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Improving Operability of Lab-Scale Spouted Bed Using Global Stochastic Optimization

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Abstract
A spouted bed is a special case of fluidization. It is an effective means of contacting gas with coarse solid particles .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.
Performance of gas-solid spouted bed benefit from solids uniformity structure with lower pressure drop (PD).Dropping of PD across a spouted bed could reduce the dissipated pumping energy and improve stability and uniformity of solid particles.
The objective of this work is to study and selecting best operating conditions that could minimize PD across the bed. Optimization technique is a powerful tool would guide the experimental work and reduce the risk and cost for design and operation Hence, PD is to be considered as objective function of the optimization process .Three selected decision variables are affecting objective function. These decision variables are gas velocity, particle density and particle diameter. Steady-state measurements were carried out in a narrow 3-inch (0.076 m ID) cylindrical spouted bed made of Plexiglas that used 60° conical shape base. Radial concentration of particles (glass and steel beads) at various bed heights under different flow patterns were measured using sophisticated optical probes. A superficial velocity of air ranging from 0.74 to 1.0 m/s .PD was measured across the bed by high accuracy pressure transducers. Stochastic Genetic Algorithm (GA) has found suitable global search for the non-linear hybrid spouted bed. Optimum results could select the best operating conditions for high-performance and stable conditions. Uniformity and stability of solid particles in the bed would enhance hydrodynamic parameters, heat and mass transfer. Best Operability of the bed was observed with low-density, large size of solid beads, low gas velocity at low PD. Size of solid particles and velocity of gas have been found the sensitive decision variables with PD mutations. Sensitivity of these variables could be increased at unlimited upper bounds of operating conditions. An advanced control system for sensitive decision variables would be recommended to improve operability of the spouted bed.
Keywords: Operability; Optimization; Pressure drop; Spouted bed; Solid particles; Stochastic

I. Introduction

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.Significant segregation is prevented by the peculiar hydraulic structure. A 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 (Rovero *etal*, 2012).

There is increasing a application of spouted such as; coating, desulfurization, CO_2 capture, combustion and gasification of coal and biomass (Limtrakul *etal.*,2004).The spouted bed is a kind of high performance reactor for fluid-solid particles reaction, also it is a hybrid fluid-solid contacting system (Wang *etal*.,2001).

Nomenclatures
dp: Diameter of solid particle, [mm]
PD: Pressure drop across spouted bed, [Kpa]
Vg: Superficial velocity of gas, [m/s]

Greek letters
ρs :Density of solid particles,[Kg/m^3]
€: Porosity of bed, [-]
Ø: Spherical factor of solid particles, [-]

In operations using spouted beds, it is of major importance, from an energy consumption point of view, to operate the process as close as possible to the minimum spout flow. At this point, the speed of the gas (for example, warm air in drying operations) is greater than the amount of heat and mass transfer involved, although it only transfers the minimum amount of momentum to maintain the spout. Therefore, by staying close to this minimum flow condition, it is possible to perform a stable operation and to obtain energy savings not only in the heating of the gas but also in its displacement by blowers (Correa, *etal.*, 1999).However, it is better to develop the design of the spouted bed to overcome the large pressure drop and instability of the operation and improve the uniformity of the products resulting from the chemical or physical treatment (Prachayawarakorn *etal.*,2005).

The objective and motivation of this work is to improve performance of the present spouted bed by selecting the best operating conditions. Study of effect of selected decision variables on PD under steady-state conditions. The optimization problem equation is correlated depends on the available experimental data of the lab-scale bed. Stochastic global search Genetic Algorithm is implemented to solve the optimization problem with different boundary conditions. The optimal results would improve the operating and performance of the spouted bed.

II. Materials and methods

2.1. *Experimental set-up*

The present work is a part of scale-up methodology -Multi-phase and Multi-scale processes Laboratory (MMPL) of Chemical and Biological Engineering Department Missouri University of Science and Technology, MO, USA.

The experimental set-up was designed and constructed in the best way to collect the data as explained in Fig.1.The cylindrical spouted bed is made of Plexiglas.The bed is 3 inches (0.076 m) in diameter and 36 inches in height. Twenty holes (0.5 inch in diameter) are drilled at vertical intervals of (1.86 inch) along the column wall in which the optical probe is placed at different radial positions of 1.5, 1.25, 1.0, 0.75, 0.5, and 0.25 inch and at axis positions of 7.5 and 5.5 inches above the conical base as shown in Fig.1. At the bottom of the bed, there is a 60° cone-shaped Plexiglas base (3 inches in height).The spouting nozzle (0.25 inch in diameter) locates in the center of the conical base.

