Optimal analysis of heat pump for freshwater and heat usage in production processes

Audu Christiana IberiI [1] and M. D. Shehu [2]

[1,2]Department of Mathematics, Federal University of Technology, Minna, Niger State, Nigeria
[1]email address: auduchristianaiberi@gmail.com
[2]email address: m.shehu@futminna.edu.ng

Abstract: In this paper, a new systematic design methodology has been proposed for simultaneous management of freshwater and energy (heat) system through the re-use of water. In addition to allowing re-use of water, issue about heat losses within the system have also been incorporated in this design method. A Linear programming (LP) model is formulated for both heating and cooling to minimize production cost, freshwater usage, heat supply and the number of heat exchangers. The result shows that if a factory circulates freshwater within the system using a heat pump, 46.5% of production cost will be reduced.

Keywords: Heat, Heat pump, Freshwater, cost of production, Non-linear programming.

1 Introduction

Water and energy are two of the most essential resources for running food production and chemical processing plants. The former is needed not only as a solvent in mass transfer processes but also as heat- transfer medium in heat exchangers. Specially, various organic and inorganic contaminants in another phase can often be removed with process water. Thus, clean water is widely considered as an effective mass-separating agent in washing or separation operations (such as absorption and extraction). In addition, the aerated and purified water is consumed in the utility systems to produce steam and cooling water for use as heat carriers. After the aforementioned usages, the resulting waste water must be treated to lower the contaminant concentrations. Some of them can then be recycled and reused, while the others discharged to the environment [3]

As noted above, none of the previous works have addressed the freshwater and energy minimization using a heat pump. Heat Pump (HP) is a device which offers energy-efficient way to provide heating and cooling in a production process. It main function is to pump heat from low temperature heat source s to high temperature heat sinks, thus providing both comforts heating and cooling. However, it is known that previous study encounter some difficulties to deal with large and complex networks and it is always a long task (with high computational time) to overcome these difficulties [6]. We proposed here an alternate methodology for freshwater and energy minimization in a very efficient way, by using a heat pump. Case study include network tackled before by [6]

To ensure an efficient use of water and heat in process industry, it is necessary to recover heat that is in excess from heated water in some part of the process and reuse it as heat source in other parts of the system through a water and heat exchanger network called heat pump. The water from which heat is absorbed is then used for cooling in other part of the process. One of the way to increase water and energy efficiency in industrial plants is to improve the design of existing water and heat exchanger network through retrofit actions.

As noted above, none of the previous works have addressed the freshwater and energy minimization with the use of a Heat Pump. **In fact, all most of the works are strictly on water** Network by stochastic algorithms. However, it is known that these methods encounter some difficulties to deal with large and complex networks and it is always a long task (with high computational time) to overcome these difficulties, we proposed here an alternate methodology for freshwater and energy minimization in a very efficient way, by using heat pump [6].

To ensure an efficient use of water and heat in process industry, it is necessary to recover heat that is in excess from heated water in some part of the process and reuse it as heat source in other parts of the system through a water and heat exchanger network called heat pump. The water from which heat is absorbed is then used for cooling in other part of the process. One way to increase water and energy efficiency in industrial plants is to improve the design of existing water and heat exchanger network through retrofit actions. To be able to calculate the energy and water savings for a given retrofit proposal, the resulting heating and cooling demands needs to be calculated for determining operational cost.

In this section, a non-linear programming model is formulated to minimize freshwater and heat usage in WAHEN system. By using this Mathematical model, the water network design with smaller number of heat exchangers and minimum operating Cost can be obtained.

1.1 Formulation of objective function

Following [3], Heat pump is embedded in their equation in other to reduce heat and water usage so as to minimize cost of production. The total production cost, as the objective function is expressed as:-

$$MinPROCOST = C_W \sum_{i=1}^{n_{operations}} Q_W + C_h \sum_{i=1}^{n_{operations}} Q_{HP} \ (W) \tag{1}$$

1.2 Analysis of Energy of the Heat Pump

This part describes the equations in the heat pump. However a description of the changes which takes place in the heat pump circuit.

- the entire heat pump system is considered a constant mass flow q_{ref}.
- we calculate the energy value of the sub-components.

It is necessary to know the temperature between individual sub-components and then enthalpy of the refrigerant can be determined. The energy of refrigerant entering into the evaporator:

$$Q_{ev} = q_{ref}.h_{ev}.T_{ev} \ (W) \tag{2}$$

The only work interaction for the evaporator is flow work. Therefore the rate at which heat is transferred per unit mass of vapor passing through the evaporator is:

$$Q_{evap} = Q_{evaporator} = h_1 - h_4(W) \tag{3}$$

The sign of the Q_{evap} will be positive, following our sign convention for heat transfer.

