SSRG International Journal of Recent Engineering Science
ISSN: 2349–7157 / https://doi.org/10.14445/23497157/IJRES-V8I2P104

Volume 8 Issue 2, 20-25, Mar-Apr, 2021

Original Article

Multivariate Optimization of a Jacketed Heating System: A Genetic Algorithm Approach

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Received: 04 March 2022 Revised: 05 April 2022 Accepted: 17 April 2022 Published: 30 April 2022

Abstract *- Many industrial processes involve the heating or cooling of fluids, and as such, it is important to figure out ways and synopsis that could effectively determine operating conditions for a desired optimum process output. In this paper, a fluid heating jacketed system was studied. The model of the jacketed heater was derived in its steady-state form for the purpose of sensitivity study in Fortran. The sensitivity study was carried out on the heater's fluid density, heat capacity, cross-sectional area, volume, and jacket output temperature. An optimization was employed using a Genetic algorithm to determine the optimum parameters of the heating system.*

The sensitivity investigation verified that the variation of density, area, and heat capacity was more effective in the performance of the jacketed heating system. An increase or decrease of these process parameters will increase or decrease the heating system's temperature, respectively. The variation in the volume was insignificant in terms of temperature.

The optimization results verified the optimum values of the parameters, as shown in Table 1. The density and heat capacity of the fluid(water) in the jacket produced an optimum temperature of 500K, while that of the fluid in the tank produced an optimum temperature of 349.99K.

Keywords *- Jacketed Heating System, Genetic Algorithm, Sensitivity study, MATLAB, Fortran Language.*

1. Introduction

Industrial processes are common and mostly constituted by either heating or cooling. These requirements are mostly done to meet up with process or production demands. In the industry, process heaters have become more and more viable in terms of design and control, and it is mandatory to keep objective functions as optimal as needed while pertinent process variables requirements are met.

According to[1], heating can be done either directly or indirectly. In an indirect manner, heating is done by placing the heater directly into the heating medium, while in indirect heating, a heat transfer medium is used to initiate the heating process. However, each of these methods has its advantages and disadvantages. Direct heating is done when a large surface area of the heater is not needed[1]. Indirect heating is employed for cases of larger surface areas. Indirect heating does not require heating fluid drainage but is intermittently recycled to save utility and energy costs [1].

1.1. Heating Fluids

Heating fluids have been in consideration for various heating processes. Industrial plants commonly make use of steam or hot water for heating[2]. The heating fluid is chosen on the basis of heating temperature[2]. [3] suggests the inefficiency of steam as a result of non-uniformity in heating which arises from condensation tendencies; it also identified the corrosion level as a function of the material type. In contrast to steam, [3] also identified the ability of thermal fluids such as water to regulate temperatures within the specified range. Thermal fluid also provides uniform heating.

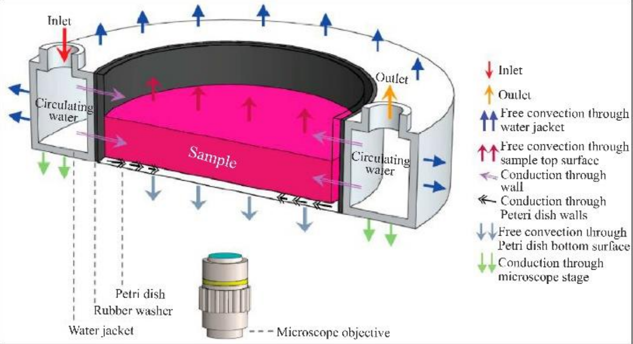

Fig. 1 Jacketed heater [4]

In this paper, we will illustrate how to implement a stochastic-based optimization technique (Genetic Algorithm) in MATLAB to optimize the fluid-jacketed heating system. Based on research done by [4], jacketed systems could effectively regulate the temperature of petri dish cell culture chambers. A typical diagram of a water-jacketed heater is shown in Fig 1[4].