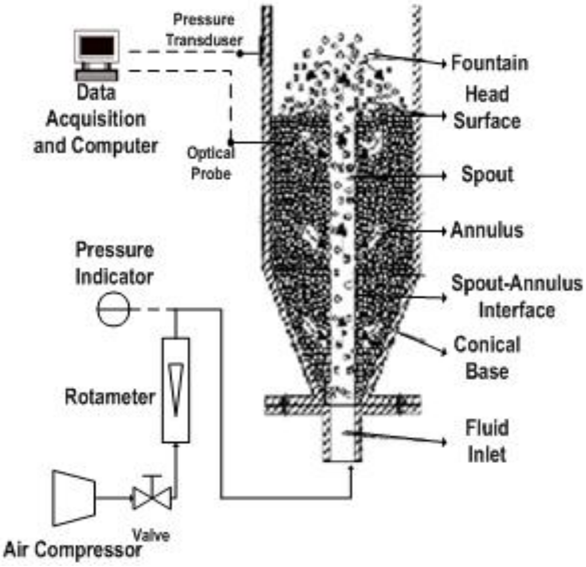


Fig.1.Experimental set-up.

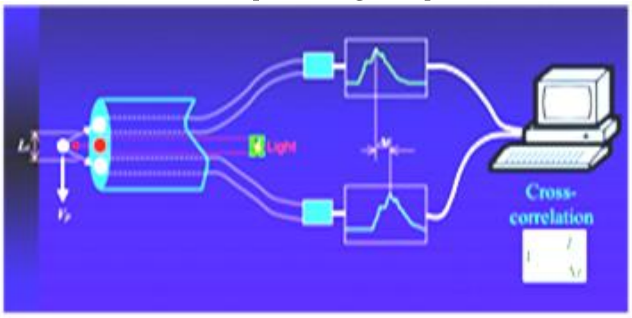

Lab-Scale Spouted Bed

The solid particles used are steel and glass beads with different diameters and properties as shown in Table1.The newly optical probes (Fig.2a) are used to measure both solids concentration and solids velocity and their fluctuation at radial and axial positions of the spouted bed as shown in Fig.2b. The concentration of solid particles are measured by the Particle Analyzer (PV6) which 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 as shown in Fig.2a The pressure drop across the bed is measured by advanced pressure transducer (Type: PX309-002G5V,Omega).

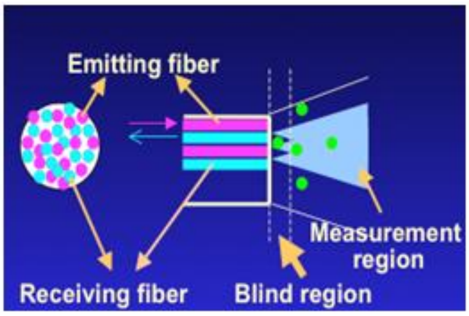
Table1. Properties of the particulate materials.

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

The pressure in the spouted bed adjusting within the desired values by using the inverted circular stabilizer, 60 mm in diameter is installed at the top of the bed column. This is preventing the spout fountain from swaying. The selected process variables, which are affecting PD in the bed, are gas velocity, particle density and particle diameter.

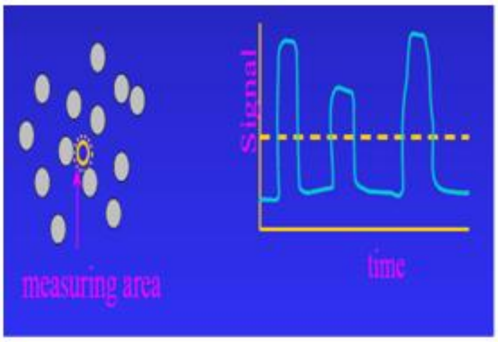


PV6-System

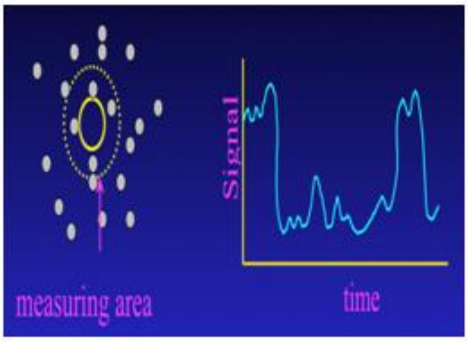


Optical Probe

Fig.2a.On-line Optical probe system for measuring the solids hold-up at different positions of the bed.



For large particles



For small particles

Fig.2b. Samples of optical probe signals for measuring the solids hold-up at different size of solids.

