Performance, Analysis, And Heat Transfer of Vapor Compression Refrigeration System Due To Condenser Fouling

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Abstract*- This research document shows the performance, thermal analysis, and simulation design by ANSYS of the Thermal behavior of the condenser coil due to fouling in the vapor compression refrigeration system. Firstly, the experimental procedure was carried out on a mechanical heat pump by doing observation, and calculation and was analyzed in the ANSYS software. Further, it was compared with scaled and without a scaled condenser. It was initiated with the definition of boundary conditions, to then delimit the geometric design and evaluation of the thermal behavior of the shell and tube condenser coil. Including various input parameters like temperature, specific heat, enthalpy, mass flow rate, area for final heat transfer rate, and coefficient of performance. The result obtained is reflected as ANSYS and theoretically calculated through experimentation. The result consisted of a 7% difference between theoretical and ANSYS simulation of condenser coil with fouling and without fouling. The heat transfer difference was about 12% in the condenser coil with fouling and without fouling. As well as the COP of the fouled condenser was less than the COP of without fouled condenser.*

Keywords*-* ANSYS, Condenser Fouling, Heat transfer, Shell and tube condenser coil, Vapor compression refrigeration.

I. INTRODUCTION

Refrigeration may be defined as the process of achieving and maintaining a temperature below that of surroundings, the being to cool some product or space to the required temperature. one of the most important applications of refrigeration has been the preservation of perishable food products by storing them at low temperatures. Refrigeration systems are also extensively used for providing thermal comfort to human beings by the means of air conditioning. The performance of the refrigeration system is evaluated in terms of COP which is the ratio of refrigeration effect to the network input given to the system. The COP of the vapor compression refrigeration system can be improved by increasing the refrigeration effect or by reducing the work input given to the system. vapor compression refrigeration systems and heat pumps systems whose operational cycle is based on the reversed Rankine cycle, require work input to accomplish the objective of transferring heat from a lower temperature source to a higher temperature sink. The operational modes of refrigeration and heat pump systems are virtually identical only different in their purpose. The low-pressure liquid refrigerant is boiled by absorbing heat via an evaporator at the heat source. It is then compressed and passed through a condenser at the heat sink, where it is condensed and heat is released to the heat sink. The high-pressure liquid refrigerant is then passed through the expansion device and returned to the heat source heat exchanger. From a thermodynamics point of view, the performance of refrigeration systems and heat pumps is evaluated by their cooling and heating capacity respectively, and coefficient of performance COP. Naveen Solanki et al. [5] have experimentally studied the effect of condenser fouling on the performance of vapor compression refrigeration systems by using different types of refrigerants. The copper tube used in the refrigeration system has been analyzed using the failure analysis method by K. Chandra et al. [6]. Mostafa M. Awad [4] has studied all the types of fouling as well as fouling materials on heat transfer surfaces. Experimental and theoretical studies on corrosion of copper in pure O_2 free water were studied by Allan Hedin et al. [1]. Nan Wang et al.[12] experimentally investigated the effect of scaling formation on copper enrichment behavior in continuous cast slab and the effects of slab surface temperature were discussed. Evaporator, Compressor, and Expansion device are the inbuilt inner parts of the system body, so we cannot make substantial changes to them. The condenser is the outer part of the system body. By doing various modifications to the condenser we can improve performance. To increase COP and heat transfer condenser is the best option so we are going to work on condenser tubes. Through the simulation in ANSYS software that will be carried out in this investigation, it will be possible to observe the heat transfer rate that each of the R134a refrigerant phases is placed in different parts of the tube. On the other hand, a base case was determined, where the COP and the heat transfer rate through the theoretical method of Thermal analysis of composite hollow cylinder by Vishal Rai and Shashank Nigam [7].

