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Optimization of Pressure Drop in a Spouted Bed via Genetic Algorithm

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Abstract

Dropping of pressure drop (PD) across the spouted bed could reduce the dissipated pumping energy and improve stability and uniformity of solid particles. The selected decision variables are; gas velocity, solid's density and solid's diameter. Steady-state measurements were carried out in the 60° conical shape spout-air bed. Concentration of solid particles (glass and steel beads) at various elevations of the bed under different flow patterns were measured by using sophisticated optical probes. Optimization technique helps the decision makers to select the best set of operating conditions. Stochastic genetic algorithm has found suitable for the non-linear hybrid spouted bed. Optimum results would provide the design and operation of the bed. It has been found that the low-density glass beads of high -particle diameter at low gas' velocity, could obtain minimum PD. Particle's density is the effective variable on PD. Velocity of gas and diameter of solid particle have found the sensitive decision variables with PD changing. The sensitivity of the variables could be increased at unlimited upper bounds.

Keywords: Genetic algorithm; Optimization; Pressure drop; Spouted bed; Solid particles

1. 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.Additionlly,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 (Figure 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: Sphersity of the solid particle, [-]

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 due to the elimination of the back mixing (Prachayawarakorn *etal*.,2005).

The objective is to minimize the pressure drop (PD) across the spouted bed. Study the effect of decision variables on PD under steady-state conditions. The optimization problem is correlated depends on the available experimental data of the lab-scale bed. Stochastic global search genetic algorithm is used to solve the optimization equation. The optimal results provide the design and operation of the spouted bed.

2. Materials and methods

2.1. Experimental set-up

The present work is a part of scale-up methodology which is investigate and develop into the Multiphase and Multiscale 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 Figure 1.The cylindrical spouted bed is made of Plexiglas. The bed is 3 inches 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. 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.

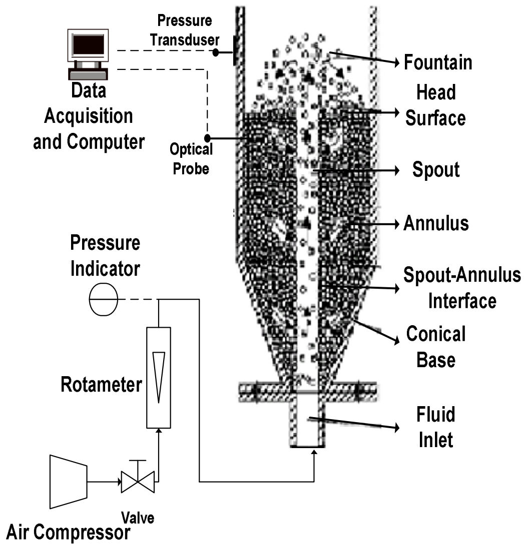


Figure 1.Experimental set-up.

The solid particles used are steel and glass beads with different diameters and properties as shown in Table 1.The newly optical probes are used to measure both solids concentration and solids velocity and their fluctuation at radial and axial positions of the spouted bed. 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. The pressure drop across the bed is measured by the pressure transducer (Type: PX309-002G5V) manufactured by omega company. The pressure into the spouted bed adjusting within the desired values

Table1. Properties of the particulate materials.

Material	dp(mm)	$\rho s(Kg/m^3)$	€	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

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 the pressure drop in the bed, are; gas velocity, particle density and particle diameter.

2.2 Optimization problem

The available experimental data have been used to correlate empirically the objective (PD) with the decision variables to facilitate the optimization scheme. The advanced nonlinear regression optimization algorithm used is Hook-Jeevs pattern moves with the aid of the computer program (Statistica version10).The optimization equation is:

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

Subject to Inequality constraints:

$$\mathbf{0.74 \le Vg \le 1.0}$$
$$\mathbf{2400.0 \le \rho s \le 7400.0} \qquad (2)$$
$$\mathbf{1.09 \le dp \le 2.18}$$

