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Review of Opportunities to Improve Steam Condenser with Nanofluids in Power Plants

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Abstract - Steam condensers are very important part of the equipment usedin power plants. The performance of steam condenser has a large influence on the overall energy efficiency of the steam power plant operating on Rankine cycle (RC). Large efforts must be done to maintain the waste heat removal in the condenser and to improve its performance. In this paper, the possibility of improving the steam condenser is provided. One important factor affects the steam condenser performance is entropy generation rate. Entropy generation rate was used to optimize the condenser performance by evaluating best operational parameters as well as fluid properties, which include the thermal conductivity and viscosity of nanofluid. The entropy generation rate due to frictional effect was much smaller than the one due to thermal effect. With increasing volume fraction of nanoparticles and angular orientation of pins for a given Reynolds number; Euler, Nusselt and Prandtl numbers increase, whereas, entropy generation rate decreases improving heat transfer performance of the system. Furthermore, with increasing the Reynolds number for a given volume fraction, Nusselt and Prandtl numbers and overall heat transfer efficiency increased while Euler number decreased for pins with the same orientation angle and it increased for pins with different orientation angles.

Key Words: Steam Condenser, Power Plants, Nanofluid, Pin Fin, Heat Sink

1.INTRODUCTION

A Currently nine out of ten power plants in the world that generate electricity from steam power require condensate cooling. These systems are categorized as either oncethrough or wet-recirculation. Once-through cooling systems discharge water directly after it has absorbed system heat. Wet-recirculating systems (wet-cooling) operate in a closed loop where a considerable amount of water is lost in the cooling towers through evaporation cooling. The remaining power plants use air for heat removal in a process called dry-cooling. This process reduces water consumption by more than 90%.

However, air as a lower heat capacity than water making this power plant less efficient resulting in significant increases in size and cost. In summer, when electricity demand peaks, ambient temperature increases, this significantly decreases the temperature difference between steam and ambient air resulting in a decrease of cooling capacity. In order to significantly reduce or eliminate the use of water for cooling power plants, a highly efficient heat exchanger for the vapor condensation is needed.

It should be noted that most of the energy lost in steam power plants is in the condenser as shown in **[Chart-1]**. For a typical vapor condensation heat exchanger, the steam from the power plant is condensed inside the heat exchanger. The heat released from the condensation is transferred through the exchanger wall and removed by the forced convection.

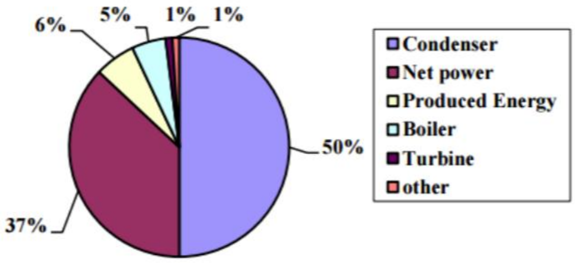

Chart -1: Energy losses in power plants

In order to enhance heat transfer of the condensation heat exchanger, the condensation heat transfer occurring inside the heat exchanger is needed to be increased and the forced convection heat transfer is needed to be enhanced as well. In the current investigation, the heat transfer enhancement of forced convection using nanofluid elliptical pin fins is investigated. At the same time, the vapor condensation occurring in the wick structure of the heat pipe is addressed.

1.1 Nanofluids

A nanofluid is a fluid containing nanometer sized particles, called nanoparticles. These fluids are engineered colloidal suspensions of nanoparticles in a base fluid. Nanofluids (NFs) have great potential for enhancing the heat transfer capability of heat transfer in power plants [1-17]. Hence, using NFs as a working fluid is great for use in high performing compact heat exchangers and heat sinks used in power plants operating on Rankine Cycle **[Chart-2]**. In comparison to conventional coolants, Nanofluids have high thermal conductivities. And this depends on the particle diameter, volume faction, thermal conductivity of base fluid and nanoparticles as well as the Brownian motion of nanoparticles.

