Multi-objective Optimization of a Spouted Bed

Ghanim Alwan*
University of Technology-Chemical Engineering Dept., Baghdad-Iraq
E*-mail: ghanim.alwan@yahoo.com

Abstract

Performance of the gas-solid spouted bed benefits from solid's uniformity structure (UI) with lower pressure drop (PD). Spouted bed system needs to be optimized to achieve the maximum performance.Therefore; the focus of this work is to maximize the UI and to minimize the PD along the bed. Three selected decision variables are affecting these objectives that are; gas' velocity, particle's density and particle's diameter. Steady-state measurements were carried out to study the effect of the decision variables on UI and PD in the 60° conical shape spout-air bed with the diameter of 3 inches and height of 36 inches. Radial concentration of particles (glass and steel beads) at various elevations of the bed under different flow patterns were measured using sophisticated optical probes. High- accuracy pressure transducer monitored the pressure drop across the bed. Solid's density has found the effective variable on both UI and PD. Multi-objective genetic algorithm (GA) has found the best stochastic technique for highly nonlinear hybrid spouted system. The reliability of optimization search can be enhanced by adaptation of the GA's operators. Optimum results have 14 sets of new operating conditions would improve the efficiency of the bed. Maximum UI obtained with high-density steel beads, and minimum PD could obtain with low-density glass beads at low gas' velocity. It was observed that the gas' velocity was the sensitive variable for UI and PD changing.

Keywords: Genetic algorithm; Optimization; Pressure drop; Spouted bed; Uniformity index.

1. Introduction

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 as reactors such as; coating, desulfurization, CO_2 capture, combustion and gasification of coal and biomass .The dual hydrodynamics, good mixing in spout ,fountain and piston flow in the peripheral annulus with alternated high and slow interphase,in the spout and in the annulus respectively, makes beds unique reactors(Rovero etal.,2012).It is a kind of high-performance reactor for fluid-solid particle's reaction, also it is a hybrid fluid-solid contacting system (Wang etal., 2001).

It is better to develop the design of the spouted bed to overcome the large pressure drop and instability of the operation and enhances the uniformity of the products resulting from the chemical or physical treatment due to the elimination of the back mixing (Wendt etal.,2007). Uniformity of solid particles enhances the mass and heat transfer in addition improves the conversion of the reactants. The pressure drop across the bed is dropped the risk of dissipated pumping energy.

Most studies, concerning solid behavior and hydrodynamic correlations of spouted bed have been done at the ambient temperature. The lack of studies at higher temperatures is due to difficulties associated with measuring techniques under these conditions (Radmanesh *etal*. 2005).

Optimization technique is a powerful tool to obtain the desired design parameters and set of operating conditions. Genetic algorithm (GA) is a global search algorithm based on mechanics of natural selection.GA is based on Darwin's theory of 'survival of the fittest'. There are several generic's operators such as; selection, crossover and mutation. Each chromosome represents a possible solution to the problem being optimized, and each bit (or group of bits) represents a value of variable of the problem .These solutions are classified by an evaluation function, giving better values, or fitness, to best solution (Gupta and Srivastava ,2006).

2. Scope of the Work

The present work focuses on study the effect of the selected decision variables (gas velocity, solid's density and solid's diameter) on the objectives UI and PD.Steady-state measurements are carried out at different operating conditions using sophisticated optical probes and high- accuracy pressure transducer. The nonlinear correlations of the optimization problem would be correlated depended on the available experimental data of the lab-scale spouted bed The objective is to maximize UI and to minimize PD.Stochastic genetic algorithm is a global search technique will implement to solve the conflicted multiobjective equations .Optimal results will enhance the performance of the hybrid spouted bed.

3. Materials and methods

3.1. Experimental set-up

The present work is a part of scale-up methodology that is developed in 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 shown in the Figure 1.The cylindrical bed is made of Plexiglas. The bed is 3 inches in diameter and 36 inches in height. 20 holes (0.5 inch in diameter) are drilled at vertical intervals of (1.86 inch) along the column. 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 base.