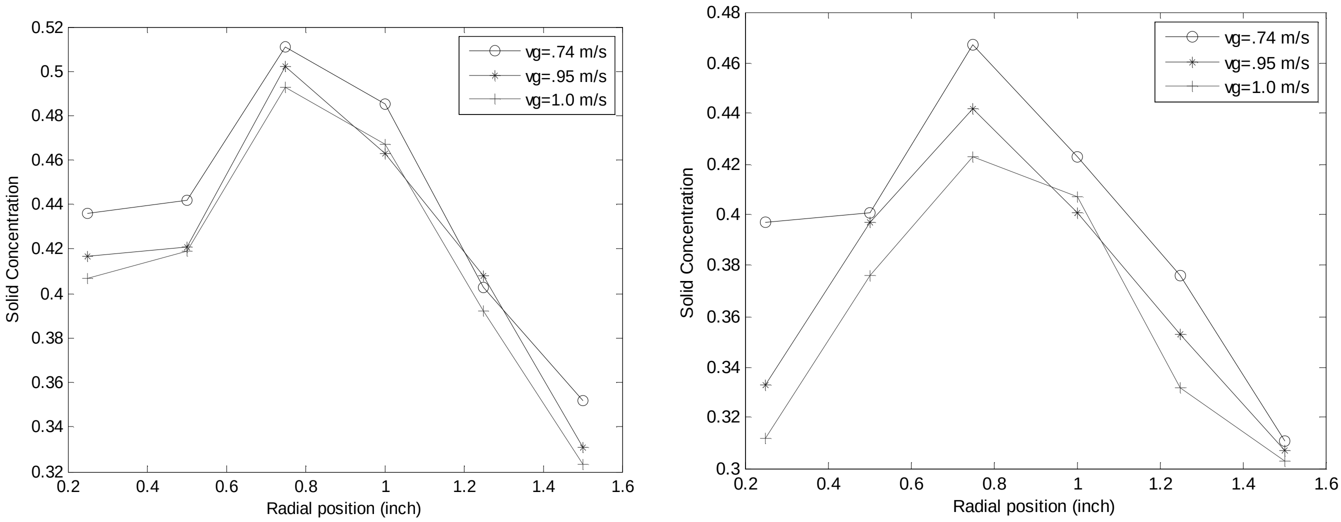
From Equation1, one can conclude that the air velocity, density of the solid particles have positive effect on the pressure drop across the bed, while the diameter of particles has negative effect.

Since the spouted-gas bed is a hybrid fluid-solid contacting system, genetic algorithm (GA) is the best global stochastic search that based on mechanics of natural selection (Gupta and Srivastava, 2006). GA implemented for optimization problem (Equation 1) with upper-lower bounds (equation 2) and with lower bounds only.

3. Result and Discussion

3.1 Stability of spouted bed

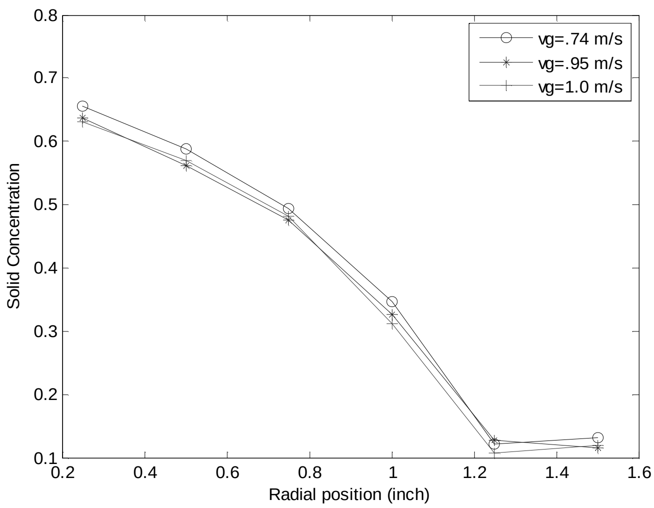
The parameters of the process are difficulty measured; also the efficiency of the spouted bed is dropped at the unstable conditions. Different flow regimes in the present spouted bed were studied to limit the stable gas velocity (Xu etal.,2009) .The optimum range of air velocity is between 0.74 to 1.0 m/s. Figures (2a and b) illustrate the effect of pressure drop on the stability of the spouted bed using concentration of glass and steel particles' distributions portrait. 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 due to high-pressure drop as a result of the 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 the triangular pulse shape and not uniform. The maximum peak of pulses represent the maximum values of solid concentrations at the middle location (0.75 inches) of radial position. Unstable spouting is characterized by swirling and pulsation of the spout (Xu *etal*. ,2009 and Rovero *etal*.,2012).