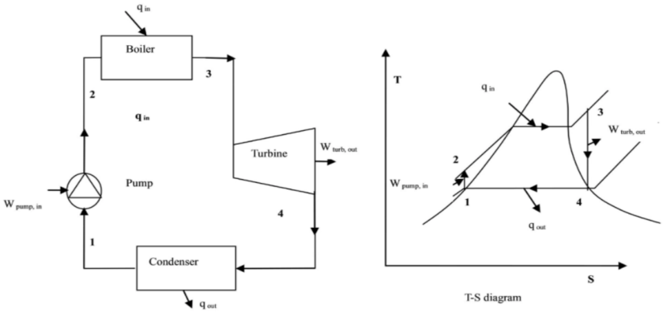

Chart -2: Schematic and T-S Diagram of Rankine Cycle

1.2 Pin Fin Heat Sink

Thermal and hydraulic analyses of elliptical pin fin heat sinks are performed by using parametric variations of many design variables. They include but not limited to pin diameter, pin height, velocity, number of pin-fins, and thermal conductivity of the material. Optimization of elliptical pin fin heat sink design and parametric behavior are introduced and compared on the basis of the selected pin fin configuration and material property.

1.3Vapor Condensation

In order to increase the heat transfer rate of the vapor condensation heat exchanger, the current investigation will focus on the condensation heat transfer and forced convection. For the vapor condensation, in order to increase the condensation heat transfer rate, heat pipe wick **[Chart-3]** is utilized to increase the condensation area, and at the same time, the condensate can be effectively removed by the capillary force. The heat released from the condensation must be efficiently removed for the forced convection. In order to increase the heat transfer coefficient of forced convection, the elliptical pin fins with nanofluid is investigated.

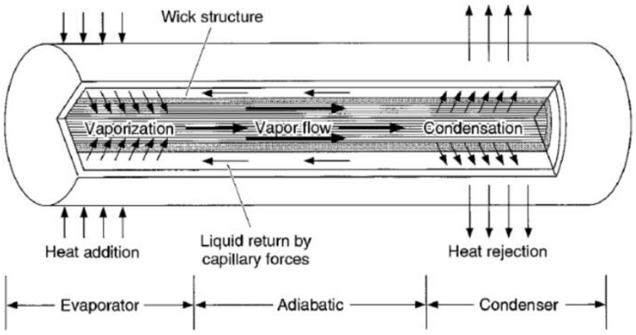

Chart -3: Heat Pipe Operation

1.4NFs in Power Plants

Nanofluids have proven to have a great potential for enhancing the heat transport capability of power plants. Therefore, using nanofluids as a working fluid is well suited for use in high performance compact heat exchangers and heat sinks used in power plants. One of the important characteristics of nanofluids is represented by their higher thermal conductivities with respect to conventional coolants. The enhancement of thermal conductivity of NFs depends on particle diameter and volume fraction, thermal conductivities of base fluid and nanoparticles as well as Brownian motion of nanoparticles, which is a key mechanism in thermal conductivity enhancement [18-22].

2. SUPER HYDROPHOBIC VS HYDROPHILIC CONDENSER

One important point is to analyze the hydraulic and thermal performance of condenser (pin fin heat sink) with super hydrophobic and hydrophilic surfaces using distilled water and SiO2 aqueous nanofluids with 0.015% and 0.030% concentrations and compare the results with conventional (without coating) condenser. Two pin fin copper micro channel heat sinks are manufactured with the help of CNC milling machine, then, they were sent to LiFong China for Super hydrophobic coating. LiFong has used modified repellix-2 technique for the required super hydrophobic coating with contact angle of 153 degree as well as coating thickness of 50 to 80 nm.Many basic themo physical properties of nanofluids such as volume fraction of nanoparticles, density, viscosity and thermal conductivity are calculated using mathematical equations and expressions provided in [23].