2. Genetic Algorithm

Genetic algorithm has its bases in the evolution theory. With the concept of natural selection, the Genetic Algorithm processes the best fitness in terms of survival of the fittest[5]. It is a type of search method that does not relatively require the use of gradient descent or derivative to estimate its optimum solution[5]. Genetic algorithm has a vast ability to eliminate issues of local minima. Genetic algorithm has found its application in multidimensional optimization involving random search problems[6].

[6] reviewed the pertinent use of the genetic algorithm in optimizing compact heat exchangers. [6] further concluded that the use of the genetic algorithm in performing auto-search in contrast to the traditional trial and error technique is more effective and powerful. Automatic control processes mostly involve the integration of optimal design analysis.[7] analyzed the controlled design of temperature-specific processes employing an integrated Genetic Algorithm.

The basic analogy behind the use of the Genetic Algorithm is shown in Fig 2. The flexibility of the genetic algorithm makes it possible to encode an initial population size into a set of randomly selected binary values[8].

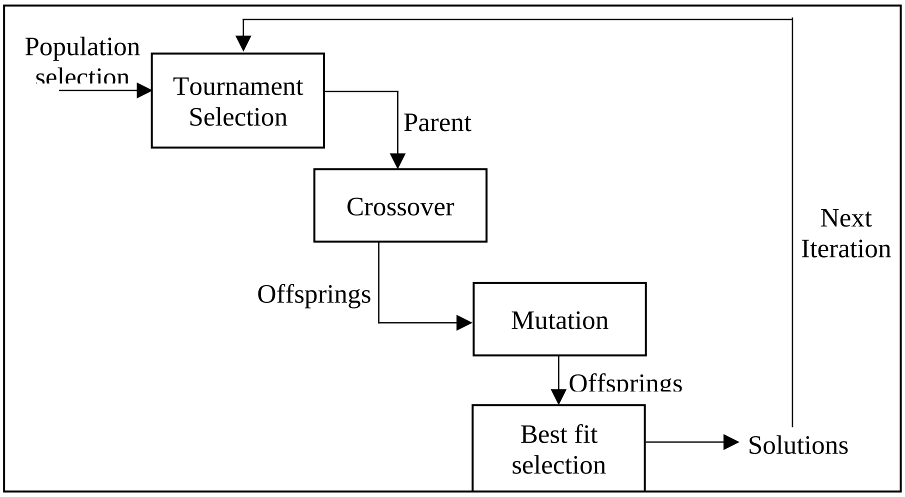

Fig. 2 Procedure in genetic algorithm application

However, binary-coded solutions can be analyzed in a real variable form. When in a binary coded form, it is necessary to convert the final iterated solutions to a real variable form. Whereas, when the population is not encoded, then the analysis will be done in real coded form.

3. Methodology

The methodology of this paper constitutes a sensitivity analysis in order to investigate the parameters that are primarily effective for the process in question. A sensitivity study aims to identify variables that negate or improve process productivity and efficiency.

The general idea of an optimization problem is given by the form:

$$\begin{gathered} \min f(x) \\ subject\ to: \quad g(x) \ \leq \ 0 \\ h(x) \ = \ 0 \\ LB \leq x \leq UB \end{gathered}$$

Where g(x) and h(x) represent inequality and equality constraints, respectively, LB and UB represent the lower and upper bound, respectively, and f(x) represents the objective function.

In the Genetic Algorithm, the solution variables are referred to as a population. These populations are initially chosen at random and represented by a binary string in the form of 0s and 1s at a user-specified population size. A population matrix is generated to carry out a tournament selection. Usually, good solutions are placed in the mating pool to perform a single-point crossover operation, while the bad ones are eliminated. The solutions selected for mating are referred to as parent solutions. During the crossover, offspring are generated. A mutation is carried out on the solutions obtained from the crossover. Fitness functions are evaluated to verify the good solutions from the generated mutation offspring.

3.1. Model Sensitivity Study

The idea behind the sensitivity study is first to identify effective parameters that can be used for optimization. The model consists of two input streams, one for the feed and the other for the heating fluid[9]. The temperature of the tank is ultimately dependent on the surrounding temperature of the heating fluid. The model is presented both in its dynamic state.