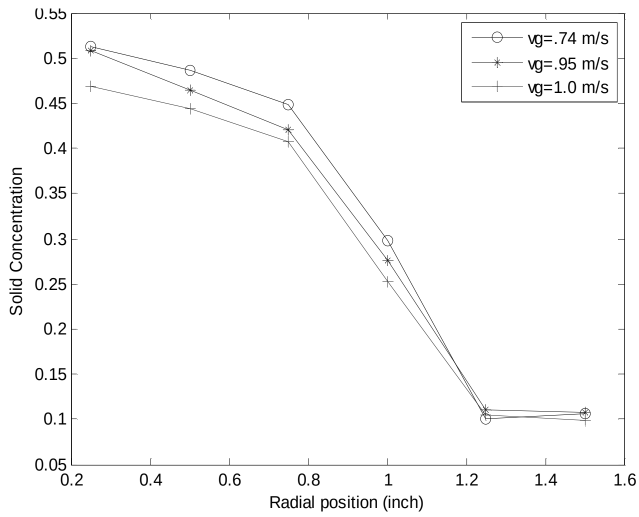
(a) (b)

Figure 2. Solid concentration distributions in zone 1 for ;(a) steel beads, (b) glass beads.

Figure 3a illustrates the portrait of steel beads distributions at the cylindrical region (zone 2) which locate at 5.5 inches above the conical base at the same operating conditions. The solid concentration profile curves have the 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 into the lower gas motion region of the spouted bed (annular part). The packed bed and stable spouting are distinguished by the formation of the stable spout. Figure 3 explains that the solid concentrations are much less in the lean bed region in the center (1.5-inch radial position) than in the dense bed region near the wall (0.25-inch radial position). Figure 3b 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 is increased with low- gas velocity and high particle's density as shown in Figure 3.However, the spouted-gas bed behaves as a hybrid fluid-solid contacting system.



(a)



(b)

Figure 3. Solid concentration distributions in zone 2 for ;(a) steel beads,(b) glass beads.

Figure 4 explains the effect of the process variables (air velocity, density and diameter of solid particles) on the pressure drop 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 (Figure 4a). The dense particles (steel) create more resistance and friction against the airflow and then tend to raise the pressure drop across the bed (Figure 4b).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 (Figure 4b).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.