2.1 Effect of Super Hydrophobic Coating On Nusselt Number

The Nusslet number depend on mass flow rate and increases with the increase in Reynolds number for all the nanofluid. Power input has major effect on Nusselt number. In the case of distilled water, Reynolds number does not increase with power input at same mass flow rate as viscosity remains the same. Super hydrophobic condenser surface provided 23.67%, 19.53% and 21.45% more Nusselt number than the conventional (hydrophilic) condenser surface for distilled water, SiO_2 (0.015%), and SiO_2 (0.030%) nanofluids respectively. The increase in thermal performance is mainly due to the repelling property of super hydrophobic surfaces. The repellence enhances shear training and demolishes thermal boundary layer referred as heat transfer barrier. Hence, fresh layers of working fluids have more chances to come in contact with the heated surface resulting in greater conventional hydrophilic heat transfer. Churning effect and Brownian motion also contributed towards the enhancement in Nusselt number [24].

2.2 Effect of Super hydrophobic coating on pressure drop

Pressure drop is amplified with increase in mass flow rate for all the fluids and for condenser surface. Pressure drop does not change with the power input because viscosity of all the working fluids is not significantly affected due to very small concentration. Super hydrophobic coating has tremendous effect on pressure drop and pumping power and a reduction of 34.21%, 29.73, and 30.12% in pressure drop and pumping power is noted for super hydrophobic condenser surface as compared to conventional hydrophilicsurface for distilled water, SiO_2 (0.015%) and SiO_2 (0.030%) nanofluids accordingly at the same Reynolds number.The decrease in pressure drop for the super hydrophobic surface is mainly due to hydrophobicity of the surface. There is a demolishment of the thermal boundary layer. This demolishment decreases the surface drag and friction and produces larger slip length [25].

2.3 Effect of super hydrophobic coating on thermal resistance

The thermal resistance for both types of condenser surfaces and all HTFs are discussed here against Reynolds number for water and SiO_2-water nanofluids. Thermal resistance dwindled with amplification in Reynolds number, as expected and increases with the increase in power input. Nanofluids provided greater performance than the distilled water as the same Reynolds number for both types of surfaces. The super hydrophobic surface performed better than the conventional hydrophilic one with 20.3%, 17.6% and 18.3% lower resistance for water, $SiO2$ (0.015%) and $SiO2$ (0.030%) nanofluids respectively. The thermal boundary layer is reduced to a minimum value in the case of superhydrophobic surfaces. Hence, fresh currents of fluid have more opportunity to touch the heated surface and enhance cooling of the surface. This creates an amplified thermal performance and produces shear thinning which in turn causes the thermal resistance to decrease [26-27].

2.4 Types of RC

The following are the various types of RC. The first one is the basic RC (BRC)**[Chart-4]**. When compared to the other varieties of RC, BRC operates in subcritical settings and requires the smallest number of components. BRC has four separate processes; isentropic compression (3-4), heat addition (4-1), isentropic expansion (1-2), and heat rejection (2-3).

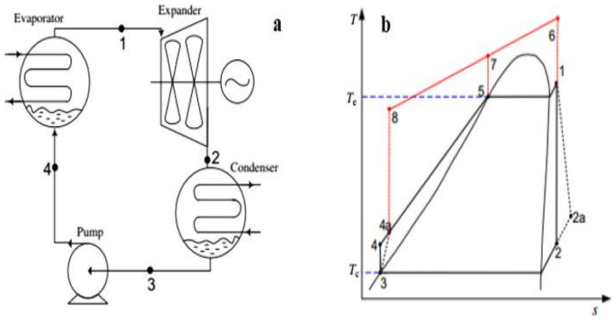

Chart -4 (a) Schematic of basic RC (BRC) and (b) T-S diagram for BRC

The second is the single stage regenerative RC (SRRC): A SRRC system is depicted in **Chart 5**. Part of the vapor is removed between 2 stages of the turbine & added to the feedwater heater in this setup. By lowering the amount of heat added from the evaporator heat source, the regenerator can improve cycle efficiency.

