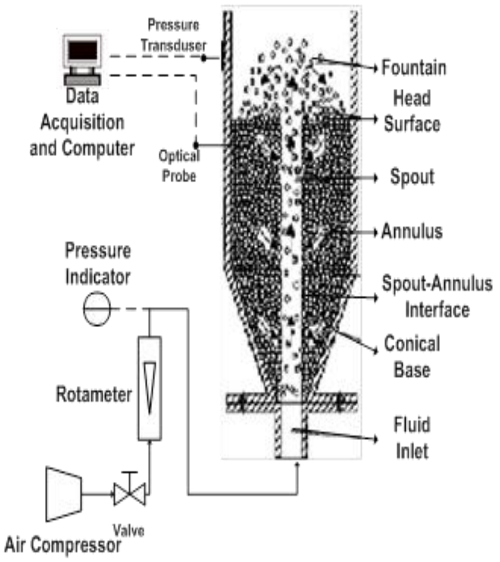


Fig.1, Diagram of Experimental Set-Up

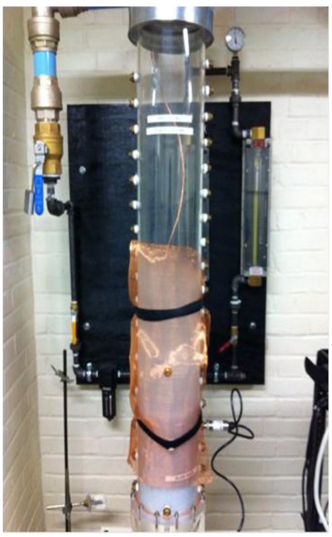


Fig.2, Photograph of Spouted Bed System

The newly optical probe (0.5x0.5mm) as shown in Figs. (3 and 4) was used to measure both solids concentration and solids velocity and their fluctuation. The concentrations of solid particles were measured in the radial and axis directions by the PV6 particle analyzer (Fig.5).PV6 was manufactured by the 'Institute of Chemical Metallurgy, Chinese,

Academy of Science'. It consists of; photoelectric converter and amplifying circuits, signal pre-processing circuits, high-speed A/D interface card and its software PV6, is adapted to the optical probes. Three decision variables were selected, which are affecting on UI of solid particles. These decision variables are; air velocity, particle's density and particle's diameter.

Table 1, Properties of Beads

Material	dp (mm)	ρs (Kg/m^3)	€	Ø
Steel beads	1.09	7400.0	0.42	1.0
Glass beads	1.09	2450.0	0.42	1.0
Glass beads	2.18	2400.0	0.41	1.0