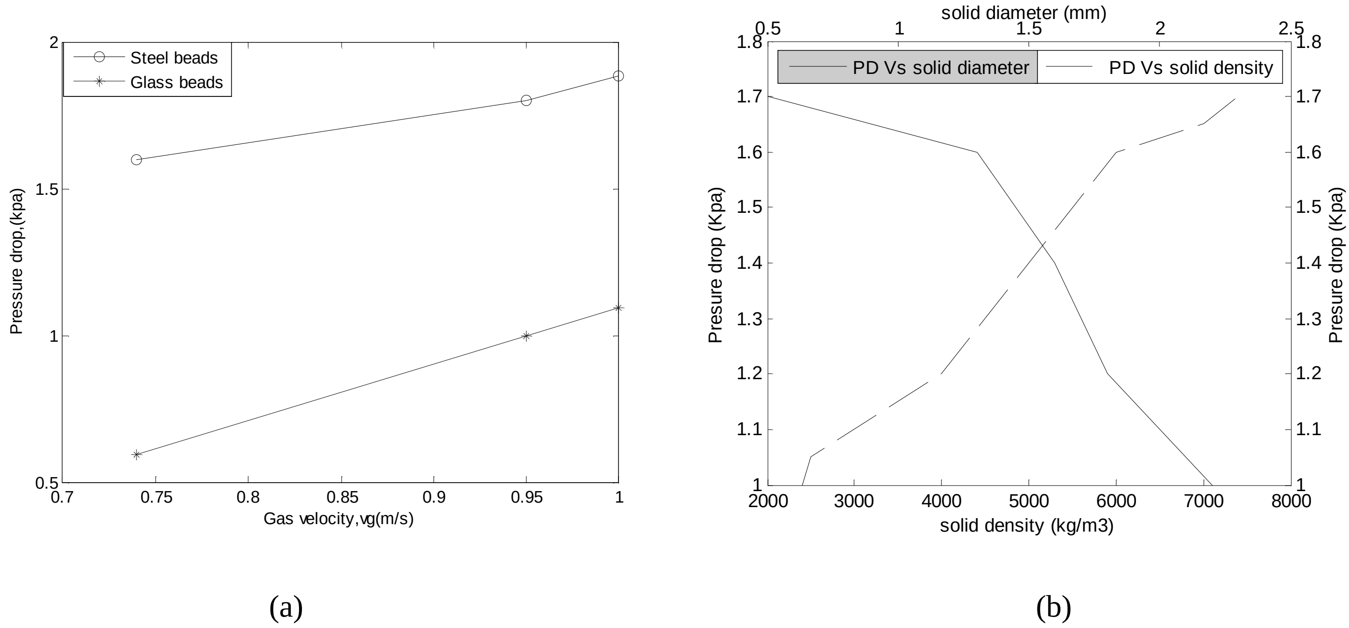


Figure 4. Pressure drop against ;(a) gas velocity,(b) solid density and solid diameter.

3.2 Optimization 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.

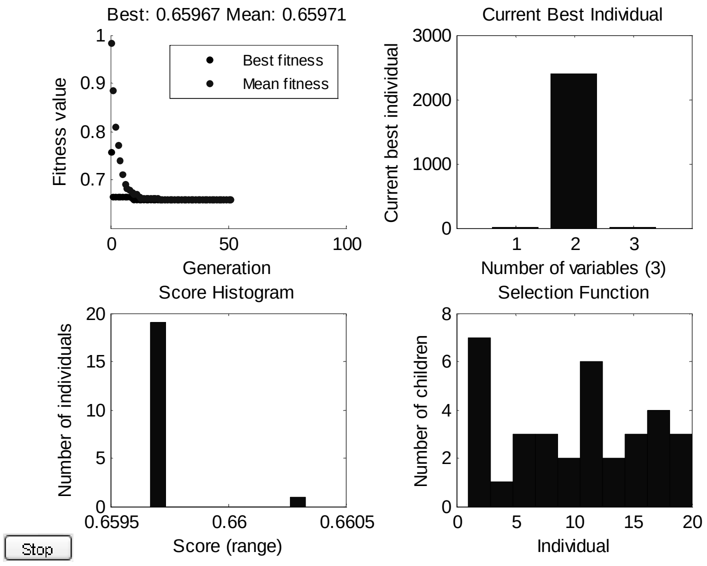
Table 2 explains the best parameters of the genetic algorithms with upper-lower and lower bounds. Figure 5a illustrates the outputs of the algorithms solutions/operators of upper-lower bounds system. GA is implemented with the pattern search by using the hybrid function as shown in Table 2 to refine the decision variables (Palonen *etal*.,2009). The best fitness, best function and score histogram as shown in the Figures 5a illustrate that the optimal pressure drop is (0.66 Kpa).The results of the optimization search (Table 3) have reasonable agreement since the values of the continuous (Vg & ρs) and discrete (dp) variables within the limits of the operating conditions (Equation 2). In addition, the optimal values improve that the minimum PD can obtain by the low gas velocity, low-density glass beads of high particle diameter as shown in Table3, Figure 4 and Figure 5a. 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 Figure 5a indicates that the density of solids (variable 2) is the effective variable on PD. Due to the nonlinearity of the spouted process (equation 1), the optimization equation of PD was solved by (51) generations as shown in Figure 5-a. The optimal sets of the three decision variables are illustrated in the Figures (6a,b and c) 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 Figure 6b.This is due to that ρs is the effective variable for

Table 2. Adapted parameters of GA technique.

