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Imperialist Competitive Algorithm (ICA) for Heat Exchanger Network (HEN) Cleaning Schedule Optimization

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Abstract

Heat exchanger network (HEN) is a process equipment that is widely used in the petrochemical industry and refinery. One of the most frequent problems is fouling. The fouling’s effects are loss of energy, decreased throughput, and increase pressure drop. In the United States, losses due to the fouling about $4.2 - 10 billion per years. One of the fouling mitigation techniques is applied cleaning schedule on HEN under fouling condition. This technique has the drawback frequently clean more cleaning cost, no cleaning increase energy loss and additional pumping due to the fouling. The optimization cleaning schedule method is required. Optimization cleaning schedule is mix integer nonlinear programming (MINLP) class which is difficult to solve due to non-convex problem with many local optimum. MINLP could be solved using a stochastic method. One of the stochastic method is imperialist competitive algorithm (ICA). In this paper applied ICA in HEN cleaning schedule. The result of HEN cleaning schedule using ICA is saving heat transfer loss about 44.83% and from an economic point, saving $1.05 million in a period of 44 months, or 22.12% of losses due to fouling.

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1. Introduction

Fouling in heat exchanger is an undesirable process that reduces the realization of maximum benefit from heat integration. Fouling is unwanted accumulation of deposits/foulant on the surface of the heat exchangers which is the resistance to heat transfer, thereby reducing the efficiency of the heat exchangers. Foulant might be in the form of crystals, biological materials, products of chemical reactions including corrosion, or particles [1][2].

Engineering Sciences Data Unit (ESDU) reported that fouling in Crude Preheat Train (CPT) is a serious problem [3]. This problem resulted in the addition of energy consumption and the refinery economically disadvantaged billions of dollars per year. Two main effects of fouling on the CPT are (i) reduce the heat is taken back and (ii) increase is in the pressure difference. From economic and environmental terms, it gives large motivation to minimize fouling thereby maximizing heat in a Heat Exchanger Network (HEN) [4].

Better design of heat exchangers such as improvements on mechanical design by designing appropriate tube and baffles arrangement can reduce the tendency of fouling [5]. Another alternative is clean heat exchangers periodic [6]. Generally, periodic cleaning is done to regain the thermal efficiency of the heat exchangers. Optimization problems on cleaning schedule HEN involve three components, HEN model, fouling model and efficient optimization technique.

Cleaning schedule optimization problems could be solved by several optimization techniques. Imperialist Competitive Algorithm (ICA) is a promising technique for solving mix integer non-linear programing (MINLP) problem. Generally, ICA is an optimization technique that most efficient in terms of the evaluation function. The solution of the problem MINLP using ICA has proven to be a valid approach to the problem of non-convex where the computing time is not a problem [7]. In subsequent research on the design of heat exchangers using the ICA get better than Genetic Algorithm (GA) [8]. Cleaning schedule optimization using GA [9] and Particle Swarm Optimization (PSO) [10] has been performed. Therefore ICA purpose to increase saving.

2. Literature Review

2.1. HEN Model

Heat exchanger is a process equipment that used to transfer heat from hot fluid to cold fluids. Most of the industries utilize this equipment, therefore HEN has an important role in a production process or operation [11]. HEN is heat exchangers system that connected in series or parallel. HEN is used to minimize energy consumption in industrial process [12]. The main function of HEN in the industries is recover heat from the product stream.

The fouling reduce the benefit of heat integration. Fouling is defined as the accumulated deposit on heat transfer surfaces [1]. The performance operation of the heat exchanger will be reduced when fouling on heat transfer surfaces. Fouling is drop the pressure therefore required to increase the pressure to maintain the flow rate through the exchanger element.

2.2. Cleaning schedule optimization HEN

Cleaning schedule optimization of HEN can be achieved by minimizing the energy lost or maximum energy recovery in each heat exchanger. The difference between the amount of heat transferred in HEN when operating in conditions of under cleaning schedule \( E_{\text{rec}}^{\text{under}} \), and the maximum amount of heat that is transferred when HEN always operate at under clean conditions \( E_{\text{rec}}^{\text{clean}} \) is given in (1). Energy saving is different heat transfer amount between about the under fouled conditions without cleaning \( E_{\text{rec}}^{\text{fouled}} \) and
under cleaning schedule conditions is given in (2). The sum of the cleaning costs, pump cost and the energy cost is the destination of the results of the optimization problem formulation cleaning schedule heat exchanger (objective function) to get minimized or maximized. In this paper, the authors chose the purpose of the objective function to obtain maximized. Therefore the equation of the objective function for energy saving can be seen in (3)

\[
\begin{align*}
\text{Energy Losses} &= E_{\text{clean}}^{\text{cs}} - E_{\text{rec}}^{\text{cs}} \\
\text{Energy Saving} &= E_{\text{rec}}^{\text{cs}} - E_{\text{fouled}} \\
\max J &= C_E \left(E_{\text{rec}}^{\text{cs}} - E_{\text{fouled}}\right) - C_{\text{clean}} - C_{\text{pump}}
\end{align*}
\]

