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RESEARCH ARTICLE

FLOW ENERGY ANALYSIS OF REVERSE OSMOSIS UNIT IN SEAWATER DESALINATION PLANT WITH ENERGY RECOVERY DEVICE

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Abstract

The demand of water is increasing day by day because of population explosion and rapid urbanisation. In this regard, desalination is one of the prominent technologies for providing potable water from saline aqueous media. Among available methods of desalination, seawater reverse osmosis is commercially viable and practiced in many countries of the world. But high energy use is one of the drawbacks of reverse osmosis process. Hence, this study aimed to analyse flow energy of reverse osmosis unit in seawater desalination plant with energy recovery device. A conventional material and energy balances is applied for the analysis. From the analysis, zero loss is observed in recirculation pump and significant loss of 66.65 kJ/s is estimated in energy recovery device. It could be concluded that energy recovery device is a suitable option to reduce the energy use in reverse osmosis unit.

Introduction:-

The need of pure water surrounds against the environmental health that has significant impact on the human beings. Pure water prevents the dehydration when it is used for drinking and utensils washing purposes. It also declines the contamination of microorganisms of extracellular nature [1]. Water being a source of transmitting the energy to each cell of the body should be clean otherwise it will damage the cells that cause health hazards for human being. It also creates nutrition in the body that is basic need for the healthy body. Pure water flushes the contamination from the body and removes the waste from intestines [2].

Desalination method is concerned with the separation of the water from the salt and other contents that are not required for water usage in any purpose [3]. Thermal and electrical as well as reverse osmosis methods are used for desalination of water [4]. Desalination method requires sufficient energy to proceed for getting purified water. Populated areas are situated near water sources, but these sources of water require processing to make the water purify. Salty water cannot be consumable for any purpose for which desalination method is adopted for water purification [5]. Desalination method provides drinking water to those areas where natural water supply is not available and purified water can be supplied to those areas. Desalination process is very expensive that requires economic and ecological conditions, which is not favourable for the developing and underdeveloped countries. The most important need of the water desalination plant is the energy that also creates negative impact for the environment [6].

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The main methods of desalination are based on heat, electricity, and membrane [4]. Thermal method of desalination is concerned with the boiling of the water; the steam is collected which leaves behind the salt and then vaporization process is started. The basic advantage of this method is that it is cheap and requires only vessels that have low pressure by which energy consumption can be reduced for desalination method. However, it has also disadvantage that it provides very slow productive water. In large scale populated areas, it cannot fulfil the needs of the people [7]. Electrical method is used when current is passed through the water and ions are separated from water. This current carries the ions of salt with it from a selected membrane. Major benefit of this method is that the amount of energy required for method is basically dependent upon the amount salt involved in the water. On the other hand, it has disadvantage when it is applied on the seawater because salt amount in seawater is high due to which energy requirement is also excessive [8].

The application of membrane method is frequently found in the industrial sector. The benefit of membrane method is that it uses the energy only based on amount of salt available in the water. It reveals that energy consumption in the method can be taken into estimation before employing the desalination method of membrane nature [9]. The major source of water is the ocean which is salty. Membrane method is not easy to be employed upon the seawater for its treatment because large amount of salt requires the more energy.The application of the membrane method is relevant to the industrial sector because many of the beverages are produced by using this method in which the components of one particle are separated from the other particles [10]. The membrane-based water desalination methods are microfiltration, ultrafiltration, ion exchange and reverse osmosis [11]. Microfiltration is used to eliminate the atoms which average weighted 400kDa. However, the used membrane in this method must have pore size from 0.05 to 10μm, while the operating pressure must not be extended from 2 bar [12]. In ultrafiltration, liquid is forced via semi-permeable membrane. The heavy weight components are sided of the membrane, while low weight contents and water are passed through the membrane and sided to permeate [13]. Ion exchange method of water treatment is concerned with the exchange of the ionic contaminants that are not suitable for water quality with the ionic contaminants that are required to be involved in the water [14]. Reverse osmosis is used for the removal of large-scale contaminants from the water. These large-scale contaminants are salt, chlorine, and dirt. It uses the membrane of semi-permeable nature [15].