2.2 Optimization problem

The available experimental data of the Lab-scale spouted bed under steady- state conditions were used to formulate the optimization equation. The objective (PD) correlated empirically with the decision variables to facilitate the optimization process. The advanced nonlinear regression optimization algorithm used is Hook-Jeevs pattern moves with the aid of the computer program (Statistica version10).The global optimization equation of the spouted bed is:

$$\boldsymbol{PD}=0.037Vg^{0.381}\rho s^{0.407}dp^{-0.221} \qquad (1)$$

Subject to Inequality constraints:

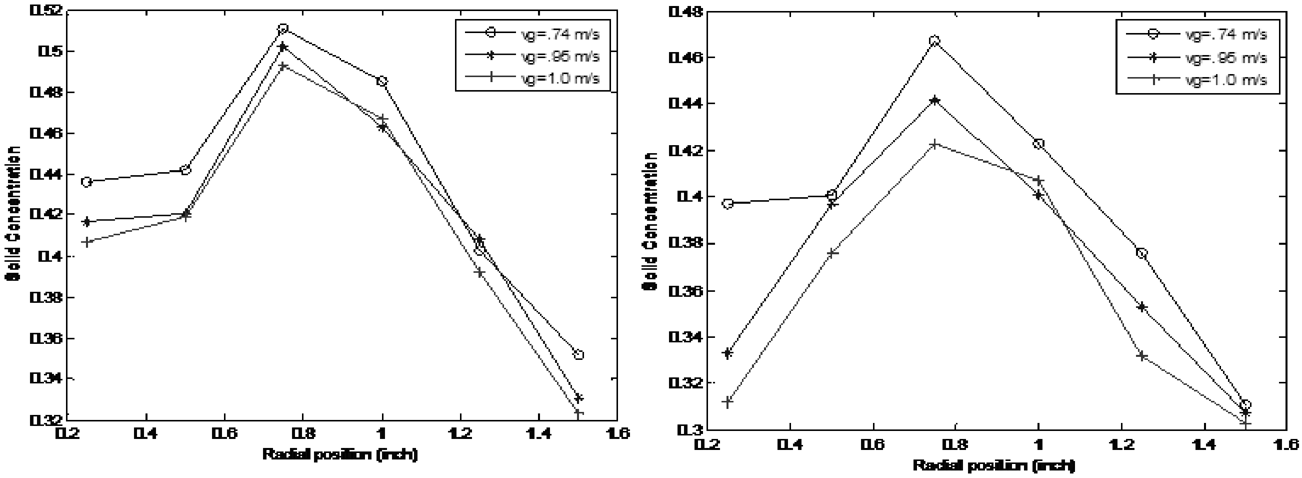
$$0.74 \leq Vg \leq 1.0, \quad 2400.0 \leq \rho s \leq 7400.0 \qquad (2)$$
$$1.09 \leq dp \leq 2.18$$

Eq.1 represents the global optimization problem equation of two zones in the spouted bed. From Eq.1, one can conclude that the air velocity, density of the solid particles have positive effect on the pressure drop across the bed, while the diameter of particles has negative effect. GA will implement for the optimization problem (Eq. 1) with upper-lower bounds and with unlimited upper bounds (Eq. 2).

III. Result and Discussion

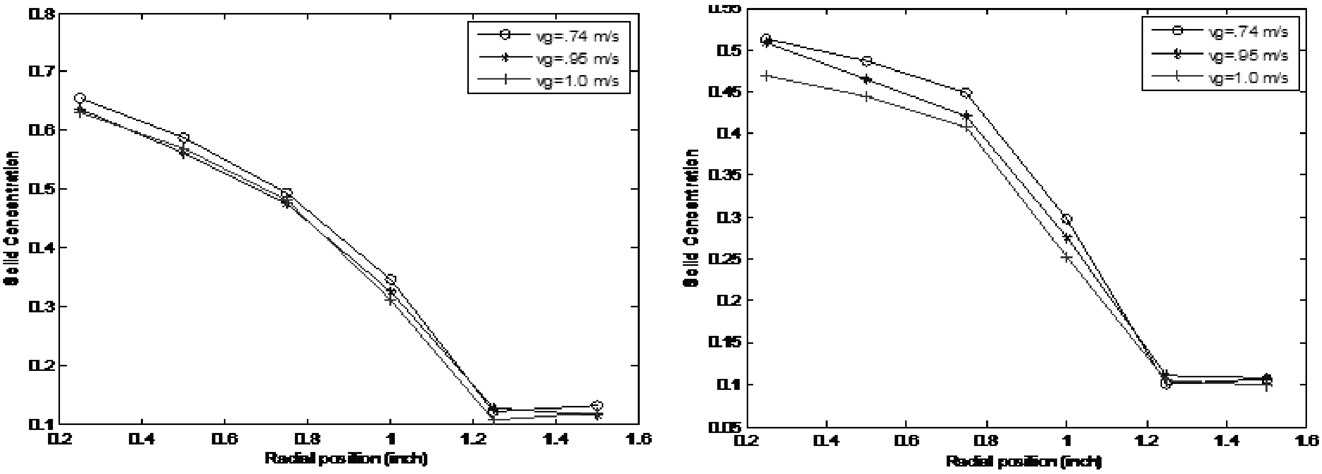
3.1 *Effect of PD on uniformity and Stability of the spouted bed*