Thermal power delivered by the compressor into refrigerant is given as:

$$Q_{comp} = \frac{Q_{comp}}{q_{ref}} = h_1 - h_2(W) \tag{4}$$

The energy input of refrigerant into the expansion valve:

$$Q_{cond} = \frac{Q_{cond}}{q_{ref}} = h_1 - h_2 (W) \tag{5}$$

Subsequently it can be expressed, that the heat flux input to the storage tank is reduced of the efficiency of the heat exchanger, which is around 70% – 80%.

The energy required for heating of the inlet freshwater to the desired temperature is given as:

$$Q_{HP} = \left[\frac{Q_{evap} + Q_{exp} + Q_{comp} - Q_{cond}}{q_{ref} \cdot \frac{h_{co} - h_c}{2}} c.q_s \right] .Q_z \ (W) \tag{6}$$

The model uses increments of energy obtained by the heat pump. In this simulation the energy inputted to an accumulation tank means that this energy is not dependent on the temperature of water output from the accumulation tank into the condenser. The calculation of mass flow of hot water into the accumulation tank is given as:

$$q_s = \left[\frac{q_{ref} \cdot \frac{h_{co} - h_c}{2}}{c} \right] (kgs^{-1}) \tag{7}$$

Where,

q_{ref} mass flow of refrigerant entering into the evaporator (kgs^{-1})

c_w Cost of water

C_h Cost of heat

h_1 Enthalpy of saturated refrigerant

h_2 Enthalpy of supersaturated refrigerant

$h_{ev} h_c$ Entropy of refrigerant behind the expansion valve, the compressor $(Jg^{-1}k^{-1})$

s_c, S_{co} Entropy of the refrigerant behind the compressor, the condenser $(Jkg^{-1}K^{-1})$

c-specific heat capacity of water $(Jkg^{-1}K^{-1})$

q_s mass flow of freshwater entering into the evaporator

For analysis purposes, the annual Minimum production Cost can be simplified by substituting Q_{HP} into its place in equation (1)

$$MinPROCOST = C_W \sum_{i=1}^{n_{operations}} Q_W + C_h \sum_{i=1}^{n_{operations}} \left[\frac{Q_{evap} + Q_{exp} + Q_{comp} - Q_{cond} \cdot}{q_{ref} \cdot \cdot \frac{s_{co} - s_c}{2}} \right] [c.q_s] \tag{8}$$

Equation (6) can be simplified by clearing fractions to become:-

$$Q_{HP} = \{Q_{exp} + Q_{evap} + Q_{comp} - Q_{cond}\} Qz \tag{9}$$

Then Equation (8) can be simplified to become:

$$MinPROCOST = C_W \sum_{i=1}^{n_{o}perations} Q_W + C_h \{Q_{exp} + Q_{evap} + Q_{comp} - Q_{cond}\} Q_Z \tag{10}$$

$$= C_W \sum_{i=1}^{n_{operations}} Q_W + C_h Q_{HP} \tag{11}$$

The basic criterion for evaluating the operational characteristics of heat pump is heating factor or the coefficient of performance (COP). The performance of a heat pump is indicated by the coefficient of performance. It measures the amount of heat energy moved (in watt), divided by the electric energy used to move it (also in Watts), at a given out door temperature. Higher COP value indicates a more efficient system. The quantity of heat pump is judged by how much heat transfer occurs into the warm space compared with how much work input is required In taking the ratio of what is spent a heat pump coefficient performance (COP) is define by Equation (12).
[5]

$$COP = \frac{Disired\ output}{Required\ input} = \frac{Heat\ effect}{Work\ input} = \frac{Q_H}{Win}$$

$$COP = \frac{h_2 - h_3}{h_2 - h_1} \tag{12}$$

2 Comparation of this model with Maja and Mao's work

Applying the new design approach to production process can provide more than $18.3Mw$, 71.4% energy saving, which is supplied by low pressure steam as hot utility. The result obtained from this model are compared with Maja and Moa's result.

Table 1. Comparison of results

Requirements	New design	Maja and Moa	savings
Freshwater	324	405	20%
Hot utility	7344	257245	71.4%
Cold utility	0	174825	100%
Number of heat exchanger	2	4	50%
Total cost #/year	#94362371.275	#138240873.92	46.5%

3 Conclusion

A nonlinear programming model for freshwater and heat usage in production process using heat pump was developed in this study. Heat pump usage help to minimize environmental problem as it reduces CO_2 emission. Recovering water from production process while recovering heat serves as a useful means of minimizing production cost and pollution control. In this study, a model composed of heating and cooling cycles using the same working fluid accompanied by a phase change was proposed. The system was optimized for maximum profit by reducing excess water and heat usage.

The result of the Optimal Analysis formulated using heat pump demonstrates 20% of freshwater, 71.45% of heat as savings thereby reducing production cost by 46.5%. Water recovery itself reduces the incidence of white plumes and smog around the factory.

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