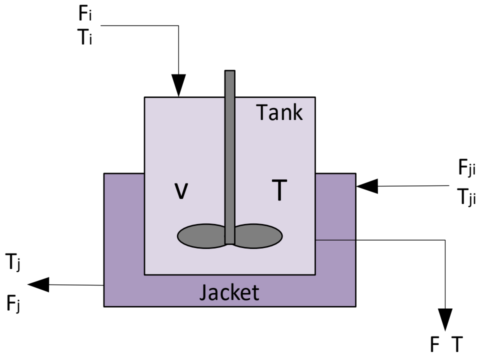

Fig. 3 Jacketed heater (2D)

Based on [10], the given model for the tank and jacket is shown in equations (1) and (2), respectively. Likewise, the derivation of these models can be gotten from[11].

$$\frac{dT}{dt} = \frac{F}{V}(T_i - T) + \frac{UA\left(T_j - T\right)}{V\rho C_p} \tag{1}$$

$$\frac{dT_j}{dt} = \frac{F_j}{V_j}(T_{ji} - T_j) + \frac{UA\left(T_j - T\right)}{V_j \rho_j C_{p_j}} \tag{2}$$

The rate of heat transfer from the jacket to the vessel is given as:

$$Q = UA(T_j - T) \tag{3}$$

Were:

T_i = Input temperature of the tank

T_{ji}= Input temperature of the jacket

T = Output temperature of the tank

T_j= Output temperature of the jacket

F= output flowrate of Tank

F_j= output flowrate of the jacket

Q = Heat transfer rate

U = overall heat transfer rate of the heater

A = Cross-sectional area of tank heater

V = volume of the tank

Equations 1 and 2 can be written in their steady-state form as shown:

$$T = \frac{\left[\frac{F}{V} T_i - \frac{UAT_j}{V\rho C_P}\right]}{\left[\frac{F}{V} - \frac{UA}{V\rho C_P}\right]} \tag{4}$$

$$T_j = \frac{\left[\frac{F_j}{V_j} T_{ji} - \frac{UAT}{V_j \rho_j C_{p_j}}\right]}{\left[\frac{F_j}{V_j} - \frac{UA}{V_j \rho_j C_{p_j}}\right]} \tag{5}$$

A sensitivity study was carried out on four cases of the model parameter. The first case considered the effect of the jacket's and tank's density; the second case considered the effect of the jacket's and heater's heat capacity. The third case considered the effect of the jacket's output temperature, while the last case considered the variation in the cross-sectional area of the heating system. Obviously, equation (1) indicates the dependence of heater temperature on the temperature value of the jacket.

3.2. Design Optimization

The objective is to optimize the heater temperature at desired parameter constraints. In this paper, five parameters were considered for the optimization. The optimization begins with setting up an initial population size within the specified variable dimensions. Here, we have five variable dimensions that are to be optimized according to the optimization mechanism used by Genetic Algorithm. A default population size was set up by the MATLAB software. The only user specifications given were the fitness function, variable dimension and range. Multi-objective optimization was carried out, as shown in equations (6) and (7).

Equations (4) and (5) can be written in their corresponding objective function, as shown below;

$maximize$: $f(\rho, C_p, T_j)$(6)

$maximize$: $f\left(\rho_j, C_{p_j} A\right)$(7)

$$S.T: \quad 1000 kmol/m^3 \le \rho, \rho_j \le 5000 kmol/m^3$$

$$5\, J/kmol.K \quad \le C_p, C_{p_j} \le 100\, J/kmol.K$$

$$0m^2 \le A \le 5m^2$$

$$A, \rho, \rho_j, C_p, C_{p_j} \ge 0$$

4. Result Discussion

4.1. Sensitivity Results

The first case of the sensitivity study considered the effect of fluid density on a variation in output heater temperature (Fig 4).