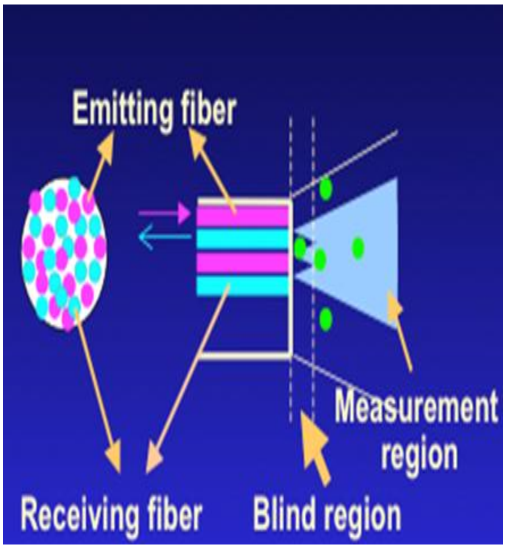


Fig.3, Structure of Optical Probe

Fig.4, Photograph of Optical Probe

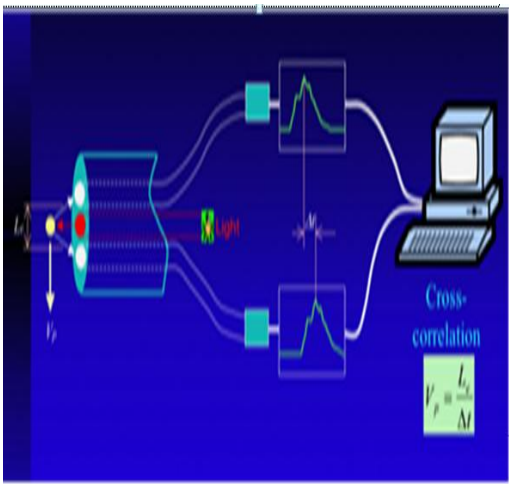


Fig.5, On-line PV6 System

2- Experimental procedures

Measuring Of Particles Concentration

The probe is inserted into the measuring port on the bed. The probe should be installed such that the direction mark on the middle part of the probe is in conformity with or opposite to the flow direction of material .The optical probe is calibrated for measuring the local particles concentration. For empty-bed state, the solids concentration is equal to zero correspond to zero voltage of probe signal. Under the bulk concentration state (material concentration is equal to 1.0), the output signal from the probe is equal to 4.5 voltages. Two or three bundles of optical fibers with diameter of 0.5 mm are arranged at certain interval according to different sizes of particles to be measured by the optical probe. The light source is introduced into the measuring area in front of the optical fibers (Fig.3). The reflecting lights of particles at the end face of the optical fibers are transmitted into the photoelectric detector in the instrument through the same bundle of optical fibers, and are converted to voltage signals corresponding to the concentration of particles as shown in Fig.(5). To choose the appropriate probe, the average particle diameter should not exceed the diameter of the optical fiber in the probe. The probe tips measure the number of particles in a measuring volume in front of them. In the actual experiments, the optical probes measure voltage and solids concentration is then obtained through the following calibration equation:

$$C_i= [(V_i-V_{min})/ (V_{max}-V_{min})]... (1)$$

Where:

C_i: Local relative concentration of solid particles, [-]

V_i: Voltage for particular run, [-]

V_{min}: Minimum voltage for the particular run, [-]

V_{max}:
Maximum voltage for the particular run, [-]

Measuring of Uniformity Index

Uniformity index (UI) is a measure of the homogeneity of solid particles across the bed. In this work, UI was evaluated by Eq. (2), which was developed by [6],[7] and [8].

For steady state, and at different operating conditions, concentration of solids was measured for each location in radiant-direction and axial-direction of the bed. From collected data,UI

would be calculated for each position by the following equation:
UI= (Cav-Cmin)/ (Cmax-Cmin)… (2)

Where;
Cav: Average solid concentration,[-]
Cmin: Minimum solid concentration[-]
Cmax: Maximum solid concentration [-]
UI: Uniformity index of the solid particles, [-]

The values of UI were confirmed by optical probe signals and Computed Tomography technique (CT) as shown in Fig.(6).CT is radioactive technique based on gamma ray. The red color indicates to high concentration of solids (solid bulk), while the blue color indicates to very low concentration of particles (gas bulk).

The calibration of the optical probe needed to about (30-40 minutes).The interval time of each measurement was within 3.0 minutes. The starting time of the experimental rig was 30.0 minutes. However, each experiment needed to about two hours and for reliability, each experiment was repeated twice.