II. PROBLEM STATEMENT & OBJECTIVE

During condensation in a water-cooled condenser, the water flows over the pipes of the Condenser for a longer period, due to which there is fouling on the condenser pipes. This may be also due to some of the chemical reactions in the fluid during the Condensation process. This fouling affects the flow rate of the fluid, transfer of heat, etc. “fouling” can also include various corrosion products and foulants such as organic matter and mud or dirt. Fouling plays important role in the overall heat transfer of the system.

1] To study the effect of condenser fouling on the performance of refrigeration systems by using experimental methods & simulation by ANSYS software.

2] To study different types of parameters (Heat transfer rate, Coefficient of performance, heat transfer resistance, and overall heat transfer) affecting the condenser performance.

3] To study various types of fouling types in condensers like particulates fouling, chemical reaction fouling, corrosion fouling, freezing fouling, and biological fouling.

4] To perform the experiment and validate it by ANSYS software.

III. MATERIALS AND METHODS

The design evolution of a shell and tube condenser, with refrigerant 134a, starts with the selection of dimensional parameters, followed by the analysis of the fluid system until reaching the heat transfer delineation necessary for condensation to result. In this sense, we seek to detail equations, perform dimensional analysis and briefly synthesize each segment of the thermal design.

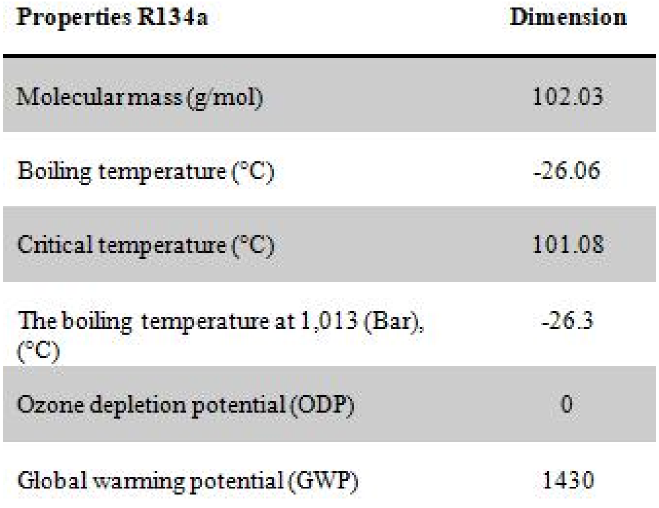
Two fluids are considered in the design of the helical condenser, the first is refrigerant 134a, subject to phase change and another fluid is water, which is going to reduce the temperature of the system and is responsible for that there is a transfer of heat to achieve the condensation process.

A. Properties of 134a Refrigerant

The working fluid that is used in the steam compression refrigeration processes in Ecuador is R134a, because the condensation process will be carried out, it is necessary to present the characteristics of this refrigerant fluid, these are described in the table 1.

The 134a refrigerant has an ozone layer destruction index of zero, which reflects that it is environmentally friendly in specific to the recovery of the ozone layer, which was affected between the 70s and 90s however, the greenhouse effect index is still large, so it is advisable not to throw it outwards.

Table 1: Physicochemical properties of refrigerant 134a

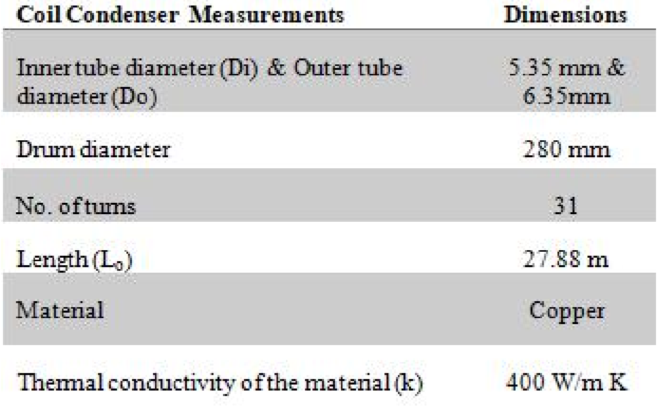


Properties R134a	Dimension
Molecular mass (g/mol)	102.03
Boiling temperature (°C)	-26.06
Critical temperature (°C)	101.08
The boiling temperature at 1,013 (Bar), (°C)	-26.3
Ozone depletion potential (ODP)	0
Global warming potential (GWP)	1430