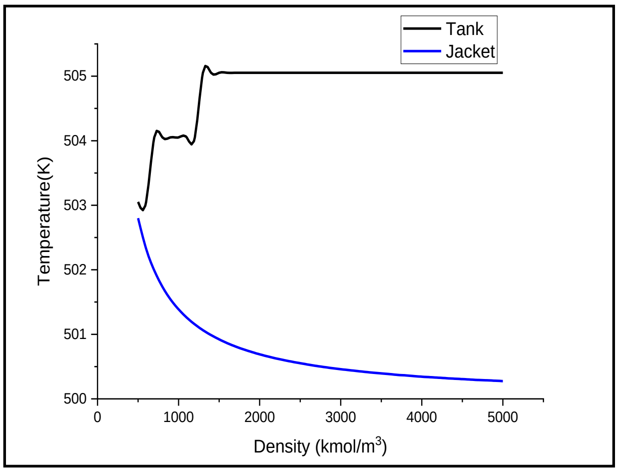

Fig. 4 Density effect on tank and jacket's temperature

The first part of the study indicated a gradual effect of the parameters.

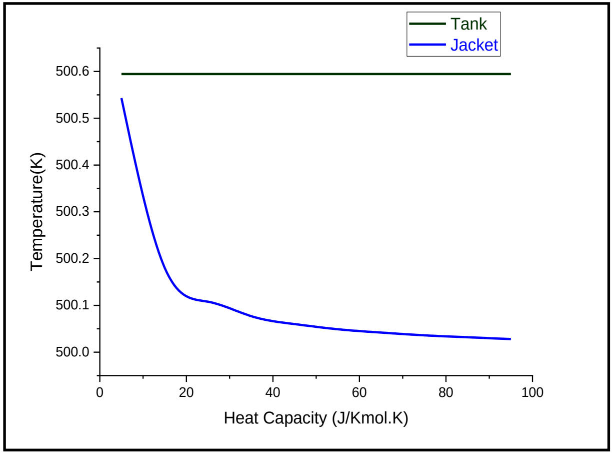

Fig. 5 Heat capacity effect on temperature

In Figure 4, it can be seen that the density has a varied effect on the output temperature of the heater. It is apparent to note that there was a reduction in temperature value when the jacket density was considered. This temperature contradicts the sensitivity of the tank. In the jacket, an increase in fluid density reduced the tank output temperature, i.e. a density of 3000$kmol/m^3$ reduced the jacket's temperature from 503K to about 500K. This implies that a heating fluid with a greater density will deplete the jacket's temperature, which will, in turn, reduce the tank's output temperature. In contrast to the jacket, the tank had a substantial increase in temperature when a fluid of higher density was fed into it. It is conclusive to say that water having a density of 1000 $kmol/m^3$ could serve as the best heating fluid when compared to other fluids of higher temperatures.

For the tank, a density of 1500 $kmol/m^3$ increased the temperature in the tank from 500K to about 505K. This could depict the need to study the density effect of feed materials in industrial processes.

Although the density variation of the tank is not as primal as that of the jacket, it is important to note the usefulness of fluid density in affecting the output temperature of the heater.

The second case considered the effect of fluid heating capacity (Fig 5). The figure shows a constant temperature in the tank throughout the change in heat capacity.
The jacket temperature is shown to have reduced with increased fluid heat capacity.

The effect of volume is insignificant as it does not directly affect the tank's temperature. Constant temperature is recorded for both the tank and jacket (Fig 7). Since the output temperature is not sensitive to the change in volume, it will not be considered a decision variable for optimization.

A larger area will result in a decrease in tank temperature, as shown in Figure (6), while a constant increase in temperature is recorded for the jacket. The overall area has a significant effect on the temperature of the tank. More emphasis is ascribed to the entire heater regarding its cross-sectional area.