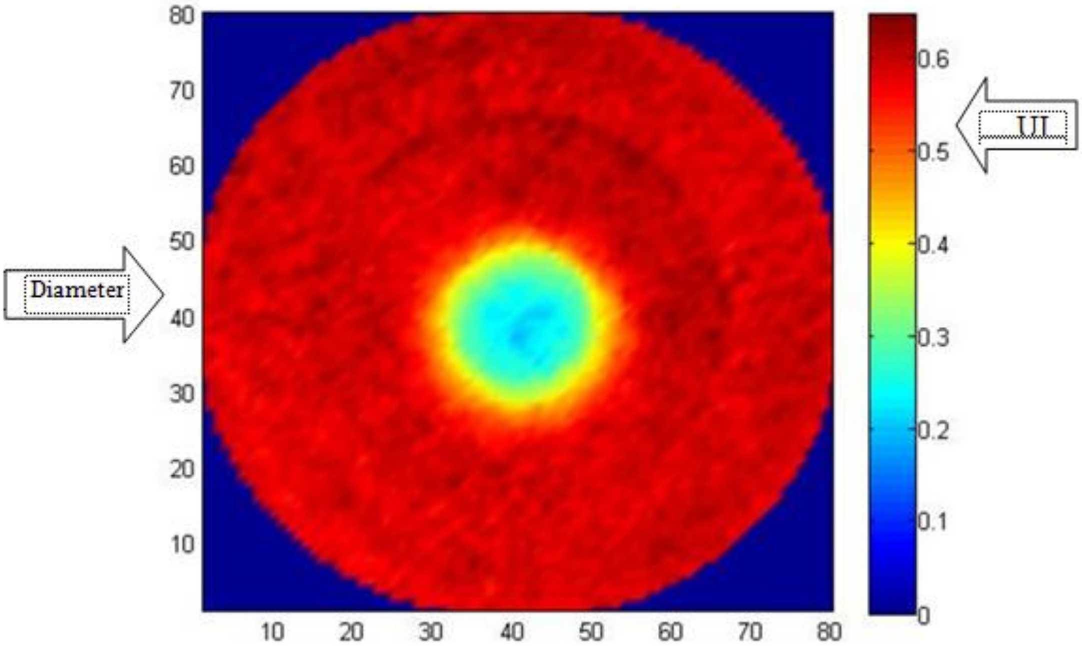


Fig.6, Image of Solids Distribution at Radiant Direction by Using CT

3- Formulating Of Optimization Problem

The available experimental data have been used to correlate the objective (UI) with the decision variables to facilitate the optimization process. The advanced nonlinear regression (Hook-Jeevs pattern moves) was implemented with aid of computer program (Statistica version10).The non-linear objective function is:

$UI=0.184Vg^{-0.214}\rho s^{0.12}dp^{-0.267}$ … (3)

Subject to inequality constraints:

$$\left.\begin{array}{rcl} 0.74 & \leq Vg & \leq 1.0 \\ 2400.0 & \leq \rho s & \leq 7400 \\ 1.09 & \leq dp & \leq 2.18 \end{array}\right\} \ldots (4)$$

Eq. (3) represents the global optimization problem equation of three positions in the spouted bed. Optimization search depends on fitness function, which is first derived from the objective function and is used in successive genetic operations. The fitness function is a blend of objective (Eq.3) and constraint function (Eq.4).Optimization problem is solving by using MATLAB version R2012a.

Results and Discussion

1- Effect of Solids Distributions

Figs. (7 and 8) explain samples of optical probe signals for non-uniform distribution of small glass beads and uniform distribution of large steel beads. Figs.(9 and 10) illustrate the solid concentration distributions in the spouted bed for different positions and flow regimes.Vg was ranged between 0.74 to 1.0 m/s for glass and steel beads .The solid concentration of steel beads (Fig.10) is higher than that of glass beads (Fig.9) because of high density of steel beads. Position 1 indicates to fountain region at which the solid concentration profile has pulse shape. Instability of fountain region is due to high vortex of flow and interaction of solid particles for different flow regimes compared to stable conditions appeared at annuals region (positions 2 and 3) as shown in