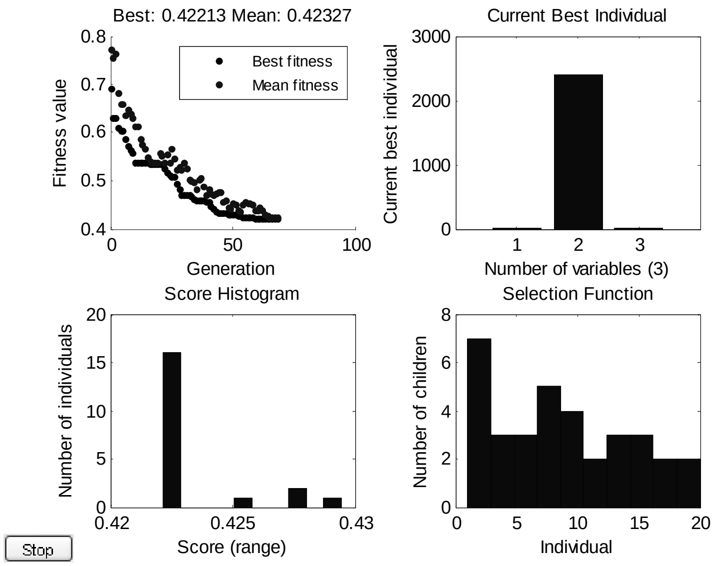
Parameter	Type and value
Population type	Double vector
Population size	100
Creation function	Feasible population
Scaling function	Rank
Selection function	Stochastic uniform
Crossover function	Scattered
Crossover fraction	0.7
Mutation function	Adaptive feasible
Migration direction	Both
Migration fraction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

Table3.Optimal values of decision variables.

Decision variables	With upper-lower bounds	With lower bounds
Gas velocity (m/s)	0.7403	0.765
Density of solid (Kg/m^3)	2400.00	2400.083
Diameter of particle (mm)	2.178	17.417



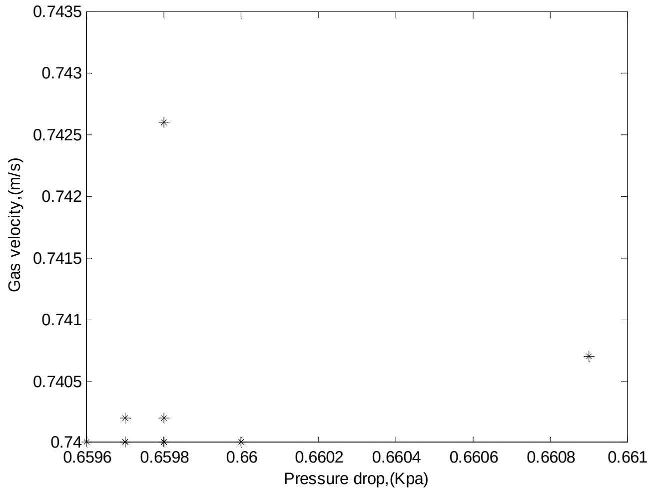
(a)



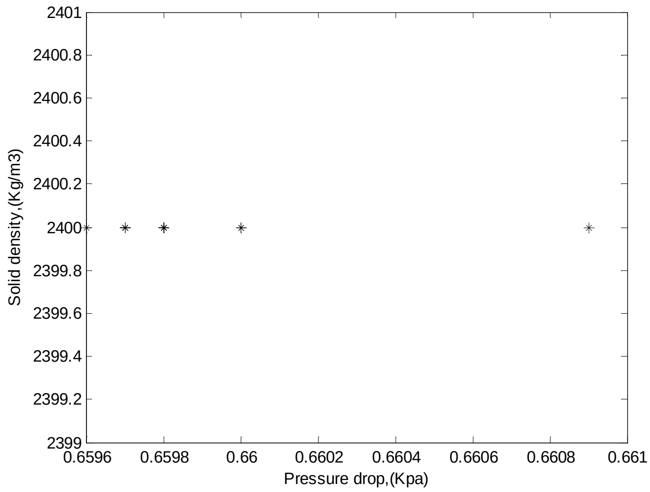
(b)

Figure 5. Results/solution of genetic algorithm with; (a) lower-upper bounds, (b) lower bounds.