The particles used are steel and glass beads with different diameters and properties as shown in the Table 1.The newly optical probes are using to measure the concentration and velocity of the beads at radial and axial positions of the bed. These probes are adapted to 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. The pressure drop across the bed is measuring by the high-accuracy pressure transducer (Type: PX309-002G5V) manufactured by Omega Company. The pressure in the bed is adjusting to the desired value by the inverted circular stabilizer of 60 mm in diameter is located at the top of the bed column. This is preventing the spout fountain from swaying.

3.2. Formulating of Optimization Problem

At steady-state conditions, the local uniformity index (UI) of the solid particles across the spouted bed (Nedeltchev *etal*. ,2000 and Zhang *etal*.,2011) is determined by Equation 1.

$$UI = (C_{avg}-C_{Min})/(C_{Max}-C_{min}) \quad (1)$$

The objectives (UI and PD) are correlated with the three decision variables. Two-advanced nonlinear regression used which are; Newton-Quasi and Hook-Jeevs pattern moves with the aid of the computer program (Statistica version10). The conflicted optimization problems are:

$$UI=0.184Vg^{-0.214}\rho s^{0.12}dp^{-0.267} \quad (2)$$

$$PD=0.037Vg^{0.38}\rho s^{0.407}dp^{-0.221} \quad (3)$$

Subject to inequality constraints:

$$0.74 \le Vg \le 1.0$$
$$2400.0 \le \rho s \le 7400.0 \quad (4)$$
$$1.09 \le dp \le 2.18$$

However, the spouted bed is highly nonlinear interacted process. GA is the best global search for solving the optimization problem of the process.

4. Result and Discussion

Figure (2a) illustrates the effect of the air velocities on the uniformity index (UI) with the steel and glass beads. The UI decreased with increasing the air velocity (Vg) because of the desperation of the solid particles is increased. Two regions appeared which represent the transition region from the packed bed flow regime at Vg of 0.74 m /s to the 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 Figure (2a) because of high scattering of the particles of low density. The density of the solid particles has the positive effect on the UI (Figure 2b). Increasing of the particles' density provides the strength and resistance of the bed against the vortex of the fountain. Then, the bed becomes uniform and stable.

The bead's diameter has negative effect on the UI as shown in Figure (2b). The particles of small size are helpful to raise the uniformity across the bed (Hao, 2008).

However, the improving of UI could enhance the mass, heat transfer and the conversion of reactants in the spouted bed.

Figures (3a and b) explain the effect of the decision variables (air velocity, density and diameter of solid particles) on the PD across the bed. PD increased with the increasing of Vg for both steel & glass beads due to the increasing of the kinetic energy and interaction of solid particles (Sathiyamoorthy, 2010). In the case of steel beads, the pressure drop is higher than that of glass particles. The dense steel particles have more resistance to the airflow than the low - density glass beads as shown in the Figure (3b).The porosity of the bed is increased with the large particle's diameter, and then the pressure drop across the spouted bed is dropped (Zhong *etal*.,2006).

However, the density of solid particles has found the effective variable on the objectives (UI and PD).

The two conflicted objective functions (Equations 2 and 3) are solved simultaneously to obtain the global optimum results. For best solution, the operators of GA were adapted as shown in Table 2. GA was implemented with the pattern search using the hybrid function to refine the decision variables (Palonen *etal*., 2009). Since the objective functions are conflicted, then the GA search could generate 14 Pareto solutions of the optimization problems as shown in Figure 4. Each solution represents a set of new operating conditions. Optimization technique could reduce the risk of experimental runs and the cost for design and operation. In addition, the optimum operating conditions enhance the performance of the spouted bed.

Figure 4 illustrates the solution/operators of the GA. The score histogram in the Figure 5 explains that the optimum UI are between 0.39 to 0.53 while the optimum PD within range of 0.66 to 1.19. The results of the multi-objective search are stayed within the limits of the operating conditions of the process (Equation 4). The decision makers can select the suitable solution .The optimum results are explained in Table 3. The maximum UI can obtain by high-density steel beads of small particle diameter at low air velocity. Low-density glass beads of large particle diameter at dropped air velocity can obtain minimum PD. 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 optimal sets of the three decision variables are illustrated in the Figures (6a, b and c) corresponding to the objective UI.The scattering and stochastic of results are appeared in these figures as a result of natural selection by GA .It is found that the optimal values of ρs are increased at its upper bound as explained in the Figure (6b). Vg is changed within its lower bound (Figures 6a). It is observed that the optimal values of dp is almost constant at its lower bound as explained in the Figure (6c).These behaviors are because of ρs has the positive effect while Vg and dp have the negative effect on UI as shown in the Figure 2. Vg is the most sensitive variable for UI changing (Figure 6a).Most optimal values of the three decision variables are stayed within the maximum value of UI, which equal to 0.534 as shown in the Figure 6.