B. Selection of Pipe for the Condenser

Cold-drawn extrusion copper pipes can achieve single-piece, smooth-walled seamless pipes, ensuring pressure resistance and minimal friction losses in fluid handling, In addition to having a high degree of thermal conductivity facilitating the transfer of heat from or to the fluid, applications range from the domestic level to large industrial facilities. The condenser is a helical spiral of extruded copper material special for heat transfer processes. The characteristics of this are displayed in table 2.

Table 2: Condenser Physical dimensions and characteristics



Coil Condenser Measurements	Dimensions
Inner tube diameter (Di) & Outer tube diameter (Do)	5.35 mm & 6.35mm
Drum diameter	280 mm
No. of turns	31
Length (L_o)	27.88 m
Material	Copper
Thermal conductivity of the material (k)	400 W/m K

C. Parameters

For the heat transfer to cause the phase change of the refrigerant fluid, one of the two fluids must be at a lower temperature than the R134a, the water is the fluid used for this purpose. On the other hand, the water will enter the process of phase change at a lower temperature T_{in} of 67 °C and after carrying out this process it will go out T_{out} of 32 °C, another indispensable aspect of the fluid is its heat capacity that for this temperature it is taken as Cp_{liquid} of 4.187 kJ/kg·K.

D. Fouling

Fouling is generally defined as the accumulation and formation of unwanted materials on the surfaces of processing equipment, which can seriously deteriorate the capacity of the surface to transfer heat under the temperature difference conditions for which it was designed. fouling of heat transfer surfaces is one of the most important problems in heat transfer equipment. There are different types of fouling as follows,

1. Particulate fouling: It is the deposition of suspended particles in the process streams onto the heat transfer surfaces. Particulate fouling may be defined as the accumulation of particles from heat exchanger working fluids on the heat transfer surface.
2. Crystallization fouling: It is the crystallization of dissolved salts from saturated solutions, due to solubility changes with temperature, and subsequent precipitation onto the heat transfer surface.
3. Chemical reaction fouling: The deposition in this case is the result of one or more chemical reactions between reactants contained in the flowing fluid in which the surface material itself is not a reactant or participant.
4. Corrosion fouling: It involves a chemical or electrochemical reaction between the heat transfer surface itself and the fluid stream to produce corrosion products which, in turn, change the surface thermal characteristics and foul it.
5. Biological fouling: It is the attachment and growth of microorganisms and their product on the heat transfer surface.
6. Solidification or freezing fouling: It is the freezing of a pure liquid or a higher melting point components of a multi-component solution onto a subcooled surface.

E. Calculation of Heat transfer

Heat transfer of condenser, case 1 with fouling/scaling can be calculated by the means of eq.1, and case 2. without fouling/scaling can be calculated by eq.2.

$$Q = \frac{\Delta T}{\sum R_{th}}$$

$$Q = \frac{T_i - T_o}{\left[\frac{r_3 \ln\left(\frac{r_2}{r_1}\right)}{LK_1}\right] + \left[\frac{r_3 \ln\left(\frac{r_3}{r_2}\right)}{LK_2}\right] + \left[\frac{1}{h}\right]}$$

Eq. (1)

The temperatures Ti and To are the temperatures of the condenser at the inlet and the outlet of the refrigerant, respectively in °C.r_1,r_2,and r_3 are the radius of the copper tube where r_1 is the inner radius, r_2 is the outer radius and r_3 is the radius with fouling/scaling film formed on the surface of the copper tube. Heat flux is denoted by h. K_2 is the conductivity of the copper carbonate hydroxide scale formed on the copper tube. K is the conductivity of copper. L is the length of the copper tube.