The performance and efficiency of the spouted bed is dropped at unstable conditions. Different flow regimes in the present spouted bed were studied to limit the stable gas velocities (Xu etal.,2009) .The optimum range of air velocity is between 0.74 to 1.0 m/s. Figs.3a and 3b illustrate the effect of pressure drop on the stability and uniformity of the spouted bed using concentration distributions of glass and steel particles.The system behaves unstable at the fountain region (zone 1), which locates at 7.5 inches above the conical base for different superficial velocities of air (0.74 to 1.0 m/s). These are because of high- pressure drop as a result of high- vortices and revolutions of the particle's bulk compared to others regions in the bed (Zhong *etal.* ,2007and Zhang *etal*., 2011).The concentration profile curves have triangular pulse shape and non-uniform. The maximum concentrations of solid concentration were observed at the center of the bed (0.75 inches of radial position). Unstable spouting is characterized by swirling and pulsation of the spout (Xu *etal.* ,2009 and Rovero *etal*.,2012).Disuniformity of solid particles decreases the heat and mass transfer in bed.



(a) Steel beads (b) Glass beads

Fig. 3. Unstable behaviors of the bed at high PD for (zone 1) at different operating conditions.



(a) Steel beads (b) Glass beads

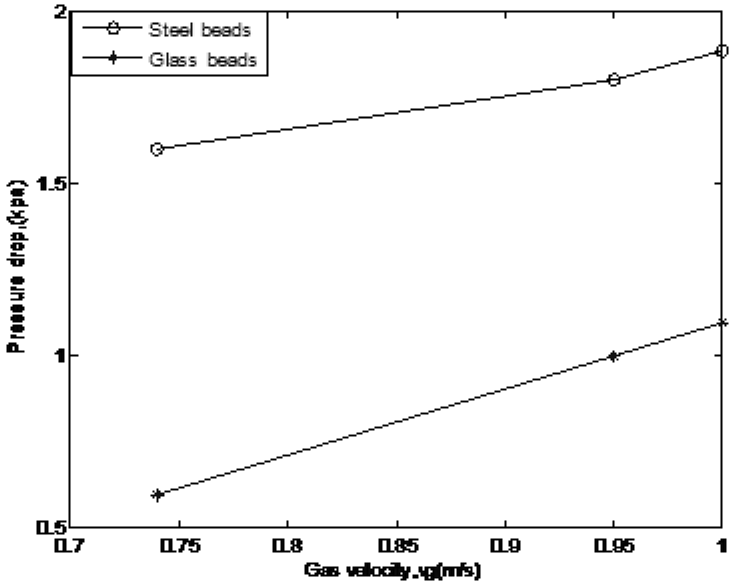
Fig. 4.Stable behaviors of the bed at low PD for (zone2) at different operating conditions.

Fig. 4a illustrates the portrait of steel beads distributions at the cylindrical region (zone 2), which locates at 5.5 inches above the conical base. For the same operating conditions, the solid concentration profile curves have uniform exponential shape. The stability conditions appeared within the behavior of the system since the particles in the bed fluidized homogenously because of low-pressure drop at this region .This position located in lower gas motion region of the spouted bed (annular part). The packed bed and stable spouting are distinguished by the formation of stable spout (Alwan, *eta.l, 2014*).Uniformity of solid particles could enhance hydrodynamic parameters, heat and mass transfer in the bed. Fig. 4b explains the solid distributions of glass beads. The similar behaviors of solid particles are appeared as explained with the steel beads system. The concentration of solid increases with low- gas velocity and high particle's density as shown in Fig.4.

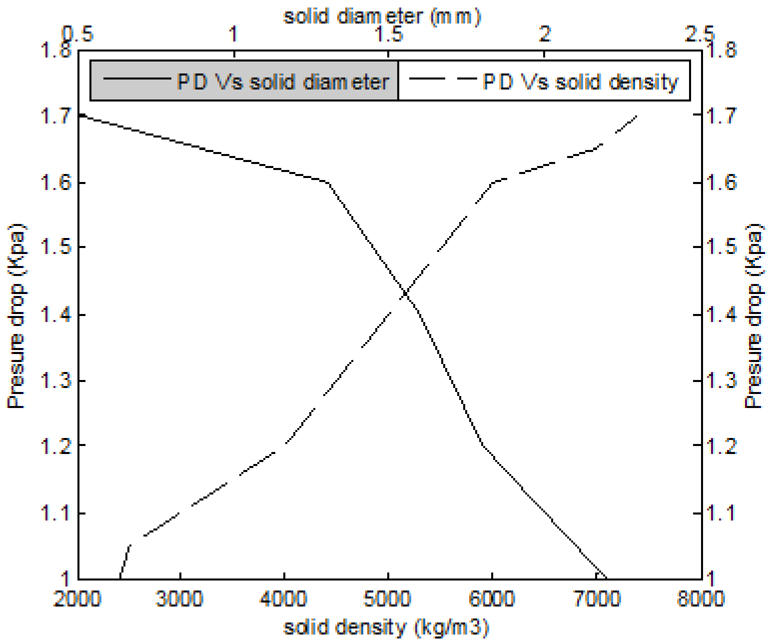
However, the spouted-gas bed behaves as a hybrid fluid-solid contacting system as explained in Figs.3 and 4. Genetic algorithm (GA) is the best global stochastic search that based on mechanics of natural selection (Gupta and Srivastava, 2006).