The optimal sets of the three decision variables are illustrated in the Figures (7a, b and c) corresponding to the objective PD.Also the scattering and stochastic of results are appeared in these figures as a result of natural selection by GA .It is found that the optimal values of ρs are changing at its lower bound as explained in the Figure (7b). Gas velocity (Vg) is changed within its lower bound (Figure 7a) and solid diameter (dp) is almost constant within its lower bound as shown in the Figure (7c). These behaviors are because of Vg and ρs have the positive effect while dp has the negative effect on PD as shown in the Figure 3. Most optimal values of the three decision variables are stayed within the optimum value of PD, which equal to 0.66 Kpa as shown in the Figure 7.It is observed that Vg is the most sensitive variable for PD changing as shown in the Figure (7a).The optimal values provide the experimental work by selecting the best operating conditions, which enhance the performance of the present spouted bed. The maximum UI could obtain by the steel beads and the minimum PD obtained by the glass beads. The success of the optimization search depended on: the best formulations of the objectives with the decision variables and the selection of the proper optimization algorithm.

5. Conclusions

1. Spouted bed is a highly interacted nonlinear process system.
2. Density of solid particles is the effective variable on the uniformity index and the pressure drop across the spouted bed.
3. High-density steel beads can obtain maximum uniformity index while the minimum pressure drop obtained by the low-density glass beads.
4. Velocity of gas is the sensitive decision variable for uniformity index and pressure drop changing.
5. Hybrid spouted bed system needs to be optimized and the optimal results could enhance the performance of the bed.
6. Reasonable agreement has obtained when compared the optimal solutions with the experimental results.
7. Success of optimization search depends on the formulation of the objective function, selection of the decision variables and selection of suitable searching technique.
8. Genetic algorithm has found the suitable stochastic search for the nonlinear spouted bed. The reliability of the search can enhance by the adaptation of the algorithm's operators.

Acknowledgment

We thank all the participants to the Chemical and Biological Department-Missouri University of S & T, Rolla, Missouri (USA).

Nomenclature

C	Relative concentration of solid
C_{avg}	Averagel concentration of solid part

C_{min}	Minimum local concentration of solid
C_{max}	Maximum local concentration of solid
dp	Diameter of solid particle, [mm]
PD	Pressure drop in the spouted bed,[Kpa]
UI	Uniformity index of solid particles
Vg	Superficial velocity of gas, [m/s]

Greek Symbols

ρs	Density of solid particles,Kg/m^3
€	Porosity of bed
Ø	Sphersity of the solid particle

References

Correa, N.A., Freire, J.T and Correa, R.J (1999).'Improving Operability of Spouted Beds Using a Simple Optimization Control Structure', *Brazilian.J.Chem.Engng*. 16, (4), Dec.Saopaulo.

Gupta, A.K. and Srivastava, R.K (2006).'Integral Water Treatment Plant Design Optimization: a Genetic Algorithm Based Approach',*IE Journal*,87,September.

Hao, H., Guoxin, H.and Fengchao, W (2008).'Experimental Study on Particles Mixing in an Annular Spouted Bed, Energy and Conversion Management, 49:257-266, Elsevier.

Nedeltchev,S.,Ookawara,S.,and Ogawa,K (2000).'Time-dependent Mixing Behaviors in Lower and Upper Zones of Bubble Column', *J.chem.Engng.of Japan*, 33, (5):761-767.

Palonen, M., Hasan, A. and Siren, K (2009).'A Genetic Algorithm for Optimization of Build-ing Envelope and HVAC system Parameters', Eleventh International IBPSA Conference, July 27-30, Glasgow, Scotland.