Case.1

$$Q = \frac{67-32}{\left[\frac{0.00343 \ln\left(\frac{0.00318}{0.00268}\right)}{27.88\times 400}\right] + \left[\frac{0.00343 \ln\left(\frac{0.00343}{0.00318}\right)}{27.88\times 2.36}\right] + \left[\frac{1}{5000}\right]}$$

$$Q = 2.51\times 10^5 \, {}^{W}\!/\!_{m^2}$$

Case.2

$$Q = \frac{65-33}{\left[\frac{0.00318 \ln\left(\frac{0.00318}{0.00268}\right)}{27.88\times 400}\right] + \left[\frac{1}{5000}\right]}$$

$$Q = 2.87\times 10^5 \, {}^{W}\!/\!_{m^2}$$

F. Coefficient of performance [COP]

Heat is known as the form of energy associated with the movement of atoms in all directions, it is also closely linked to the first principle of thermodynamics according to this, two bodies in contact exchange heat between them until reaching thermal equilibrium. The coefficient of performance of a refrigeration system is the ratio of useful heating or cooling provided to work required. Higher COPs equate to higher efficiency, lower energy consumption, and thus lower operating costs.

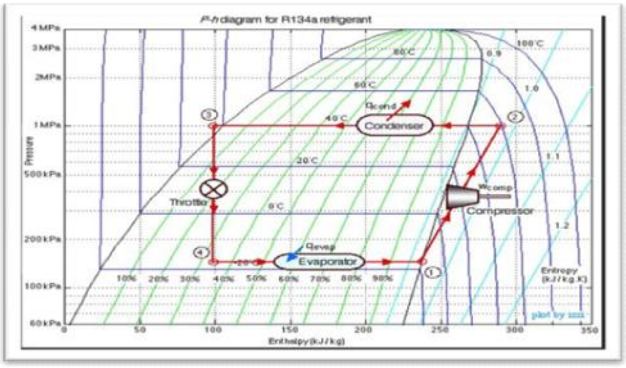


Figure 1. Condensation with R134a

Case 1.

$$COP = \frac{H_1 - H_4}{H_2 - H_1} = \frac{412 - 250}{452 - 412} = 4.05 \qquad \textbf{Eq. (3)}$$

Case 2.

$$COP = \frac{H_1 - H_4}{H_2 - H_1} = \frac{414 - 240}{453 - 414} = 4.46 \qquad \textbf{Eq. (4)}$$

G. Parameters affecting fouling

The fouling process is a dynamic and unsteady one in which many operational and design variables have been identified as having the most pronounced and well-defined effects on fouling. These variables are reviewed in principle to clarify the fouling problems and because the designer influences their modification. According to many investigators, the most important parameters are:

1. **Fluid flow velocity:** The flow velocity has a strong effect on the fouling rate where it has direct effects on both the deposition and removal rates through the hydrodynamic effects such as the eddies and shear stress at the surface. It is well established that, increasing the flow velocity tends to increase the thermal performance of the exchanger and decrease the fouling rate. Uniform and constant flow of process fluids past the heat transfer surface favors less fouling. foulants suspended in the process fluids will deposit in low-velocity regions, particularly where the velocity changes quickly, as in heat exchanger water boxes and on the shell side. Higher shear stress promotes dislodging of deposits from surfaces. Maintain relatively uniform velocities across the heat exchanger to reduce the incidence of sedimentation and accumulation of deposits.
2. **Surface temperature:** The effect of surface temperature on the fouling rate has been mentioned in several studies. These studies indicated that the role of surface temperature is not well defined. The literature shows that "increase surface temperature may increase, decrease, or does not affect the fouling rates". This variation in behavior does indicate the importance to improve our understanding of the effect of surface temperature on the fouling process, A good practical rule to follow is to expect more fouling as the temperature rises. This is due to a “baking on” effect, scaling tendencies, increased corrosion rate, faster reactions, crystal formation and polymerization, and loss inactivity by some antifoulants.
3. **Surface material**: The selection of surface material is significant to deal with corrosion fouling. Carbon steel is corrosive but the least expensive. Copper exhibits biocidal effects in water. However, its use is limited in certain applications: (1) Copper is attacked by biological organisms including Fouling of Heat Transfer Surfaces 517 520 Heat Transfer - Theoretical Analysis, Experimental Investigations, and Industrial Systems sulfate-reducing bacteria; this increases fouling. (2) Copper alloys are prohibited in high-pressure steam power plant heat exchangers since the corrosion deposits of copper alloys are transported and deposited in high-pressure steam generators and subsequently block the turbine blades. (3) Environmental protection limits the use of copper in the river, lake, and ocean waters since copper is poisonous to aquatic life. Noncorrosive materials such as titanium and nickel will prevent corrosion, but they are expensive and have no biocidal effects. Glass, graphite, and Teflon tubes often resist fouling and/or improve cleaning but they have low thermal conductivity. Although the construction material is more important to resist fouling, surface treatment by plastics, vitreous enamel, glass, and some polymers will minimize the accumulation of deposits [4].
4. **Surface Roughness:** The surface roughness is supposed to have the following effects: (1) The provision of “nucleation sites” that encourage the laying down of the initial deposits. (2) The creation of turbulence effects within the flowing fluid and, probably, instabilities in the viscous sublayer. Better surface finish has been shown to influence the delay of fouling and ease of cleaning. Similarly, non-wetting surfaces delay fouling. Rough surfaces encourage particulate deposition and provide a good chance for deposit sticking. After the initiation of fouling, the persistence of the roughness effects will be more a function of the deposit itself. Even smooth surfaces may become rough in due course due to scale formation, formation of corrosion products, or erosion.
5. **Fluid Properties:** The fluid propensity for fouling is depending on its properties such as viscosity and density. The viscosity is playing an important role in the sublayer thickness where the deposition process is taking place. On the other side, the viscosity and density have a strong

effect on the shear stress which is the key element in the removal process.

6. **Impurities and Suspended Solids**: Seldom are fluids pure. The intrusion of minute amounts of impurities can initiate or substantially increase fouling. They can either deposit as a fouling layer or act as catalysts to the fouling processes [6]. For example, chemical reaction fouling or polymerization of refinery hydrocarbon streams is due to oxygen ingress and/or trace elements such as Va and Mo. In crystallization fouling, the presence of small particles of impurities may initiate the deposition process by seeding.
7. **Heat Transfer Process:** The fouling resistances for the same fluid can be considerably different depending upon whether heat is being transferred through sensible heating or cooling, boiling, or condensing.
8. **Design Considerations**: Equipment design can contribute to increasing or decreasing fouling. Heat exchanger tubes that extend beyond tube sheets, for example, can cause rapid fouling. Some fouling aspects must be considered throughout the equipment design such as 1. Placing the More Fouling Fluid on the Tube Side As a general guideline, the fouling fluid is preferably placed on the tube side for ease of cleaning. Also, there is less probability of low-velocity or stagnant regions on the tube side. 2. Shell-Side Flow Velocities are generally lower on the shell side than on the tube side, less uniform throughout the bundle, and limited by flow-induced vibration. Zero-or low-velocity regions on the shell side serve as ideal locations for the accumulation of foulants. If fouling is expected on the shell side, then attention should be paid to the selection of baffle design. Segmental baffles tend to have poor flow distribution if spacing or baffle cut ratio is not incorrect proportions. Too low or too high a ratio results in an unfavorable flow regime that favors fouling. Fouling of Heat Transfer Surfaces 519 522 Heat Transfer - Theoretical Analysis, Experimental Investigations and Industrial Systems 3. Low-Finned Tube Heat Exchanger There is a general apprehension that low Reynolds number flow heat exchangers with low finned tubes will be more susceptible to fouling than plain tubes. Fouling is of little concern for finned surfaces operating with moderately clean gases. Fin type does not affect the fouling rate, but the fouling pattern is affected for waste heat recovery exchangers. Plain and serrated fin modules with identical densities and heights have the same fouling thickness increases in the same period. 4. Gasketed Plate Heat Exchangers High turbulence, absence of stagnant areas, uniform fluid flow, and the smooth plate surface reduce fouling and the need for frequent cleaning. Hence the fouling factors required in plate heat exchangers are normally 10-25% of those used in shell and tube heat exchangers. 5. Spiral Plate Exchangers High turbulence and scrubbing action minimize fouling on the spiral plate exchanger. This permits the use of low fouling factors. 6. Seasonal temperature changes When cooling tower water is used as a coolant, considerations are to be given for winter conditions where the ambient temperature may be near zero or below zero on the Celsius scale. The increased temperature driving force during the cold season contributes to more substantial overdesign and hence overperformance problems unless a control mechanism has been instituted to vary the water/air flow rate as per the ambient temperature. Also, the bulk temperature of the cooling water used in power condensers is changed seasonally. This change influences the fouling rate to some extent.