Sharqawy and Zubair (2011) performed a second law analysis of a reverse osmosis desalination plant using reliable seawater exergy formulation instead of a common model in literature that represents seawater as an ideal mixture of liquid water and solid sodium chloride. The analysis is performed using reverse osmosis desalination plant data and compared with results previously published using the ideal mixture model. It is demonstrated that the previous model has serious shortcomings, particularly regarding calculation of the seawater flow exergy, the minimum work of separation, and the second law efficiency [16]. Liu et al., (2011) introduced a new concept of ideal RO process in their study for a more appropriate assessment of energy efficiency of water desalination, in which all the extra energy above the thermodynamic minimum is spent to maintain the required permeate flux. A pressure-recovery diagram was developed as a graphical method for better analyses and presentations of energy consumption in cross flow RO. It was demonstrated that the total energy input to a cross flow RO was much higher than the thermodynamic minimal energy for water desalination [17]. Bilton et al., (2011) presented a generalized methodology to evaluate the feasibility of photovoltaic-powered reverse osmosis (PVRO) systems for small and remote communities in challenging environments. The economic feasibility is determined by comparing the cost of water from a photovoltaic reverse osmosis system with the cost of water obtained using conventional diesel-powered reverse osmosis. For PVRO systems, the feasibility is a function of location due to variation in solar resource, water type, system demand and local governmental policies [18].

From the analysis of literature, thermodynamics-based flow energy analysis has been carried out for many configurations of reverse osmosis unit in seawater desalination plants [19-21]. Hence, this study aimed to analyse flow energy of reverse osmosis unit in seawater desalination plant with energy recovery device using conventional material and energy balances.

Methodology:-

Process description of seawater desalination plant:

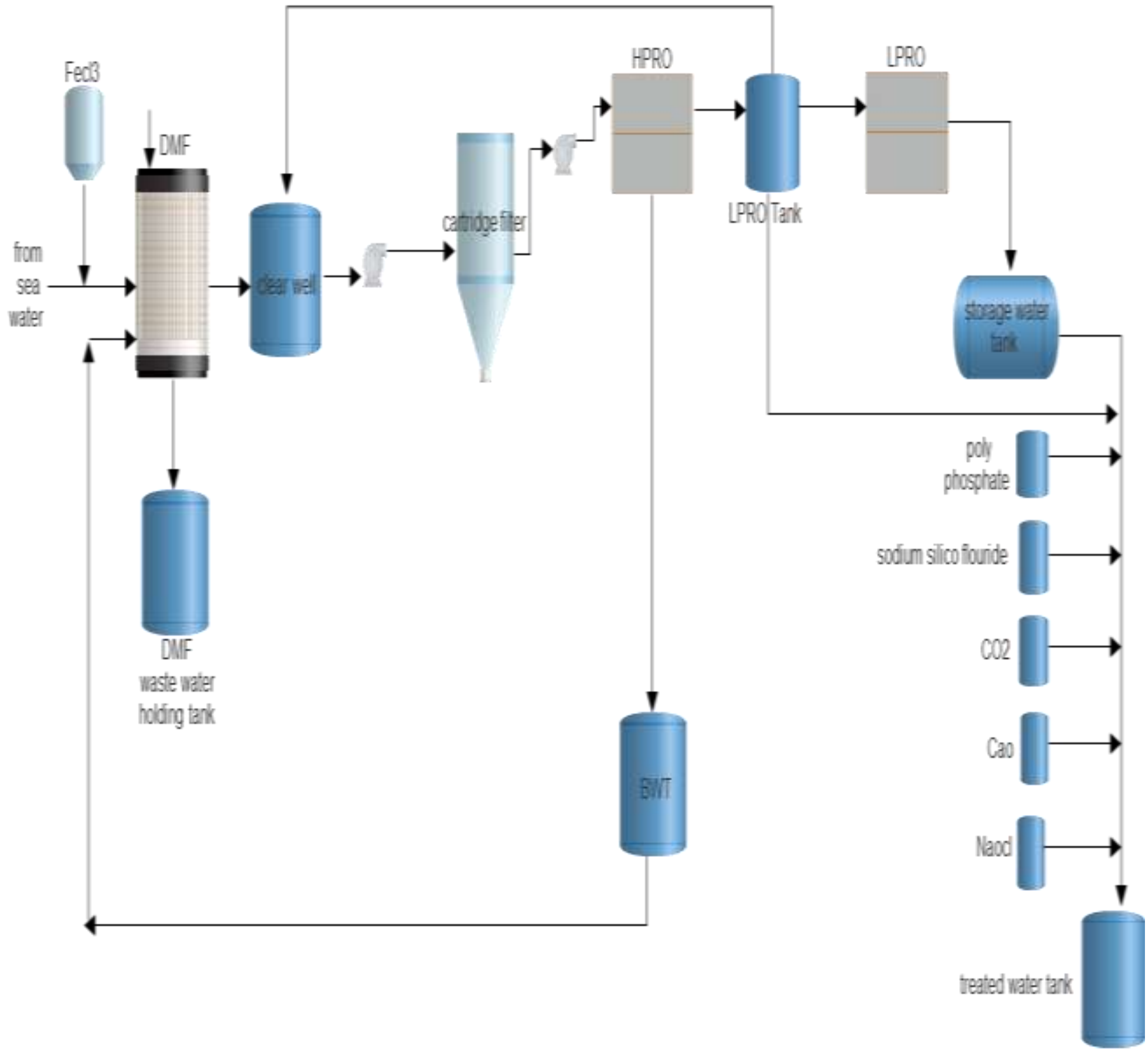

Figure 1:- Process flow diagram of seawater desalination plant (CDF – Dual media filtration, HPRO – high pressure reverse osmosis, LPRO – low pressure reverse osmosis, BWT – Backwash water tank).

Desalination by reverse osmosis membrane technology that is used to allow the flow from solute of higher concentration to lower concentration by the application of pressure [22-24]. The three stages of desalination are pretreatment, which involves seawater intake, dual media filtration, and cartridge filtration, treatment, which involves seawater reverse osmosis (SWRO) (or) high reverse (HPRO), and post treatment, which involves remineralisation (Figure 1).

Seawater intake:

Seawater contains 10 ppm total suspended solids (TSS), 3900 ppm total dissolved solids (TDS) and the remaining water. In Sembcorp Salalah Company, seawater is taken 500 m away from beach. Seawater intake is monitored through a flow meter (rotameter).

Dual media filtration (DMF):
In dual media filtration, turbidity of seawater is removed using 2 materials (Anthracite and Sand). Sand beds are used in three layers – Fine sand, pebbles, and gravel. The filter bed is supported by 2 strainers **–** one each at the top and the bottom. In DMF, 90% of TSS is removed with 1-2 % removal of TDS.

Cartridge filtration:
TSS is removed in cartridge filtration. Before sending water to the SWRO unit, silt density index (SDI) and TSS of water should be < 5 and 2 ppm. Respectively. Cartridge filter removes very tiny particles in the size from 5 to 50 μm.

SWRO:
In general, the SWRO module consists of 6 racks with 1 rack as standby, depending on seawater intake capacity. Each rack contains 188 vessels arranged horizontally. Each vessel contains 7 membranes connected through coupler. Seawater from cartridge filtration is pressurized using high pressure pump from atmospheric pressure to more than 60 bar. After SWRO. pure water is produced with negligible solids in permeate. Another stream of liquid is recycled to water body with higher concentration of solids as concentrate or retentate or reject.

Low pressure reverse osmosis (LPRO):
The LPRO moduleconsists of two pass process. In LPRO. the pressure of water is decreased from 60 bar to atmospheric pressure using low pressure pump.

Remineralisation:
The necessary salts are added in remineralisation to meet the requirements of drinking water. Sodium hypochlorite, sodium silicofluoride,sodium tripolyphosphate**,** time and CO_2 gas are passed through the water for disinfection, fluoridation, stabilization and to maintain alkalinity, respectively.

Results and Discussion:-

Flow Energy Analysis With Energy Recovery Device:

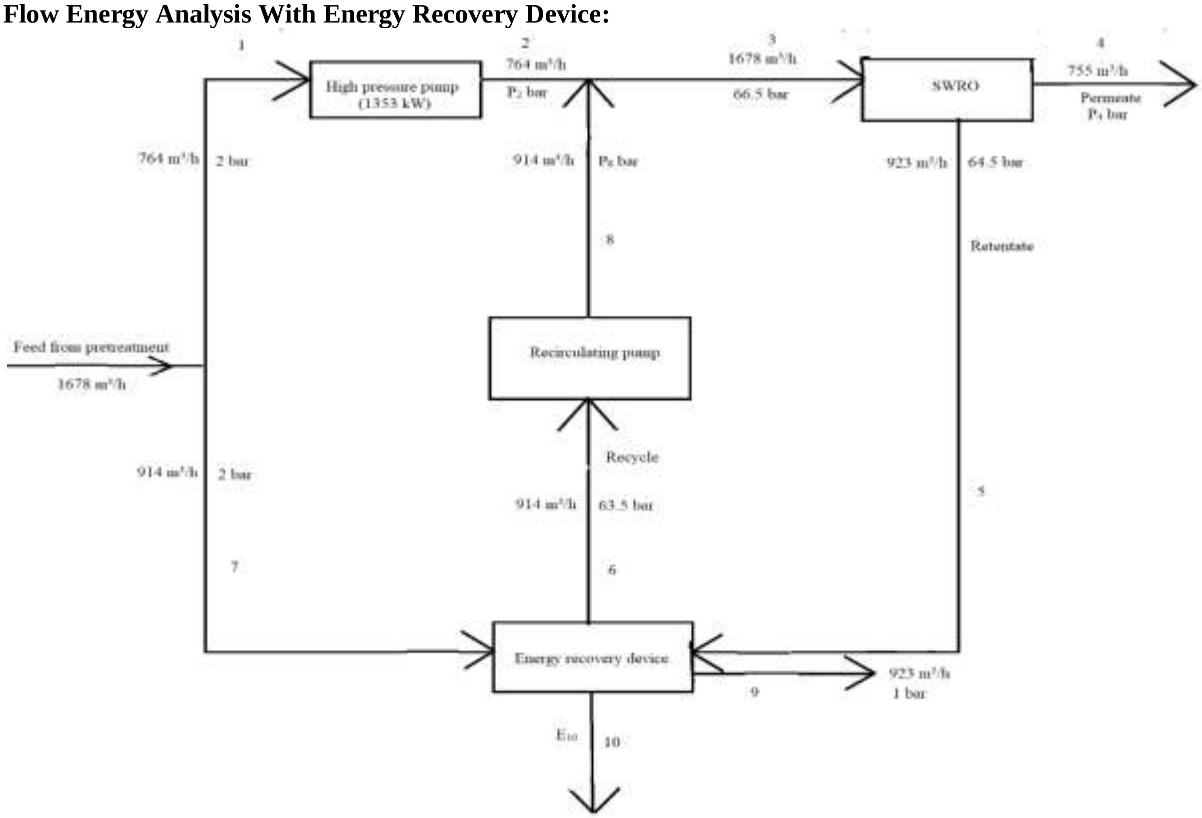

Figure 2:- Reverse osmosis unit in seawater desalination plant with energy recovery device (P – Pressure and E – Flow energy).

According to first law of thermodynamics. flow energy (E) is defined as the product of pressure and volume. Being a continuous process, flow energy is represented as per unit time. Hence, time is considered as basis for this system. Feed from pretreatment after removal of TSS is branched to two streams (1 and 7). 1678 m^3/h is flowed to stream 1 at the rate of 764 m^3/h and stream 7 at the rate of 914 m^3/h. Pressure remains constant at 2 bar in all the three streams. The pressure along stream 1 is increased using high pressure pump at the rate of 1353 kW and leaves at the same rate of 764 m^3/h and pressure of P_2 bar. The recycled stream from recirculating pump (Stream 8) is mixed with stream 2 and enters SWRO unit as stream 3 at the flowrate of 1678 m^3/h and pressure of 66.5 bar.

The feed from SWRO produces permeate (Stream 4) and retentate (Stream 5) at 45 and 55%, respectively. Therefore, permeate and retentate leave at the rate of 755 and 923 m^3/h, respectively. The pressures at permeate and retentate are P_4 and 64.5 bar, respectively. The energy loss from retentate is recovered using energy recovery device and energy is recycled with stream 2 through recirculating pump. The recirculation is required to optimize the sizing of high pressure pump. Energy recovered from energy recovery device is recycled to recirculating pump as stream 6 at flowrate of 914 m^3/h and pressure of 63.5 bar. The pressure along stream 6 is increased using recirculating pump at the rate of 92 kW and leaves at the same rate of 914 m^3/h and pressure of 63.5 bar. The recycled stream from recirculating pump (Stream 8) is mixed with stream 2 at flowrate and pressure of 914 m^3/h and P_8bar. The vent from energy recovery device releases water at 923 m^3/h and 1 bar pressure through stream 9.

Because of reduction in pressure of 64.5 bar from stream 5 to 63.5 bar along stream 6 and pressure from 2 bar from stream 2 to 1 bar along stream 1, energy loss is expected in energy recovery device and calculated along stream 10 (E_{10}).