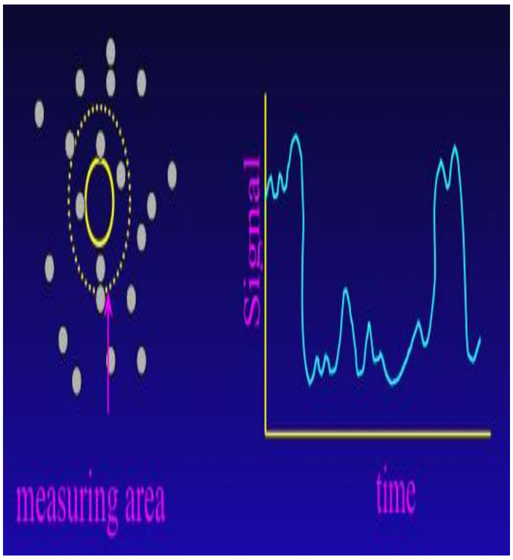


Fig.7, Optical Probe Signals of Non-Uniform Solids Distributions

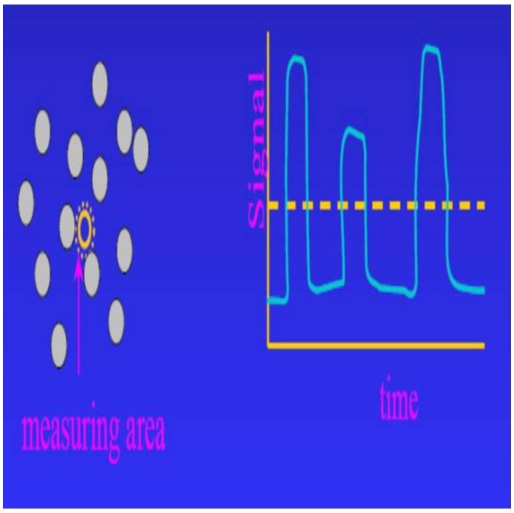


Fig.8, Optical Probe Signals of Uniform Solids Distributions

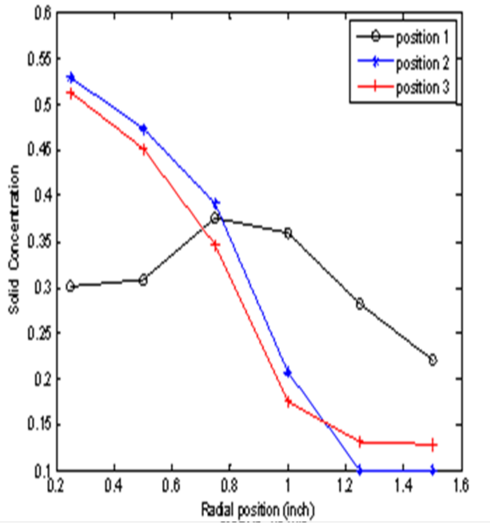


Fig.9, Solids Concentration Distribution of Glass Beads

Figs.(9 and10). The solid concentration profiles have uniform exponential form at annulus region for the same flow regimes. The spouted-air bed behaves as hybrid gas-solid system. Performance of the spouted bed is dropped at unstable conditions as explained by [9] and [10].A stable bed is observed when the particles fluidized homogenously as shown in Figs. (8, 9 and 10).

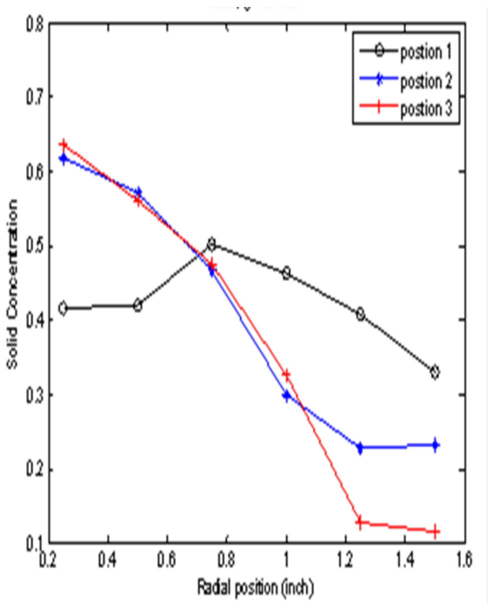


Fig.10, Solids Concentration Distribution of Steel Beads

The solid concentration is much less in the lean bed region at the center than in the dense bed region near the wall as shown in Figs.(9 and10). This reduces heat and mass transfer and reactants conversion. Therefore, in case of spouted bed reactor, the unconverted concentration of material at the center is higher than that at the spouted wall.

2- Effect Of Decision Variables on UI

Fig.(11) illustrates the effect of air velocities on UI for steel and glass beads. UI was decreased with increasing air velocity (Vg) because of increasing of desperation of solid particles due to the kinetic energy of the solid particles is increased.In addition, two regions are appeared in these curves, which represent the transition region from packed bed flow regime at Vg of 0.74 m/s to stable spouting flow regime at Vg of 0.95 and 1.0 m/s.UI of steel beads is higher than that of glass beads as shown in Figs. (9 and 10) because of high scattering was occurred with the particles of low density. Low concentrations of solid particles were obtained for all positions with the glass beads system, which would affect on values of UI.Density of solid particles has positive effect on UI across the spouted bed (Fig. 12).