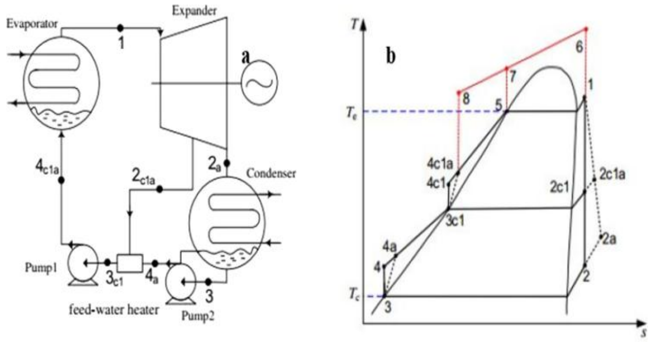

Chart -5(a) Schematic of single stageregenerative RC (SRRC) and (b) T-S diagram for SRRC

The next type is the double stage regenerative RC(DRRC): A DRRCsystem is seen in **Chart 6**. Thistechnique is similar to SRRC, except the extractionoccurs in two steps. By lowering the evaporator load,the DRRC improves the cycle's thermal efficiency.

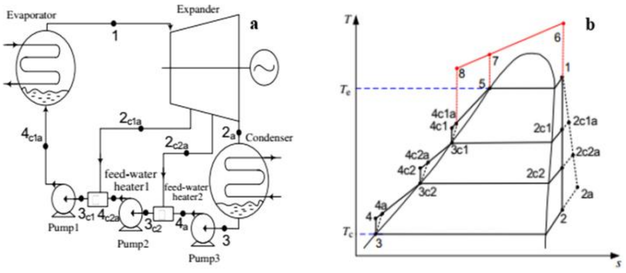

Chart-6 (a) Schematic of double stageregenerative ORC (DRRC) and (b) T-Sdiagram for DRRC

A RRC system is shown in **Chart 7**. The first turbine in this system receives high-pressure vapor from the evaporator portion. The exit vapor then returns to the evaporator, where it is warmed with the heat source prior to actually entering a new lower pressure turbine. The RRC system's goal is to remove the moisture from the steam at the end of the expansion phase.

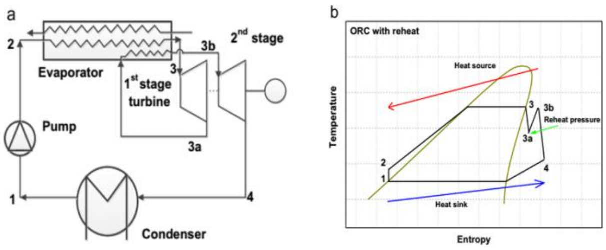

Chart -7(a) Schematic of reheat RC (RRC) and (b) T-S diagram for RRC

An RC with something like a recuperator is shown in **Chart 8**. The elevated temperature operating fluid from the turbine runs through the low-pressure side of IHX, while the low temperature operating fluid out from pump flows through the high-pressure side of IHX to increase efficiency of the power plant.

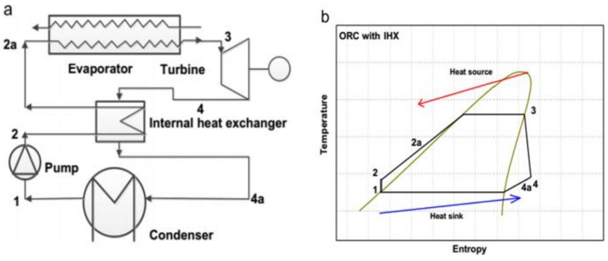

Chart-8(a) Schematic of RC with recuperator and (b) T-S diagram for RC with recuperator

Dual loop RC (DLRC) system is shown in **Chart 9**. The HT loop is utilized to retrieve the waste source of heat in this system. The LT loop is utilized to retrieve the jacket cooling water as well as the HT loop's surplus heat. By reducing the heat load dissipated to the environment, this technology improves the cycle's overall efficiency of the power plant.