H. Computational Models

The computational mesh is a description of the spatial domain in which the numerical simulation is performed, in the regions of interest a greater refinement is used, however, these days the meshing process has become the bottleneck of all the numerical simulations, to solve finer meshes, strong computational requirements are needed in the field of processing.

Case 1.

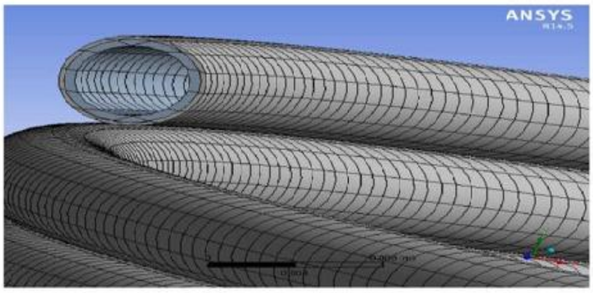


Figure 2: Meshing of condenser coil with fouling.

Case 2.

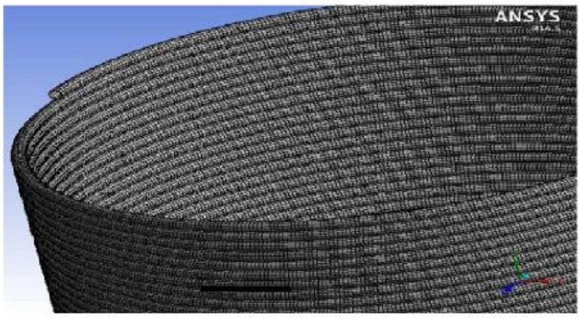


Figure 3: Meshing of condenser coil without fouling.

This is a Tetrahedral type of meshing. Figure 2 & 3 shows the meshing of the shell and tube condenser with and without fouling respectively, which is analyzed in this research work. It is recurrent to elaborate a mesh convergence, for this the Skewness tool is used, this stresses that if the values are close to zero the mesh is good and on the contrary, if these values tend to one the mesh degenerates.

IV. RESULTS AND DISCUSSION

In the simulation carried out in this study, it is the condensation process of R134a in a shell and tube exchanger with the variables obtained by analytical techniques, detailed in table 2 and observed in figure 4 & 5. Here Heat Flux carried out in simulation at different temperatures can be seen.

Case 1.