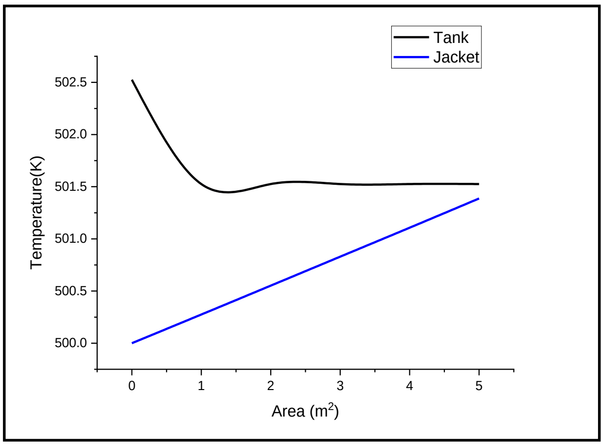

Fig. 6 Area effect on temperature

An increase in jacket temperature will yield an increase in the tank temperature (Fig 8). It is important to note that the tank's temperature is entirely dependent on the jacket's temperature. At a jacket temperature of 500K, the tank's temperature was recorded to have increased to 525K. This makes the sensitivity analysis viable.

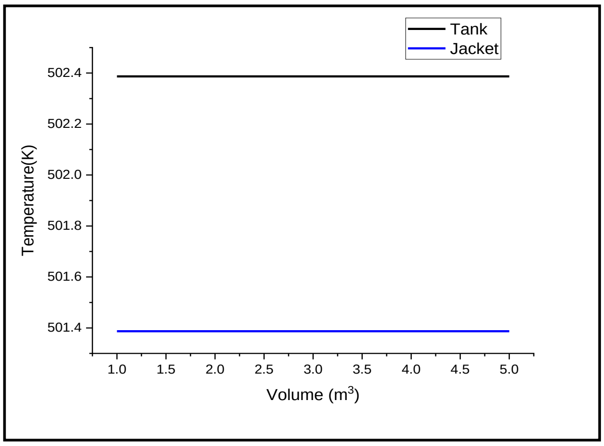

Fig. 7 Volume effect on temperature

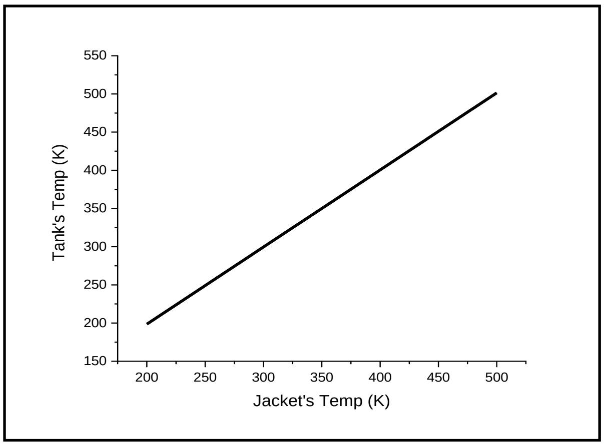

Fig. 8 Effect of jacket's temperature on tank's output temperature

4.2. Optimization Results

The optimization result is shown in Table 1.

Table 1. Optimum solutions

Variable	Optimum value	Optimum Temperature (K)
ρ $(\mathbf{kmol/m^3})$	4771.143	349.97
$\mathbf{C_p (J/kmol.K)}$	98.9	349.99
ρ_j $(\mathbf{kmol/m^3})$	1000	500.423
$\mathbf{C_{p_j} (J/kmol.K)}$	5	500.423
$\mathbf{A(m^2)}$	$3.78 * 10^{-5}$	349.99

The results in Table 1 indicate the optimum solution obtained using a genetic algorithm. The optimum output temperature of the tank at a density of $4899 kmol/m^3$ and heat capacity of $98.9 J/kmol.K$ was estimated to be 349.97K, while that of the jacket at a density of $1000 kmol/m^3$ and heat capacity of $5 J/kmol.K$ is shown to be approximately 500.423K. These results show the efficacy of the tank and jacket fluids to an increase or decrease in temperature. Obviously, since water density is a constant value of 1000 $kmol/m^3$, the optimum jacket's fluid density remains constant, as shown by the algorithm.