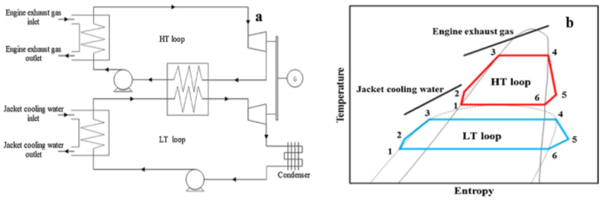

Chart-9(a) Schematic of dual loop RC (DLRC) and (b) T-S diagram for DLRC

3. RESULTS AND DISSCUSIONS

Investigations into the optimization of geometrical structures of micro/mini heat sinks, and the use of nanofluids in cooling devices for cooling power plants are still embryonic; much more study is required in order to better understand the thermal and fluid dynamic characteristics of these equipments with this very promising new family of coolants and different geometries.

3.1Enhancement of Pin Fin Shapes

An analysis was conducted to determine the effect of SiO_2nanofluid on the heat transfer performance in an elliptical pin-fin heat sink used in power plant including the influence of pin orientation. An effective thermal conductivity model, which takes into account the mean diameter of nanoparticles and Brownian motion,was utilized.

3.2Entropy Generation

The influence of changing volume fraction of nanoparticles causes the entropy generation rate toincrease. The influence of SiO_2- water nanofluid coolant is large causing the thermal entropy generationrate to increase in the heat sink. When compared to pure water, SiO_2- waternanofluid coolant had a smaller total entropy generation rate. Entropy generationrate due to thermal effect is much larger than the one due to frictional effect. The frictional contributionof entropy generation rate increases with increasing volume fraction, which means that the hydraulicefficiencyof thepower plant decreases withincreasing volume fraction, buttheamount of enhancementin frictional entropy isverysmall. Withincreasingvolumefaction ofnanoparticles, thetotal entropygeneration rate due toheattransfer decreases moretherebyimprovingtheheattransfer performanceof thepower plant. Optimization results of three parameters i.e., entropy generation, resistance and pressure ratioat different Reynolds, Nusselt and Prandtl numbers are provided in **[Table 1]**.

Table -1: Optimization of three parameters

***Re*, *Nu*,*Pr*Numbers**		**OptimizedDesignVariables**			**R_{hs} °C/W**	**Eu**	**S_{gen}W/K(x10^{-3})**
		x(mm)	U_m(m/s)	N_T× N_L			
30,2,3.5	In-Line	2.74	4.94	2 × 3	3.059	0.47	3.1
	Staggered	3.2	2.49	3 × 2	2.296	0.54	2.3
90,8.5,6	In-Line	0.8	3.04	6 × 4	1.233	0.41	1.2
	Staggered	0.1	0.35	5 × 5	0.191	0.45	0.23

3.3 Effect of super hydrophobic coating on LMTD

The thermal performance of the power plant system is predicted by LMTD. This is based on wall base temperature and thermal resistance. The wall base temperature and R_{th} are decreased by preparing super hydrophobic coating on the active surfaces of condenser (pin fin heat sink). The log mean temperature difference LMTD decreases with the increase in Reynolds number based on the normal phenomenon. Super hydrophobic coating has a huge effect on LMTD and it decreases by 21.03% for water, 18.13% for SiO_2 (0.015%) and 19.23% for SiO_2 (0.030%) nanofluid as compared to conventional hydrophiliccondenser surfaces. The LMTD is lower because of the enhanced heat transfer caused by the super hydrophobic surfaces [28].

4. CONCLUSIONS

Heat transfer and fluid flow analyses are employed in this study to optimize the geometry of steam condenser such as heat sink in power plants. An entropy minimization technique is employed to optimize the overall thermal performance. The performance of heat sink is identified by its thermal resistance and pressure drop, because they substantially affect the thermal resistance during forced convection cooling of power plants. The design of different configurations of heat sinks are studied and the thermal and hydraulic behaviors are compared. Entropy generation rate is obtained using mass, energy and entropy balance over a control volume. The average heat transfer coefficient of the heat sink is developed using an energy balance equation over the control volume. This heat transfer coefficient is a function of the heat sink material, fluid properties, fin geometry, pin-fin configuration. The super hydrophobic condenser surface performed better than the conventional hydrophilicsurface with 24.76%, 20.93% and 23.18% augmentation in Nusselt number for distilled water, SiO2 (0.015%) and SiO2 (0.030%) nanofluids respectively at the same working parameters.

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