Radmanesh,R.,Mabrouk,R.,Chaouki,J.,and Guy,C (2005).'Effect of Temperature on Solids Mixing in a Bubbling Fluidized Bed Reactor',*International Journal of Chemical Reactor Engineering*,3,A16.

Rovero,G.,Massimo,C.,and Giuliano,C (2012).'Optimization of a Spouted Bed Scale-Up by Square-Based Multiple Unit Design',Advances in Chemical Engineering,Chapter16,Published with InTech ,ISBN:987-953-51-0392-9.

Sathiyamoorthy, D (2010).'Plasma Spouted-Fluidized Bed for Materials processing', Journal of Physics, Conference Series 208.

Wang, Z., Chen, P., Li, H., Wu, C.and Chen, Y (2001).'Study on the Hydrodynamics of a Spouting-Moving Bed', *Ind.Engng.Chem.Res*, 40:4983-4989.

Wendt, D.S, Bewley, R.L. and Wides, W.E (2007).'A Spouted Bed Reactor Monitoring System For Particulate Nuclear Fuel', proceeding of space nuclear conference, Boston, Massachusetts, June 24-28, paper 2023.

Zhang, Y., Zhong, W.and Jin, B (2011).'New Method for the Investigation of Particle Mixing Dynamic in a Spout-Fluid Bed', *Powder Technology*, 24, January.

Zhong, W., Chen, X.and Zhang, and M (2006).'Hydrodynamic Characteristics of Spout-Fluid Bed: Pressure Drop and Minimum Spouting/Spout-Fluidizing Velocity', *Chemical Engineering Journal*, 118: 37-46.

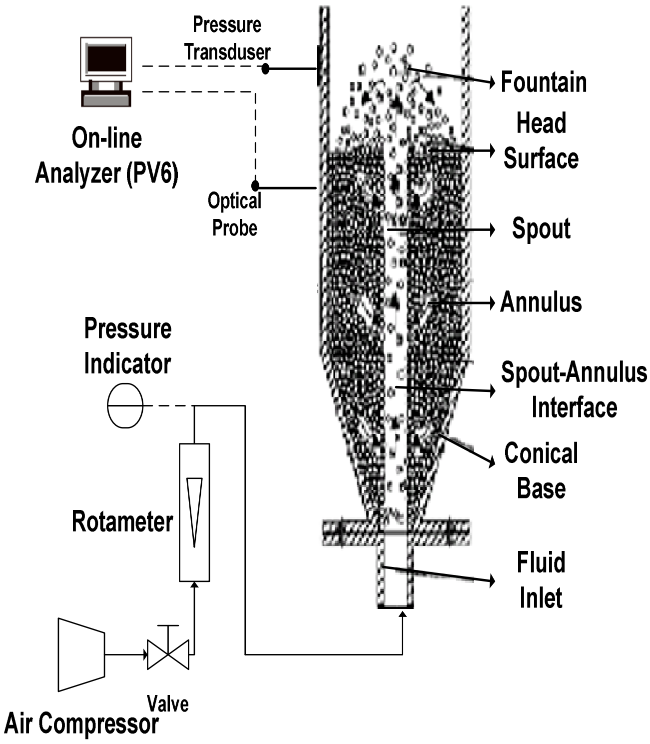
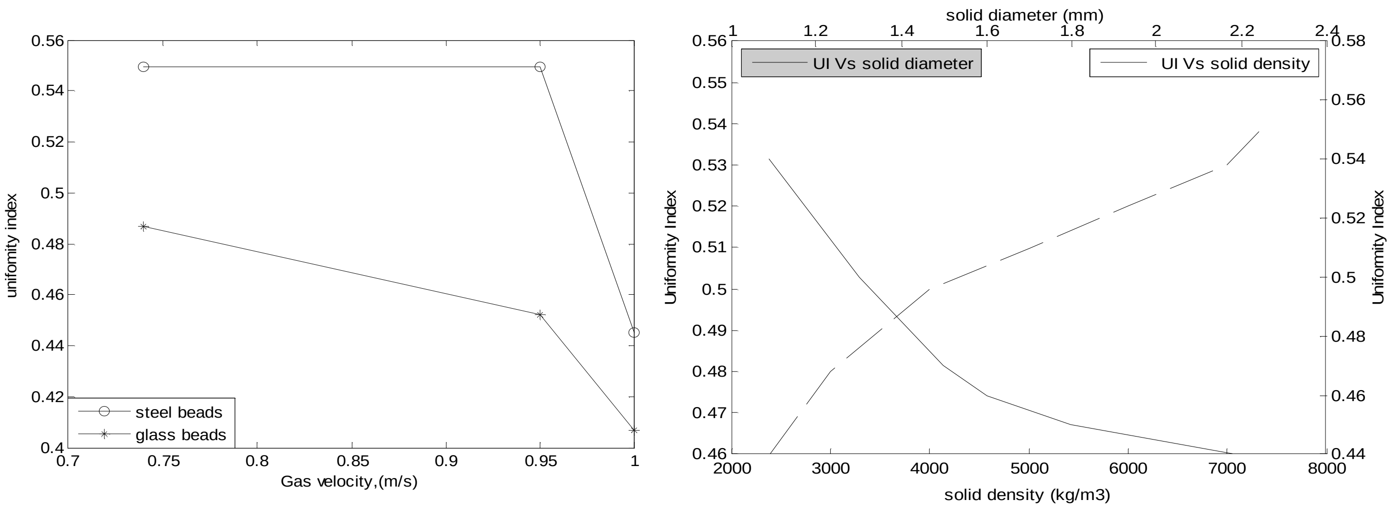