Fluid density and heat capacity are both significant parameters that obviously determine a fluid's temperature. The optimization suggests the need to determine the best heating fluid for any industrial process.

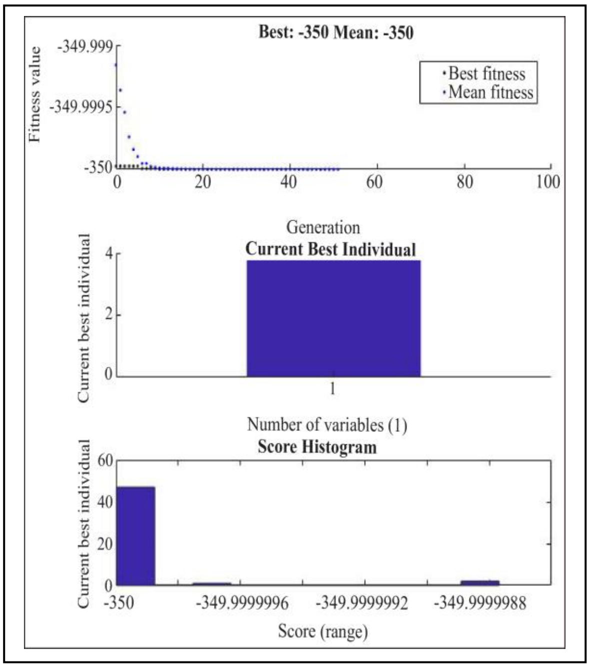

Fig. 9 Function plot for area

An estimated fitness value of 350K was verified (Fig 9). The fitness value was recorded for 10 generations. While the current best was estimated to be $0.0000378m^2$ for the area, a total of about 46 individuals generated a more optimum fitness value. The range value shows to be less different from the final solution.

The negative value of the fitness value indicates a maximization problem. This is because the MATLAB optimization toolbox is set by default for the minimization problem. From Figure 9, a total of less than 5 individuals produced a fitness function of 349.99K; this value is analogous to the fitness value of 349.99K produced by 8 individuals. An exact fitness value of 350K was produced by 44 individuals (Fig9).

Since the variables under investigation are not more than 5, a random population size of 50 was used for the initiation. Crossover and mutation probability are used as the default value of the MATLAB optimization toolbox.
The mean fitness value was recorded to be 350K analogously.

The jacket's density recorded a fitness value of 500K(Fig 10), with a mean fitness value of 500.543K. The current best individual is recorded to be $1000\ kmol/m^3$ for a population size of 50. The maximum number of individuals for 10 generations was recorded to be 14 approximately. These 14 individuals were recorded to have produced the optimum solution.

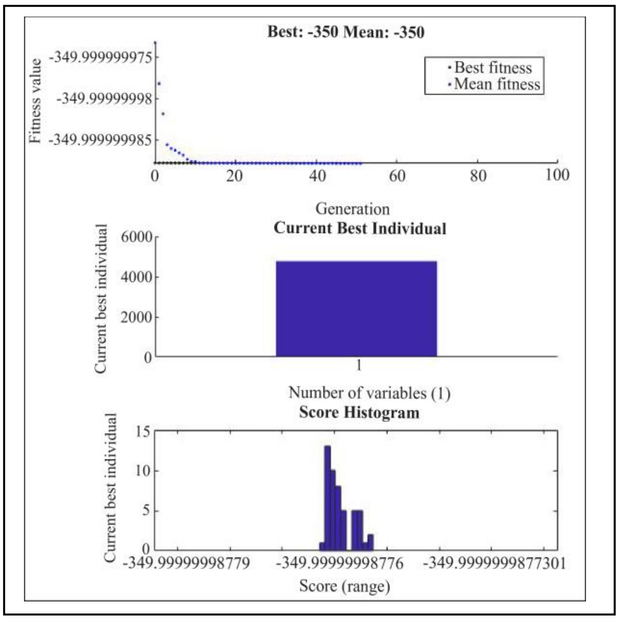

Fig. 10 Function plot for jacket's density

According to Figure 10, optimizing the density gave a significant optimum temperature of 500K. A larger jacket density gave an increase in tank output temperature. The best, worse and mean scores were insignificantly different due to a very low difference. The highest number of individuals produced more offspring as compared to the fewer individuals.