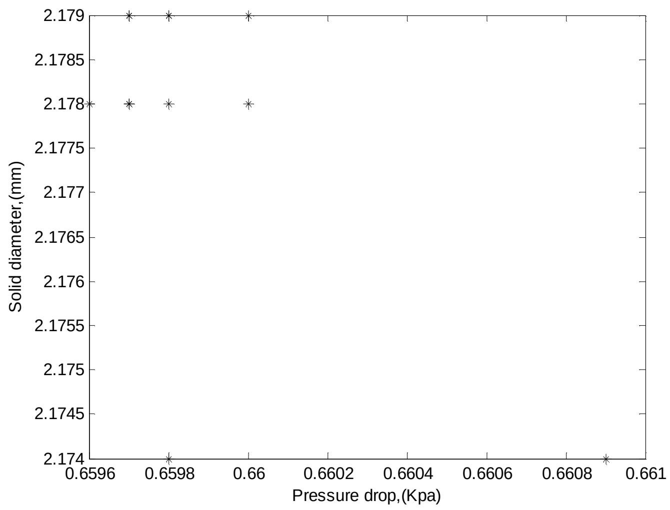
PD as shown in the Figure 5a.Gas velocity (Vg) is changed within its lower bound (Figure 6a) and solid diameter (dp) is fluctuated within its upper bound as shown in Figure 6c. These behaviors are because of Vg and ρs have positive effect while dp has negative effect on PD as shown in the Figure 4. Most optimal values of the three decision variables are stay within optimum value of PD which equal to 0.66 Kpa as shown in the Figure 6.It is observed that Vg and dp are the most sensitive variables for PD changing as shown in the Figures (6a and c).


Gas velocity,(m/s)
0.7435
0.743
0.7425
0.742
0.7415
0.741
0.7405
0.74
0.6596
0.6598
0.66
0.6602
0.6604
0.6606
0.6608
0.661
Pressure drop,(Kpa)

(a)

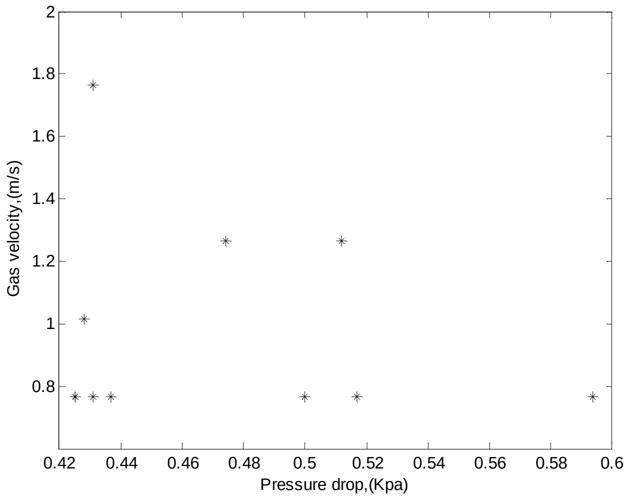

Solid density,(Kg/m3)
2401
2400.8
2400.6
2400.4
2400.2
2400
2399.8
2399.6
2399.4
2399.2
2399
0.6596
0.6598
0.66
0.6602
0.6604
0.6606
0.6608
0.661
Pressure drop,(Kpa)

(b)

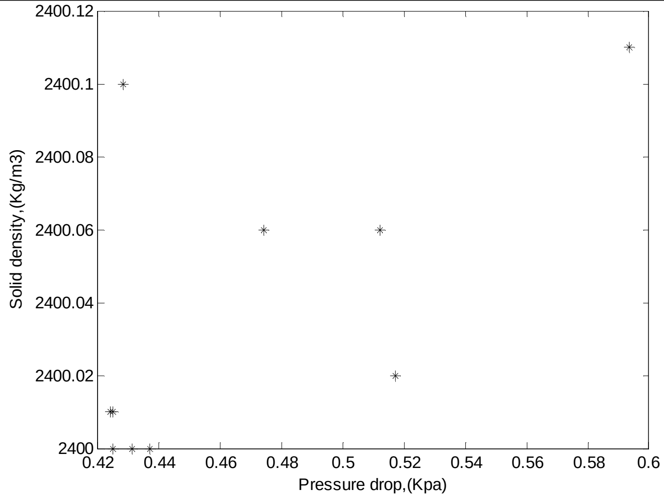


(c)