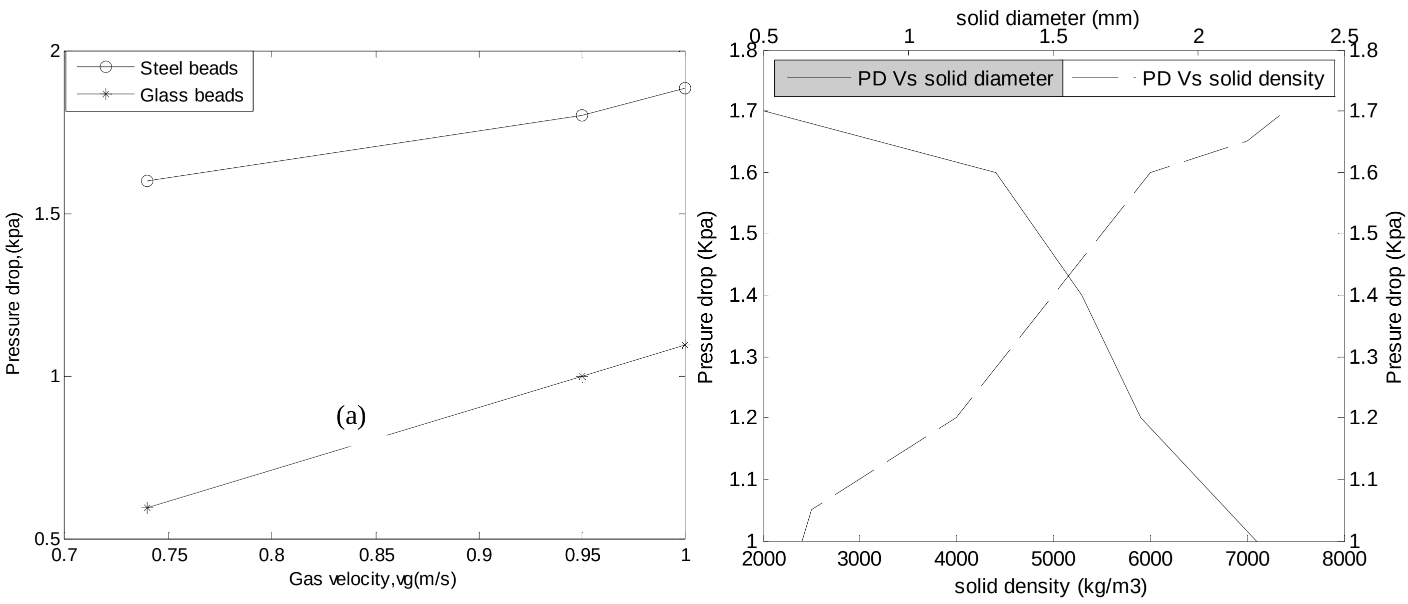
Figure 1. Experimental set-up.

 www.iiste.org



(a) (b)

Figure 2. Uniformity index against ;(a) gas velocity,(b) solid density and solid diameter.