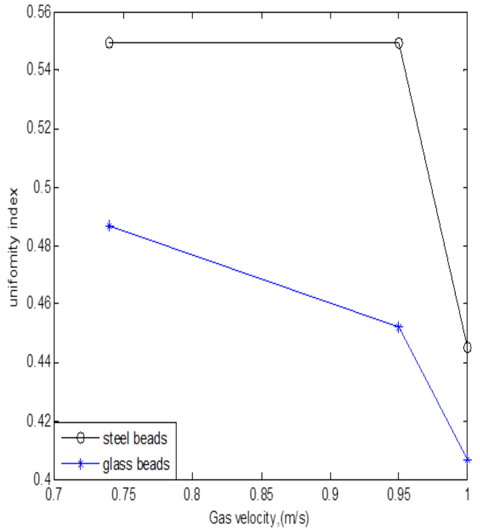


Fig.11, Uniformity Index versus Gas Velocity

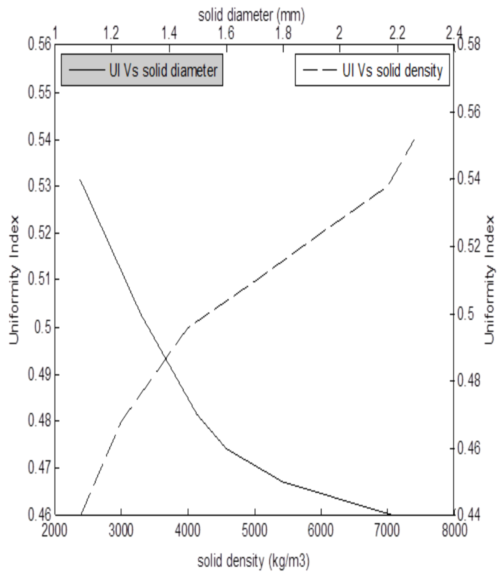


Fig.12, Uniformity Index versus Solid Density and Solid Diameter

Increasing of the particles' density could provide the bed more strength and resistance against vortex of the fountain. Therefore, it gives the solid particles more stability and uniformity. The denser material is continued to spout in the central region while the less dense particle formed vortex around the central spout. The solid beads diameter has negative effect on UI of the solid particles as shown in Fig.(12). The particles of small size are helpful to raise the mixing speed .This provides the smaller particles more uniformity in the radial distribution.This was concluded by [11]. However, the uniformity of particles will enhance heat and mass transfer, and conversion of reactants in the bed because of improving of hold-up and voids distributions of solids.

3- Optimization Search

The spouted-gas bed is nonlinear hybrid system as explained in sections (3.2 and 4.1). Hence, Genetic algorithm (GA) is the suitable global stochastic search for solving optimization problem.GA is the most popular form of evolutionary algorithm. A population of chromosomes represents a set of possible solution. These solutions are classified by an evaluation function, giving better values, or fitness to better solutions as explained by [12]. The operators of genetic algorithm search were adapted to obtain best results.

Table (2) explains the best parameters of the genetic algorithms. Fig. (13) illustrates the results of GA search. GA implemented with the pattern search by using the hybrid function as shown in Table (2) to refine the decision variables as explained by [13].

Table 2, Adapted Parameters of GA

Parameter	Type/value
Population type	Double vector
Population size	80
Creation function	Feasible population
Scaling function	Rank
Selection function	Roulette
Crossover function	Scattered
Crossover fraction	0.8
Mutation function	Adaptive feasible
Migration direction	Forward
Migration fraction	0.1
Hybrid function	Pattern search
Number of generation	51
Function tolerance	1.0E-6

The best fitness, best function and score histogram as shown in Fig.13 illustrate that the optimal UI is (0.534).The results of the optimization search (Table 3) have reasonable agreement because of values of decision variables (Vg , ρs and dp) are within the limits of operating conditions (Eq. 4). In addition, the maximum UI could be obtained by low gas velocity, high-density steel beads of low particle diameter as shown in Table (3) and Fig.(13). Therefore, by staying close to this minimum flow condition, it is possible to perform a stable operation and to obtain energy savings. Also [14] concluded this. The histogram of the variables in Fig. (13) indicates that the density of solids (variable 2) is the effective variable on UI. Due to the nonlinearity of the spouted process (Eq. 3), the optimization equation of UI was solved by (51) generations as shown in Fig.(13).