2.3. Imperialist Competitive Algorithm (ICA)

Imperialist Competitive Algorithm (ICA) was introduced in 2007 by Esmaeil Atashpaz. This algorithm is a computational algorithm that refers to the competition authority [13]. ICA is one of the optimization methods in modern systems. The ultimate goal of the optimization of the ICA is to get the optimal solution of definite problems. In the resolution of optimization problems, ICA has several stages of operation.

Generating initial empires are the first stage of the ICA operation. At this stage, ICA forming an array of variables to be optimized value. Array of ICA known as country, while on the other optimization methods such as Genetic Algorithm (GA) is known as chromosomes. In a country is 1 x Nvar array. Afterwards, imperialist to lead the empire from one of the best country. The rest of the population will form colonies owned by the empire. An empire has an imperialist and a few colonies. Country initialization equation can be expressed by (4). Variable \((P_1, P_2, P_3, ..., P_{N\text{var}})\) is the variable to be optimized \((N\text{var})\). Cost of each country can be determined by evaluating the position of each country is given in (5).

\[
\begin{align*}
country &= [P_1, P_2, P_3, ..., P_{N\text{var}}] \\
cost = f\left(\text{country}\right) &= (P_1, P_2, P_3, ..., P_{N\text{var}})
\end{align*}
\]

Second stage for ICA operation is moving the colonies toward the imperialist. At this stage, the imperialists will try to improve its colony by moving all the colonies towards imperialist. If the colony continuous movement, it will make all the colonies moved towards imperialist. In the movement colony towards imperialist, the colony did not directly move towards imperialist. A random number of irregularities added in the direction of movement to model this fact.

At the time of moving colony towards imperialist, a colony is possible to have a better cost than imperialist. When it happens, it will cause to exchange of positions between imperialist and colony. The algorithm will continue with the new imperialist and the new colony.

Some imperialist be allowed to move to the same position at the time of the colony and imperialist movement towards global minimum. The new empire will be formed when the distance between the two imperialists less than the distance threshold. The new imperialist also be formed at a position where the two imperialist meet each other.

The strong empire influenced by the imperialist. However, the strength of the colony also provides a small effect on the strength of the empire. The total cost of an empire can be defined as the sum of imperialist cost and the average colonies cost possessed by imperialist at one empire is given in (6). Value of \(\xi\) shows the influence of the contribution of the colony and a positive value less than 1. \(T.C_N\) is
the total cost of the empire \( n \)th. In total strength result, that imperialist influenced empire rather than a colony

\[
T \times C_n = cost(\text{imperialist}_n) + \zeta \text{mean} \left( \text{cost} \left( \text{colonies of empire}_n \right) \right)
\]  

(6)

All the empire will strive to control the other colonies of the empire. This competition gradually will increase power of the strong empire and will reduce power of the weak empire. This competition can be modelled by taking some or one of the weakest colony owned by a weak empire among all the empire. It will create competition between all the empires which has a more powerful force to control the colonies. To start the competition, it will find the probability of ownership in each the empire based on the total strength. Empire elimination occurs when the empire lost all its colonies. Empire eliminates because the weakest empire will collapse power and colonies in the competition. The empire will be distributed colony to other

At the last stage, convergence occurs when all of the empire collapsed and there is only one of the most powerful empire that will control all the colonies. All the colonies would have the same cost and position with the imperialists on the new ideal world. In this conditions, the power competition ends and stops algorithm (convergent).

2.4. Methodology of Cleaning Schedule Optimization Using ICA

Fig. 1 shows the flow chart of the optimization HEN using ICA to get the optimal cleaning schedule. First steps is determine the number of countries and number of imperialists. Application of ICA in cleaning schedule optimization was designed using 40 countries and 3 imperialists. Since, the number of colonies are the number of countries subtract the number of empires, therefore the number of colonies in the empire is 37 colonies. The value of imperialist is restricted from 1 up to 44 because in this paper cleaning schedule has been done for 1-44 months. Total number of the imperialists equals the number of variables that will be optimized. Optimizing HEN cleaning schedule has 11 heat exchanger, therefore total number of variables is 11. It is the position of an imperialist. Then the empire randomly generates the number imperialist and colonies.