(a) (b)

Figure 3. Pressure drop against ;(a) gas velocity,(b) solid density and solid diameter.

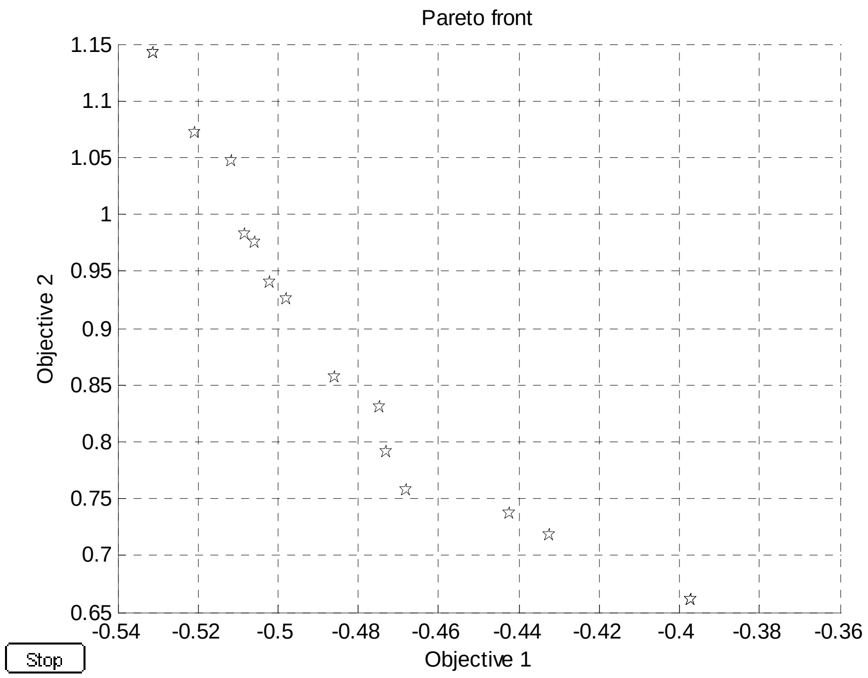


Figure 4. Pareto front of multi-objective genetic search.