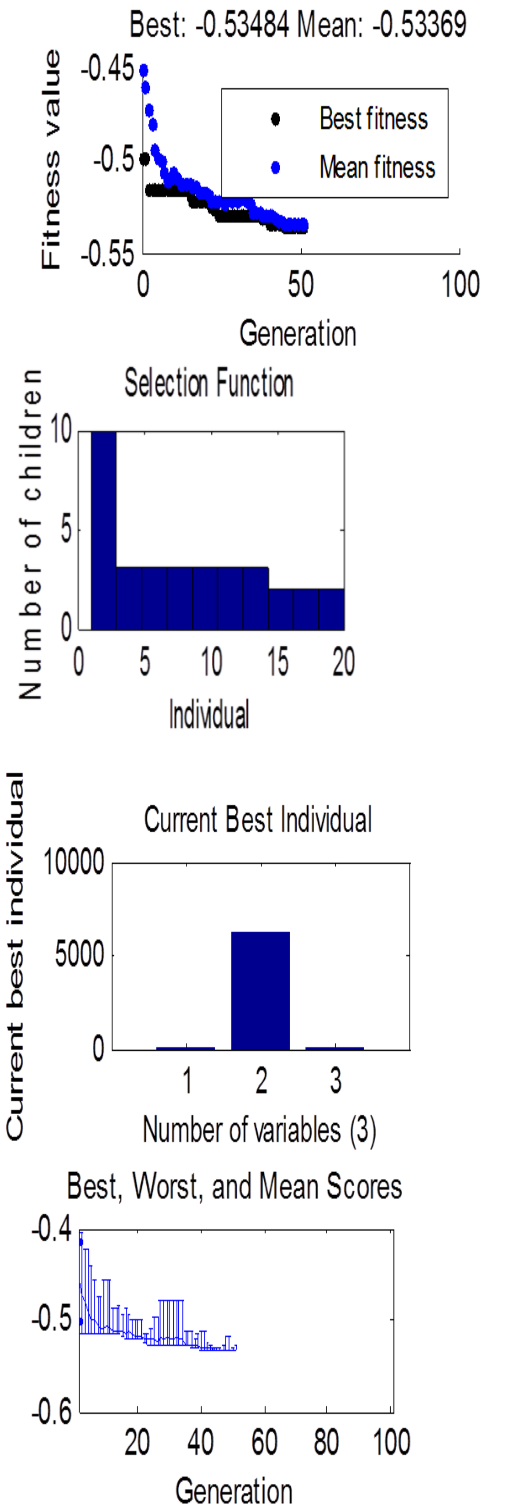


Fig.13, Stochastic Results of GA Search

Table 3, Optimal Values of Decision Variables

Decision variables	Optimum value
Gas velocity (m/s)	0.74
Density of solid (Kg/m^3)	6648
Diameter particle (mm)	1.09

Optimum results could guide the experimental work and enhance uniformity of solids across the bed as shown in Fig.(14).Performance of the bed would be improved. Success of optimization search depends on formulation of objective function, selection of decision variables and selection of suitable searching technique.

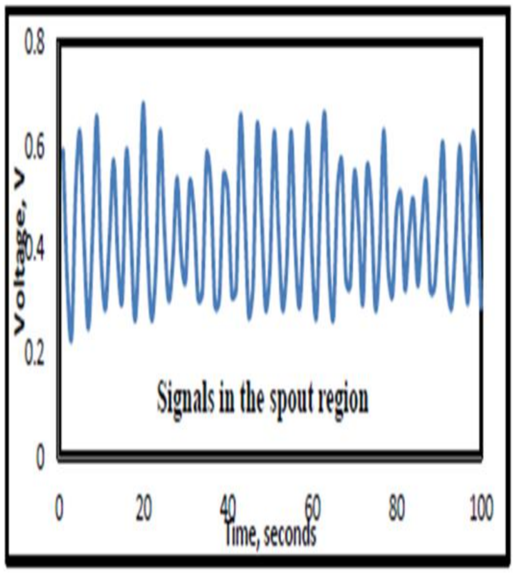


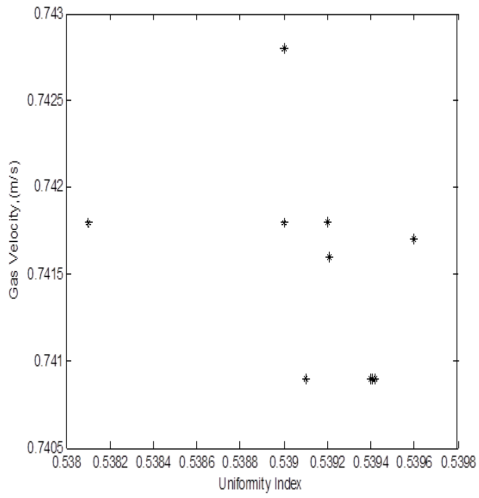
Fig.14, Improving of Solids Uniformity at Optimum Operating Conditions