Second step is determine the fitness value in imperialist cost by using a HEN model simulation. Output simulation is the maximum savings. ICA is a minimum optimizer, therefore determine the maximum saving of the fitness value should be 1 / saving. Fitness value is affected by the strength of the colonies and imperialist. The lower fitness value is the strongest imperialist.
Third step is move the colony toward the imperialist. In this paper, the displacement of the colonies to the imperialist affected by assimilation rate and assimilation angle coefficient. In this paper, assimilation rate is 2 and assimilation angle coefficient is 0.5 [13]. The process is called assimilation.

The next step is revolution. Revolution is change position some colonies randomly. In this process is affected by the revolution rate. In this paper, revolution rate is 0.3 based on prior research [13]. If there is a colony in an empire which has stronger than imperialist, the colony changing position into imperialist. All empires calculate the fitness value. Imperialist competition continued if there are colony and imperialist in the empire. Imperialist with the weakest colonies would give them colonies to the stronger imperialist. Imperialist deleted if imperialist do not have a colony. If there is not only one empire, repeat again in moving colonies toward their relevant imperialist until 500 decades. It stops when an empire only has one of the strongest imperialist. The strongest imperialist has the minimum fitness value therefore maximum savings.

3. Result

3.1. Cleaning schedule optimization HEN with ICA

The mean cost and minimum cost meets at one point and has the same value. At the time it was optimal conditions. The optimal condition is an empire only have the strongest imperialist. The result of cleaning schedule optimization HEN by using 40 colonies, 3 imperialists and 500 decades is the strongest imperialist it showed in Fig. 2. The strongest imperialist has fitness value about 0.938. Fig. 2 shows the minimum fitness value. The strongest imperialist has 11 imperialist position value where the imperialist has 11 random variables has a range of 1 to 44. 11 imperialist position values are 11 heat exchanger cleaning schedules. Table 1 shows the heat exchanger cleaning schedule and interval cleaning schedule for 44 months. Interval cleaning schedule resulted from 44 months divided with interval cleaning schedule for each heat exchanger in HEN.
Fig. 2 Minimum cost and mean cost

Table 1 Interval cleaning each heat exchanger

| HE 1 | HE 2 | HE 3 | HE 4 | HE 5 | HE 6 | HE 7 | HE 8 | HE 9 | HE 10 | HE 11 |
|------|------|------|------|------|------|------|------|------|-------|-------|
| Cleaning | 16   | 21   | 23   | 29   | 9    | 28   | 15   | 5    | 17    | 5     | 29    |
| Interval | 2    | 2    | 1    | 1    | 4    | 1    | 2    | 8    | 2     | 8     | 1     |

3.2. Analysis of the heat transfer

Fig. 3 show heat duty under clean condition, under fouled condition and under cleaning schedule. The condition under cleaning schedule on the first day until 150<sup>th</sup> day has not seen any result of optimization because in this period only 2 times cleaning heat exchanger (HE 8 and 10). With the cleaning schedule, in the next period HEN has the advantage. Total profit of heat transfers energy resulting from the HEN at 7.46 GW. The amount is derived from the total heat transfer HEN on under cleaning schedule (70.92 GW) subtract total heat transfer HEN in under fouled conditions (63.46 GW). Therefore the energy saving increase 44.83%.

Fig. 3 Recovery energy in HEN
3.3. Analysis of the economics

The objective function in the optimization aims to reduce the energy lost in order to create maximum condition. The maximum condition itself is when saving economically. Economic savings are obtained after the optimization is $1.05 million. The cleaning cost, energy recovery costs, and costs resulting from the pressure drop becomes a parameter to calculate the economic savings. Table 2 shows the details of the cleaning cost, energy recovery costs, and costs incurred by the fall of pressure on each heat exchanger. Losses generated by the optimization smaller than without cleaning or fouled condition. The losses cost resulting after optimization is $3.7 million. The amount obtained from the total energy recovery HEN under clean condition \((\text{Energy Recovery clean} - \text{Pump Cost clean})\) subtract the total energy recovery HEN in under clean schedule \((\text{Energy Recovery cs - Cleanup Costs cs} - \text{Pump Cost cs})\). Where the total energy recovery HEN in under clean schedule is $21.1 million subtract total energy recovery HEN in under cleaning schedule condition is $17.4 million obtained loss $3.7 million.