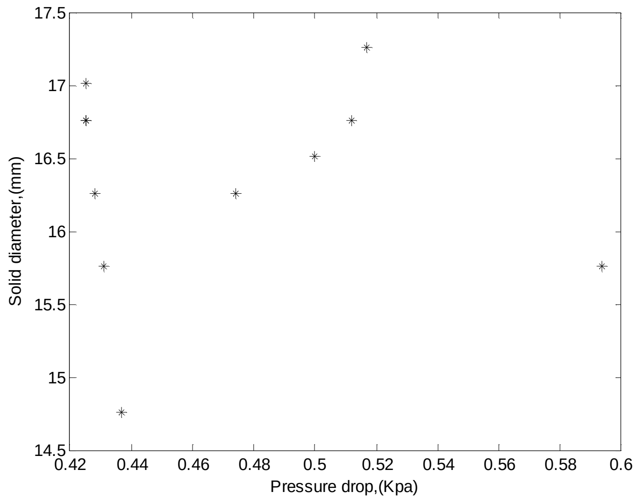
Figure 6. Optimal values of decision variables with lower-upper bounds corresponding to objective PD.



(a)



(b)



(c)

Figure 7. Optimal values of decision variables with lower bounds corresponding to objective PD.

For scale-up process and to extend the limits of operating conditions, it is better to start the search from the initial points of Equation 2. The solution/operators of GA search with lower bounds only of Equation 2 are explained in the Figure 5b. GA's operators, which are selected in Table 2, have found the best values for solving the optimization problem (Equation 1). The best fitness, best function and score histogram as shown in the Figure 5b illustrate that the optimal pressure drop is (0.422 Kpa). The optimal values explain that the minimum PD could obtained by the low gas velocity, low-density glass beads of high particle diameter as shown in Table 3, Figure 4 and Figure 5b.The number of generations in this case are increased to (68) as shown in the Figure 5b.This is because of unlimited upper bounds which needed to additional search- iterations compared with the GA search of limited upper-lower bounds. So that The scattering stochasticity of GA is high as shown in the Figures (7a, b and c). The optimal sets of the decision variables are illustrated in these Figures corresponding to the objective PD.It is found that the optimal values of Vg and ρs have small changes within its lower bounds as explained in the Figure (7a and b). Dp is increased to new upper limits to obtain the minimum PD as shown in Figure 7c. These behaviors are because of Vg and ρs have positive effect while dp has negative effect on PD as shown in the Figure 4. The sensitivity of the three decision variables is enhanced with unlimited bounds because of increasing the number of generations and the natural selection as shown in the Figure 7. Most optimal values of the three decision variables are stay within the region of optimum PD equal to 0.422 Kpa as shown in the Figure 7.In addition; it is observed that Vg and dp are the most sensitive variables for PD variations as shown in the Figures (7a and c). However, the success of optimization search depends on the formulation of the objective function, the selection of the decision variables and the selection of the suitable searching technique.

4. Conclusions

1. Spouted bed is a hybrid nonlinear process system.
2. Dropping of the pressure drop across the bed will reduce the risk of the dissipated pumping energy and enhances the uniformity and stability of solid particles.
3. Density of solid particles is the effective variable on the pressure drop across the spouted bed.
4. Velocity of gas and diameter of solid particle are the sensitive decision variables with pressure drop changing. The sensitivity can increase at unlimited upper bounds.
5. Minimum pressure drop could obtain by the low-density glass beads of high particle diameter at low values of gas' velocity.
6. Success of optimization search depends on the formulation of the objective function, the selection of the decision variables and the selection of the suitable searching technique.
7. Genetic algorithm has found the suitable stochastic global search for the hybrid nonlinear spouted bed. The reliability of the search can be enhanced by adaptation of the algorithm operators.

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