3.2 Effect of decision variables on PD

Fig.5 explains the effect of the process variables (air velocity, density and diameter of solid particles) on the pressure drop (PD) across the bed. The pressure drop increased with increasing the velocity of air for both steel and glass beads due to increasing the kinetic energy and the interaction of the solid particles. In the case of steel beads, the pressure drop is higher than that with glass beads because of high strength and friction with steel beads (Fig.5a). The dense particles (steel) create more resistance and friction against the airflow and then tend to raise the pressure drop across the bed (Fig.5b).The porosity of the bed increased with the large particles diameter, so that the strength of the solids to the airflow then reduced. These tend to reduce the pressure drop across the spouted bed (Fig.5b).These conclusions also confirmed by (Zhong *etal.*, 2006).However, the design of the spouted bed is developed to reduce the pressure drop and instability of the operation and enhance the uniformity of solid beads.



(a)



(b)

Fig. 5. Pressure drop is relates with ;(a) gas velocity,(b) solids density and solids diameter.

3.3 Genetic algorithm search

Several experiments were carried out to obtain the optimal solution of the optimum problem. In addition, the operators of genetic algorithm search were adapted to obtain the best solution.

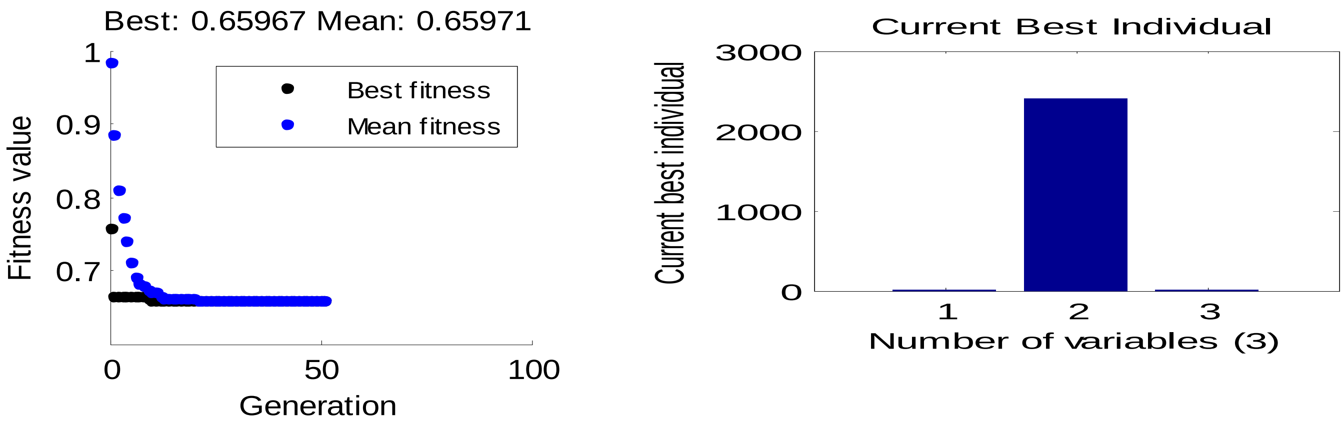
Table 2 explains the best parameters of genetic algorithms with upper-lower and unlimited upper bounds. Fig.6a illustrates the outputs of GA solution with upper-lower bounds system. GA is implemented with the pattern search by using the hybrid function as shown in Table 2 to refine the decision variables (Palonen *etal.*,2009). The best fitness, best function and score histogram as shown in Fig.6a illustrate the optimal pressure drop is (0.66 Kpa).The results of the optimization search as shown in Table 3 have been reasonable agreement because of the values of continuous variables (Vg &dp) and discrete variable (ρs) are within limits of the operating conditions (Eq. 2). In addition, the optimal values explain that the minimum PD can be obtained at low gas velocity, low-density glass beads of high particle diameter as shown in Table 3, Figs. 5 and 6a. Therefore, by staying close to this minimum flow condition, it is possible to perform a stable operation and to obtain energy savings. (Correa *etal*., 1999).The histogram of the variables in the Fig. 6a indicates that the density of solids (variable 2) is the effective variable on PD. Due to the nonlinearity of the spouted process (Eq. 1), the optimization equation of PD was solved by (51) generations as shown in Fig.6a.