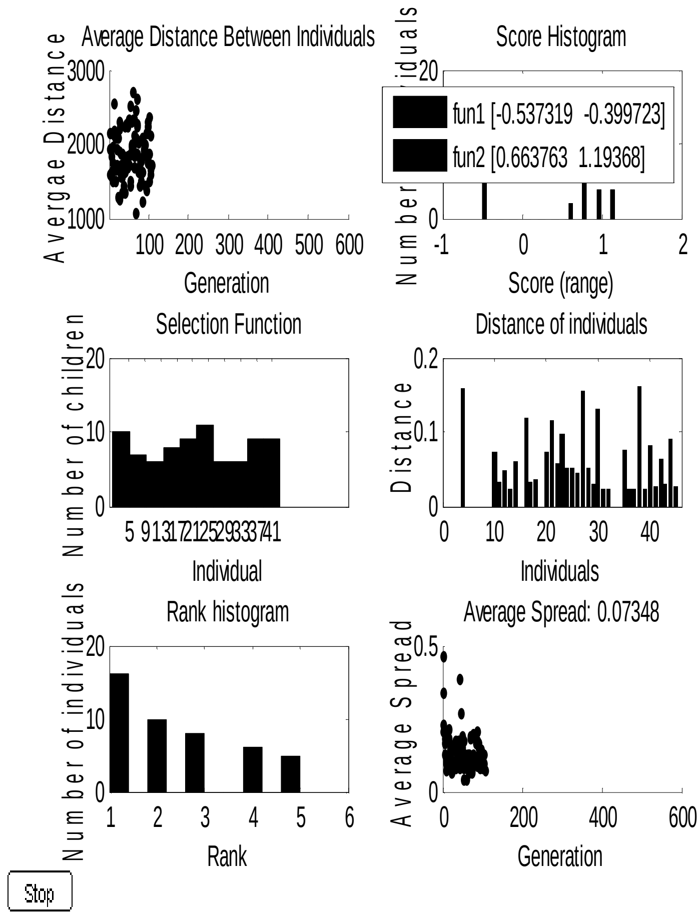
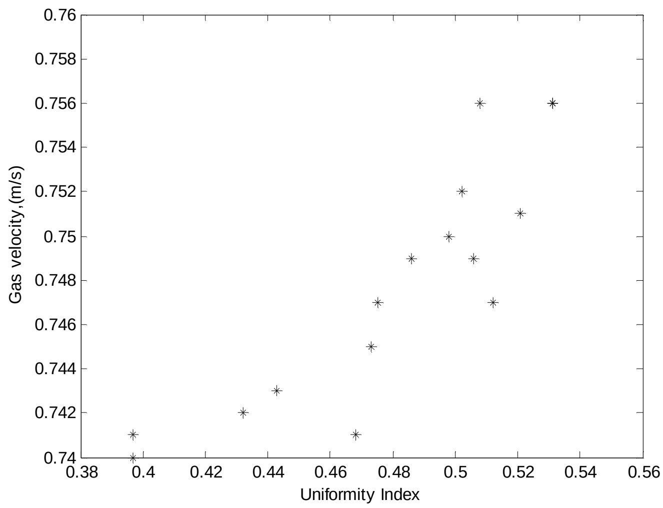
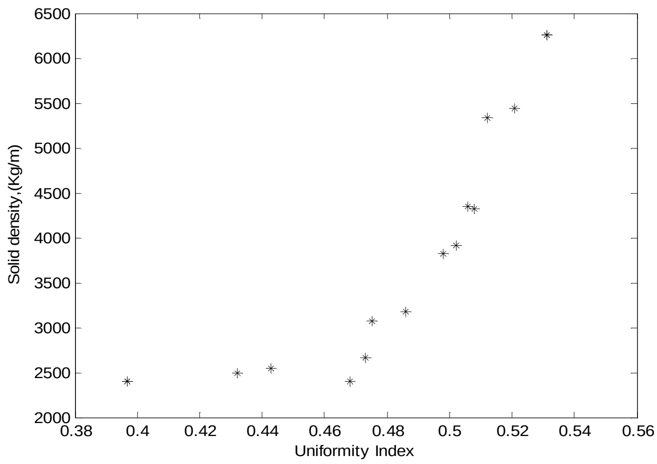


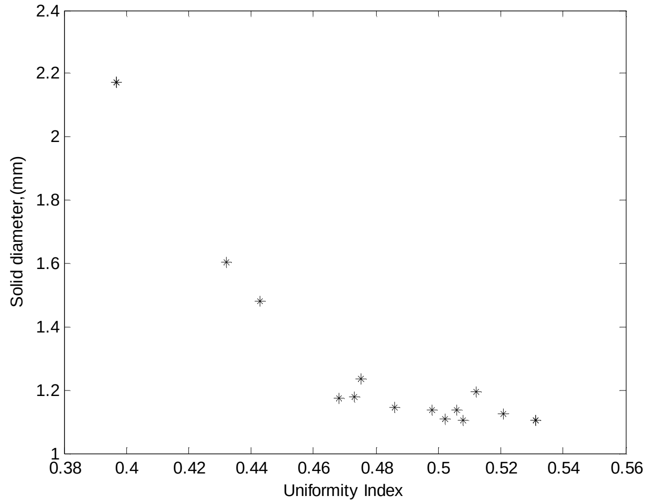
Figure 5. Solution/operators of multi-objective genetic algorithm.