4- Stochastic Mutation of decision variables

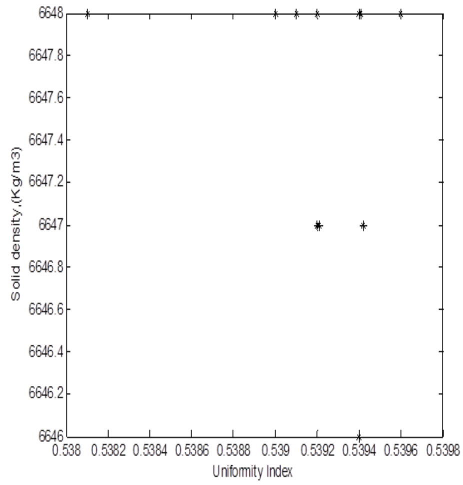
The optimal sets of the three decision variables are illustrated in Figs.(15a, 15b and 15c) are corresponding to UI mutations. The scattering and stochastic results are appeared behaviors of variables because of natural selection by GA .It is found that the optimal values of solid density (ρs) are stay within its upper bound as shown in Fig. (15b). Gas velocity (Vg) and solid diameter (dp) are changed within its lower bounds (Figs. 15a and 15c).These behaviors are because of ρs has positive effect while Vg and dp have negative effect on UI as shown in Figs.(11 and 12). Most optimal values of the three decision variables are stayed within optimum value of UI, which equal to (0.534) as shown in Fig.(13).It is observed that Vg and dp are more sensitive variables for UI mutations as shown in Figs. (15a and 15c).

Conclusions

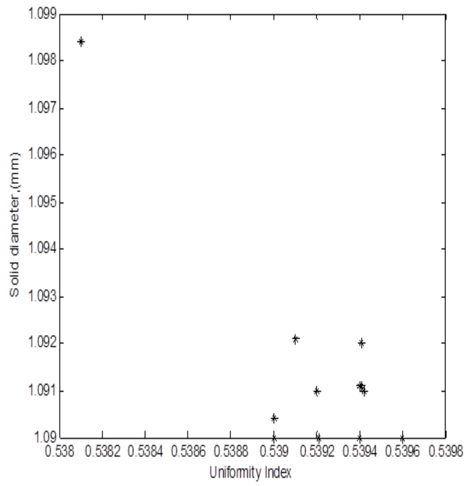
Uniformity of solid particles enhances performance of the spouted bed. Hydrodynamic parameters, heat and mass transfer in the bed would be increased because of improving of hold-up and voids distributions of solids. Optimization search could guide the experimental work and would select best operating conditions. GA has been found suitable global search for the hybrid nonlinear spouted bed. Reliability of the search could be increased by adaptation of genetics' operators. Success of optimization search depends on formulation of objective function, selection of decision variables and selection of suitable searching technique. Reasonable results have been obtained when compared optimal values with experimental data. Maximum uniformity has been observed with high-density steel beads of low particle's diameter at low gas velocity. Density of solid particles is the effective variable on uniformity distributions of beads across the bed. Optimal velocity of spouted gas and diameter of solid particles are the sensitive decision variables corresponding to UI mutations.



(a)



(b)



(c)

Fig.15, Stochastic Mutations of Decision Variables with Objective UI

Nomenclatures

C: Relative concentration of solid particles,[-]
Dp: Diameter of solid particle, [mm]
V: Optical signal,[volt]
Vg: Superficial velocity of gas, [m/s]

Greek Symbols

Ps: Density of solid particles,[Kg/m3]
€: Porosity of bed, [-]
Ø: Sphercity of solid particle,[-]

Acknowledgments

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