Table 2.Adapted parameters of GA technique for different operation.

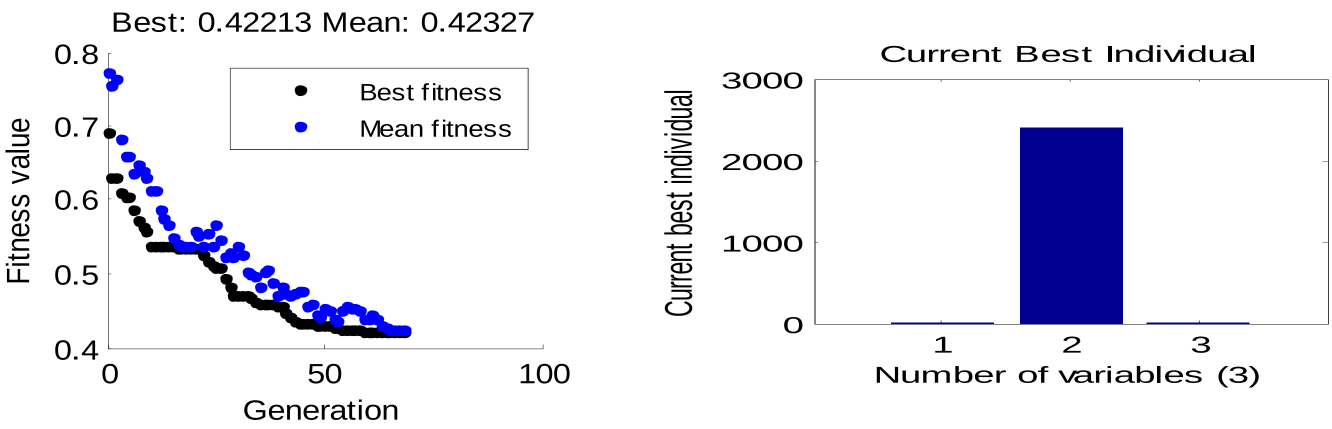
Parameter	Type and value
Population type	Double vector
Population size	100
Creation function	Feasible population
Scaling function	Rank
Selection function	Stochastic uniform
Crossover function	Scattered
Crossover fraction	0.7
Mutation function	Adaptive feasible
Migration direction	Both
Migration fraction	0.2
Hybrid function	Pattern search
Number of generation	51 (case 1) 68 (case 2)
Function tolerance	1.0E-6

Table 3.Optimal values of decision variables.

Decision variables	upper-lower bounds	unlimited upper bounds
Gas velocity (m/s)	0.7403	0.765
Density of solid (Kg/m^3)	2400.00	2400.00
Diameter of particle (mm)	2.178	17.14



(a)



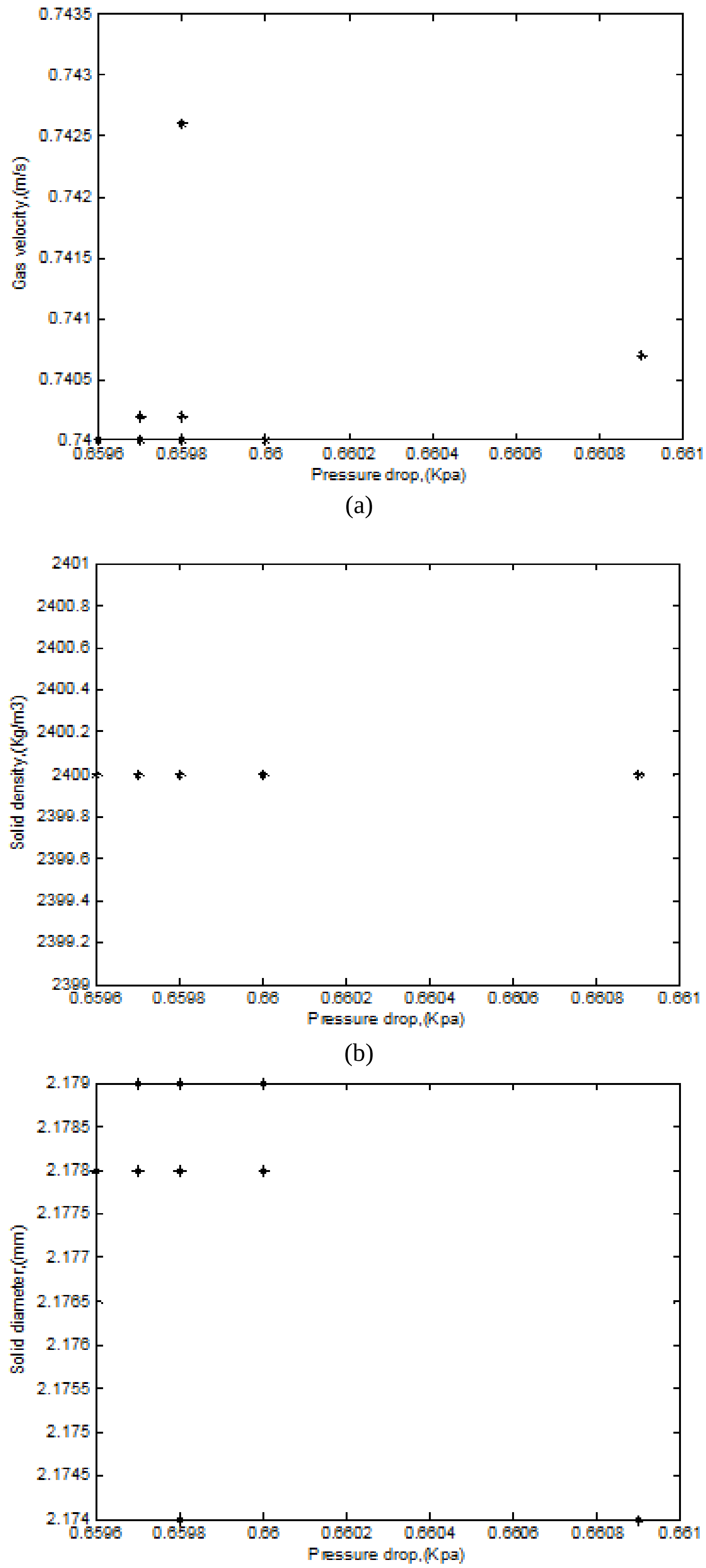
(b)