Nomenclature:

P_1 = Pressure along stream 1
P_2 = Pressure along stream 2
P_3 = Pressure along stream 3
P_4 = Pressure along stream 4
P_5 = Pressure along stream 5
P_6 = Pressure along stream 6
P_7 = Pressure along stream 7
P_8 = Pressure along stream 8
P_9 = Pressure along stream 9
P_{10} = Pressure along stream 10
v_1 = Volumetric flowrate along stream 1
v_2 = Volumetric flowrate along stream 2
v_3 = Volumetric flowrate along stream 3
v_4 = Volumetric flowrate along stream 4
v_5 = Volumetric flowrate along stream 5
v_6 = Volumetric flowrate along stream 6
v_7 = Volumetric flowrate along stream 7
v_8 = Volumetric flowrate along stream 8
v_9 = Volumetric flowrate along stream 9
v_{10} = Volumetric flowrate along stream 10
E_1 = Flow energy along stream 1
E_2 = Flow energy along stream 2
E_3 = Flow energy along stream 3
E_4 = Flow energy along stream 4
E_5 = Flow energy along stream 5
E_6 = Flow energy along stream 6
E_7 = Flow energy along stream 7
E_8 = Flow energy along stream 8
E_9 = Flow energy along stream 9
E_{10} = Flow energy along stream 10
E_{hp} = Input energy from high pressure pump
E_{rp} = Input energy from recirculating pump

Basis: One second
Material and flow energy balance around high pressure pump:
Volumetric flowrate along stream 1 = Volumetric flowrate along stream 2
$764 = 764\ m^3/h$

Flow energy along stream 1 + Input energy from high pressure pump = Flow energy along stream 2
$P_1v_1 + E_{hp} = P_2v_2$
Since 1 bar = 100 kPa and 1 h = 3600 s, $(2x100) \times (764/3600) + 1353 = (P_2 \times 100) \times (764/3600)$
$P_2 = 65.75$ bar

Material and flow energy balance around junction point before SWRO:
Volumetric flowrate along stream 2 + Volumetric flowrate along stream 8 = Volumetric flowrate along stream 3
$764 + 914 = 1678\ m^3/h$

Flow energy along stream 2 + Flow energy along stream 8 = Flow energy along stream 3
$P_2v_2 + P_8v_8 = P_3v_3$
$(65.75x100) \times (764/3600) + (P_8x100) \times (914/3600) = (66.5 \times 100) \times (1678/3600)$
$P_8 = 67.13$ bar

Material and flow energy balance around SWRO:
Volumetric flowrate along stream 3 = Volumetric flowrate along stream 4 + Volumetric flowrate along stream 5
$v_3 = v_4 + v_5$
Here, 45% goes to stream 5 (permeate) and 55% goes to stream 4 (retentate). Therefore, volumetric flowrate of permeate = $0.45x1678 = 755\ m^3/h$, and volumetric flowrate of retentate = $1678 – 755 = 923\ m^3/h$.
Hence, $1678 = 923 + 755\ m^3/h$

Flow energy along stream 3 = Flow energy along stream 4 + Flow energy along stream 5
$P_3v_3 = P_4v_4 + P_5v_5$
$(66.5 \times 100) \times (1678/3600) = (64.5x100) \times (923/3600) + (P_5 \times 100) \times (755/3600)$
$P_5 = 68.95$ bar

Material and flow energy balance around energy recovery device:
Volumetric flowrate along stream 4 + Volumetric flowrate along stream 2 = Volumetric flowrate along stream 6 + Volumetric flowrate along stream 9
$v_4 + v_2 = v_6 + v_9$
$923 + 914 = 914 + 923 = 1837\ m^3/h$

Flow energy along stream 4 + Flow energy along stream 2 = Flow energy along stream 6 + Flow energy along stream 9 + Energy loss along stream 10
$P_4v_4 + P_2v_2 = P_6v_6 + P_9v_9 + E_{10}$
$(64.5 \times 100) \times (923/3600) + (2x100) \times (914/3600) = (63.5 \times 100) \times (914/3600) + (1 \times 100) \times (923/3600) + E_{10}$
$E_{10} = 66.65$ kJ

Material and flow energy balance around recirculating pump:
Volumetric flowrate along stream 6 = Volumetric flowrate along stream 8
$v_6 = v_8$
$914 = 914\ m^3/h$

Flow energy along stream 6 + Input energy from recirculating pump = Flow energy along stream 8
$P_6v_6 + E_{rp} = P_8v_8$
$(63.5x100) \times (914/3600) + E_{rp} = (67.13 \times 100) \times (914/3600)$
$E_{rp} = 92.16$ kW

From the analysis, zero loss is observed in recirculation pump and significant loss of 66.65 kJ/s is estimated in energy recovery device.

Conclusion:-

The present study aimed to analyseflow energy of reverse osmosis unit in seawater desalination plant with energy recovery device. A conventional material and energy balances is applied for the analysis. From the analysis, zero loss is observed in recirculation pump and significant loss of 66.65 kJ/s is estimated in energy recovery device. It could be concluded that energy recovery device is a suitable option to reduce the energy use in reverse osmosis unit.

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