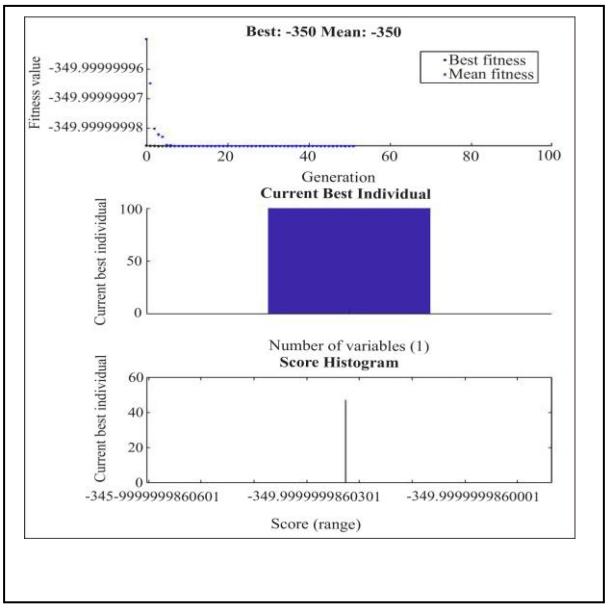

Fig. 11 Function plot for tank's density

The tank heat capacity at about 100 produced an optimal temperature of 349.99K, while the mean score of 350K was also recorded. About 50 offspring were produced by themating of 100 individuals. The tank heat capacity estimated a fitness value of 349.99K with a current best individual of 98.9 $kmol/m^3$. The optimization verified the efficacy of intrinsic fluid properties in the optimum temperature of the tank output fluid.

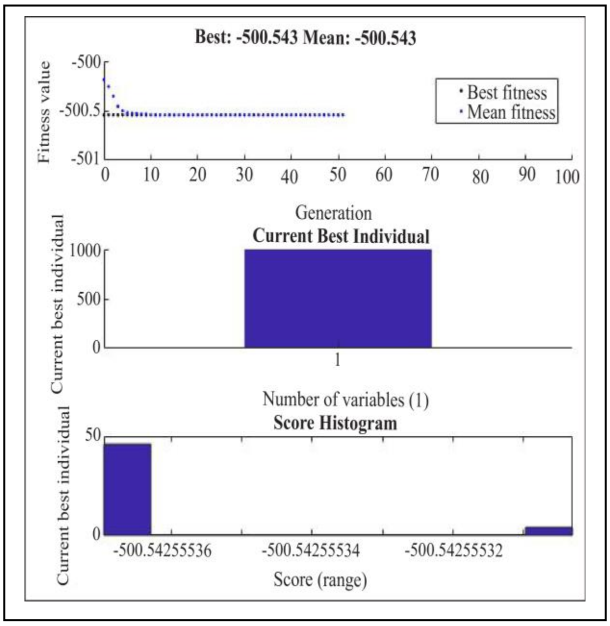

Fig. 12 Function plot for tank's heat capacity

5. Conclusion

Pertinent fluid properties have great significance in affecting the operating condition of industrial process units. The genetic algorithm was used to carry out the optimization. Genetic algorithm is found to be useful in problems of larger dimensions, and it is not restricted to problems where local minima are prevalent.

The study conclusively asserted that the density and heat capacity of fluids directly affects the output temperature of the tank's fluid. Optimum solutions were gotten to improve the temperature suitable for the demand at hand.

It is recommended that the next study on the fluid jacketed heating system be made based on material and utility costs. It is also recommended that a study should be made regarding the effect of manufacturing material on the temperature of the fluid. Other evolutional search methods can be employed in the study of the above aforementioned recommendations.

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