Fig. 6. Stochastic results of GA search for; (a) lower-upper bounds, (b) unlimited upper bounds.

3.4 Stochastic mutation of decision variables

The optimal sets of the three decision variables are illustrated in Figs.7a,7b and 7c corresponding to the objective PD.The scattering and stochastic of results are appeared in these figures as a results of natural selection by GA .It is found that the optimal values of the solid density (ρs)are almost constant at its lower bound as explained in the Fig.7b.This is due to that ρs is less sensitivity for variations of PD as shown in Fig. 7b.

Gas velocity (Vg) is changed within its lower bound (Fig. 7a) and solid diameter (dp) is fluctuated within its upper bound as shown in Fig.7c. These behaviors are because of Vg has positive effect while dp has negative effect on PD as shown in Fig.5. Most optimal values of the three decision variables are stay within optimum value of PD equal to 0.66 Kpa as shown in Fig. 7.It is observed that gas velocity and size of solids are more sensitive than solids' density for PD mutations as shown in Figs.7a and 7c.

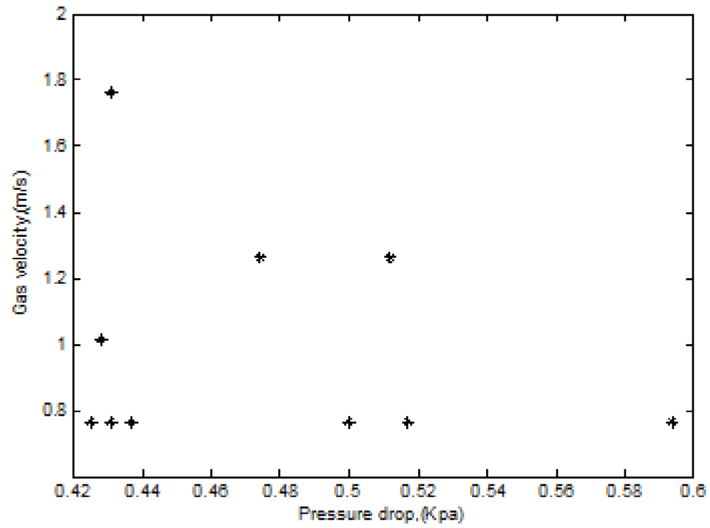


(a)

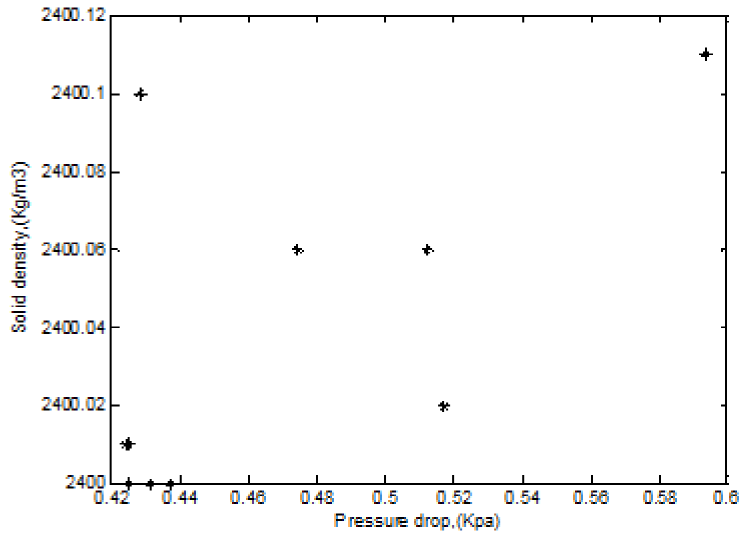
(b)

(c)

Fig. 7. Stochastic mutation of decision variables at lower-upper bounds corresponding to objective PD.