Gas velocity,(m/s)
Uniformity Index
0.76
0.758
0.756
0.754
0.752
0.75
0.748
0.746
0.744
0.742
0.74
0.38
0.4
0.42
0.44
0.46
0.48
0.5
0.52
0.54
0.56

(a)

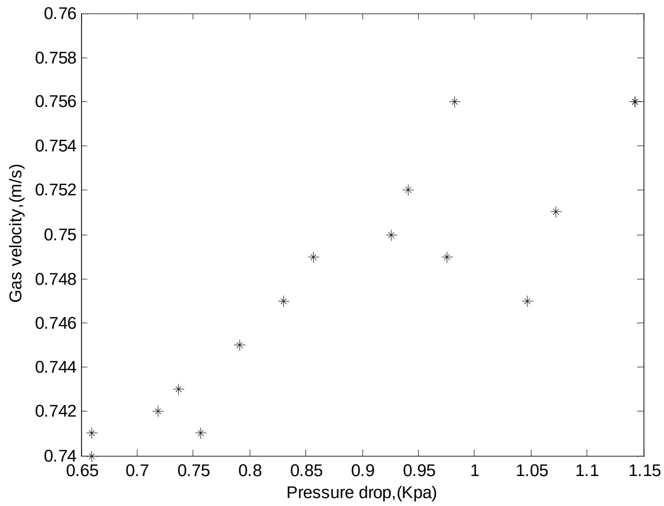

Solid density,(Kg/m)
Uniformity Index
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
0.38
0.4
0.42
0.44
0.46
0.48
0.5
0.52
0.54
0.56

(b)

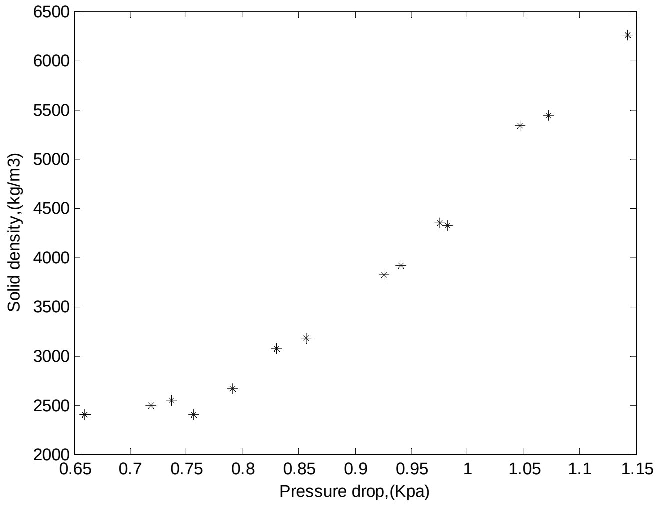


(c)

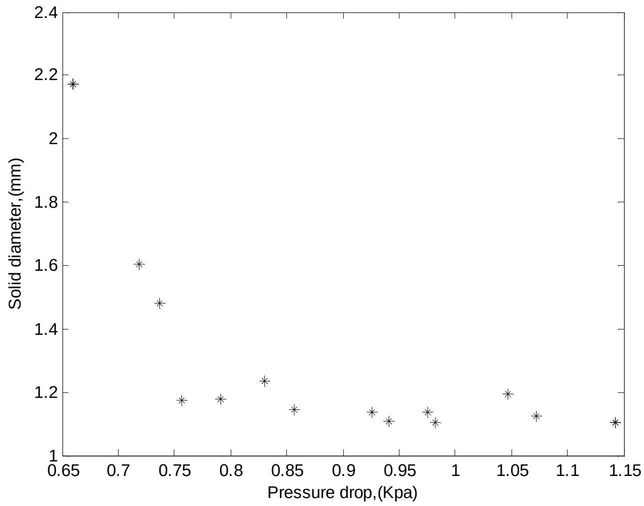
Figure 6.Optimal values of decision variables corresponding to objective UI.



(a)



(b)



(c)

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

Table 1. 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

Table 2. Adapted parameters of multi-objective GA.

Parameter	Type/Values
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	107
Function tolerance	1.0E-6

Table 3. Optimum results by Multi-objective GA.

Decision variables	Min.	Max.
Gas velocity (m/s)	0.740	0.756
Density of solid (KG/M^3)	2400	6259
Diameter of particle(mm)	1.109	2.178
Value of objective	UI = 0.39 – 0.53 PD = 0.66 – 1.19	