Fig. 4 show savings cost from each heat exchanger. The biggest savings can be seen in the HE 8. Where the savings resulting from the presence of the cleaning schedule reached $1.23 million. In addition to the HE 1 also profit costs savings of $0.84 million. Not all of the heat exchanger HE benefits at HE 2, HE 3, HE 4, HE 6, HE 7, HE 9 and HE 11. Although at the HE 2, HE 3, HE 4, HE 6, HE 7, HE 9

| HE | Recovery Energy (USD) | Pump Cost (USD) | Total Recovery Energy (USD) | Recovery Energy (USD) | Pump Cost (USD) | Total Recovery Energy (USD) | Recovery Energy (USD) | Cleaning Cost (USD) | Pump Cost (USD) | Total Recovery Energy (USD) |
|----|-----------------------|-----------------|-----------------------------|-----------------------|-----------------|-----------------------------|-----------------------|-------------------|-----------------|-----------------------------|
| 1  | 5,410,043             | 39,724          | 5,370,319                   | 3,994,067             | 49,748          | 3,944,319                   | 4,881,913             | 54,600            | 42,163          | 4,785,150        |
| 2  | 1,451,776             | 26,659          | 1,425,117                   | 997,260               | 90,593          | 906,667                     | 950,544               | 52,416            | 83,045          | 815,083          |
| 3  | 2,190,191             | 16,251          | 2,173,940                   | 1,672,050             | 58,699          | 1,613,352                   | 1,326,064             | 29,211            | 56,281          | 1,240,572        |
| 4  | 1,329,890             | 17,250          | 1,312,640                   | 1,754,625             | 65,157          | 1,689,469                   | 1,073,882             | 41,496            | 58,620          | 973,766          |
| 5  | 2,186,877             | 10,081          | 2,176,797                   | 1,598,207             | 50,486          | 1,547,721                   | 2,100,589             | 163,800           | 33,262          | 1,903,527        |
| 6  | 429,848               | 19,854          | 409,994                     | 419,054               | 51,355          | 367,699                     | 422,516               | 13,650            | 46,783          | 362,083          |
| 7  | 346,670               | 13,701          | 332,969                     | 450,052               | 23,049          | 427,003                     | 432,733               | 27,300            | 21,060          | 384,373          |
| 8  | 2,163,345             | 11,250          | 2,152,095                   | 2,148,148             | 34,281          | 2,113,867                   | 3,807,113             | 454,272           | 13,044          | 3,339,797        |
| 9  | 1,216,458             | 10,686          | 1,205,772                   | 1,170,214             | 26,392          | 1,143,822                   | 1,101,969             | 32,214            | 20,075          | 1,049,680        |
| 10 | 1,652,171             | 39,243          | 1,612,929                   | 1,518,239             | 54,435          | 1,463,804                   | 1,636,164             | 104,832           | 41,687          | 1,489,644        |
| 11 | 2,936,072             | 12,214          | 2,923,858                   | 1,165,279             | 41,832          | 1,123,447                   | 1,137,945             | 49,959            | 38,524          | 1,049,462        |
| HEN | 21,313,342            | 216,912         | 21,096,430                  | 16,887,196            | 546,028         | 16,341,169                  | 18,871,433            | 1,023,750         | 454,544         | 17,393,138       |

Fig. 4 show savings cost from each heat exchanger. The biggest savings can be seen in the HE 8. Where the savings resulting from the presence of the cleaning schedule reached $1.23 million. In addition to the HE 1 also profit costs savings of $0.84 million. Not all of the heat exchanger HE benefits at HE 2, HE 3, HE 4, HE 6, HE 7, HE 9 and HE 11. Although at the HE 2, HE 3, HE 4, HE 6, HE 7, HE 9
and HE 11 get losses however overall, HEN still get saving $ 1.05 million. Hence the total energy savings are 22.12% base on fouled condition.

Results of the HEN cleaning schedule optimization could be optimized further. It could be seen from the energy losses. Energy losses from this method still have a large difference amount about $ 3.7 million. The energy losses could be decreased by modified ICA. The results from the cleaning schedule HEN using ICA less optimal because algorithms are spread the colony freely. Therefore needs to be modified ICA algorithm in order to achieve the optimal objective function over again.

4. Conclusion

Optimization of HEN cleaning schedule is MINLP class which is difficult to solve due to non-convex problem with many local optimum. Searching method in the stochastic algorithm will try to find out the global optimum within many local optimum randomly. One of the stochastic method is ICA. The result of HEN cleaning schedule using ICA is has minimum fitness about 0.95. The result of this optimization is saving heat transfer loss about 44.83% and from an economic point, saving $ 1.05 million in a period of 44 months, or 22.12% of losses due to fouling.

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