(a)



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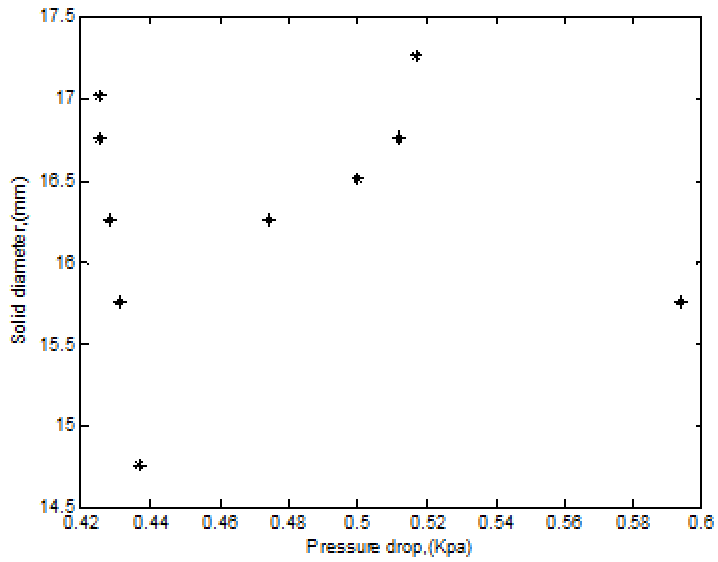

(c)

Fig.8. Stochastic mutation of decision variables at unlimited upper bounds corresponding to objective PD.

For scale-up methodology process, it is better to start the optimization search from the initial boundary conditions of Eq. 2. The results of GA search with lower bounds only are explained in Fig. 6b. GA's operators, which are selected in Table 2, have found the best values for solving the optimization problem (Eq. 1). The best fitness, best function and score histogram as shown in Fig.6b illustrate that the optimal pressure drop is (0.422 Kpa). The optimal values explain that minimum PD could be obtained at low gas velocity, low-density glass beads with high particle diameter as shown in Table 3, Fig. 5 and Fig. 6b.The number of generations in this case are increased to (68) as shown in Fig. 6b.This is because of unlimited upper bound, which would need to additional search- iterations compared with GA search of limited upper-lower bounds. So that, the stochasticity scattering of GA is high as shown in Figs.8a, 8b and 8c. The optimal sets of the decision variables are illustrated in these figures corresponding to the objective PD.It is observed that the optimal values of Vg and ρs have small change compared to previous case as shown in Table 3, Figs. 8a and 8b. dP is increased to new values to obtain the minimum PD as explained in Fig. 8c and Table 3. These behaviors are because of Vg and ρs have positive effect, while dp has negative effect on PD as shown in Fig. 5. Sensitivity of the three decision variables shall be increased with unlimited bounds because of increasing number of generations and natural selection as shown in Fig. 6b and Table 2.Optimal values of decision variables are stay within the region of optimum PD equal to 0.422 Kpa as shown in Fig.8.In addition; it is observed that Vg and dp are more sensitive variables for PD variations as shown in Figs.8a and 8c. However, the success of optimization search depends on formulation of the objective function, selection of decision variables and selection of the suitable searching technique.

IV. Conclusions

Dropping of pressure drop across the spouted bed will reduce the risk of the dissipated pumping energy and enhances the uniformity and stability of solid particles that would improve performance of the bed. Uniformity of solid particles could enhance hydrodynamic parameters, heat and mass transfer. Genetic Algorithm has found the suitable stochastic global search for the hybrid nonlinear bed. Optimal results would guide for selecting of best operating conditions of the bed. Reliability of the search could be enhanced by adaptation of GA's operators. Success of optimization search depends on formulation of the objective function, selection of the decision variables and selection of suitable GA's operators. It has been found that best operability was achieved with low-density,large size of solid beads ,low gas velocity at low PD. Velocity of gas and diameter of solid particles have found the sensitive decision variables on PD mutations. Sensitivity of these variables would be increased at unlimited upper bounds. Reliable control system for sensitive decision variables is recommended to operate the spouted bed within best conditions.

V. Acknowledgments

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