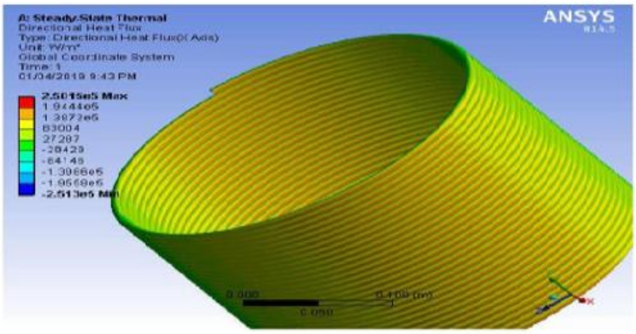


Figure 4: Heat flux with fouling/scaling

Case 2.

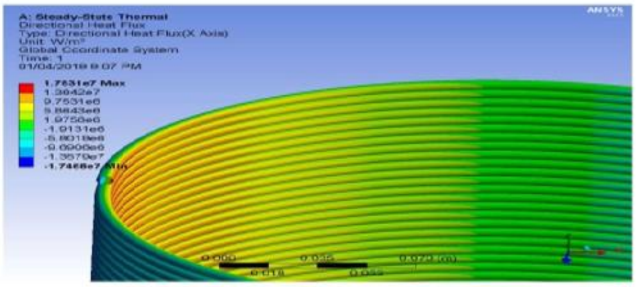


Figure 5: Heat flux without fouling/scaling

Discussing the heat flux in the simulation the heat flux rate in the condenser with scaling is less than the heat flux of the condenser without scaling. This is clear from the experimentation also that the heat transfer rate of a condenser without scaling is 12% more than that of heat transfer in a condenser with scaling.

Further simulation of steady-state thermal where the temperature can be calculated at the point on the condenser coil is taken. It is the surface temperature that is taken into consideration. Fig 6 & 7 shows steady-state thermal of with and without fouling.

Case 1.

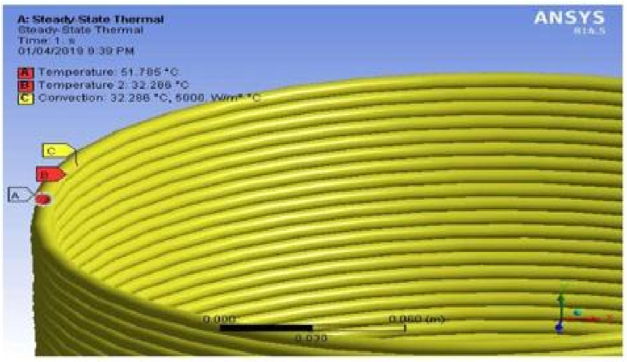


Figure 6: Steady-state thermal with fouling/scaling

Case 2.

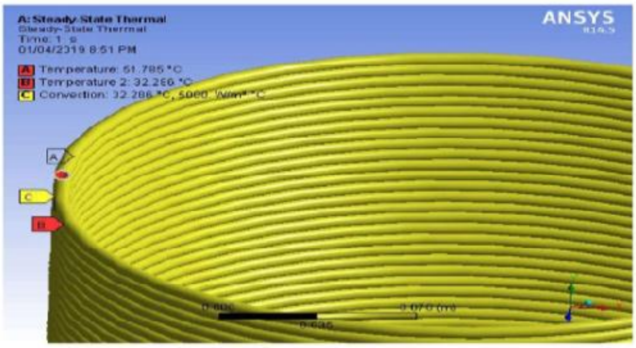


Figure 7: steady-state thermal without fouling/scaling

A different point of surface temperatures can be observed from the above figure with and without fouling steady-state thermal simulation. The point of surface temperature with fouling is less than the point of surface temperature without fouling.

There are different ways by which the fouling can be reduced in the condenser coil. Because fouling is the major factor that affects the heat transfer of the equipment and final costs increases due to this reason. Mechanical cleaning can be done by manually cleaning in 6 months during the maintenance. On other hand, there is the chemical cleaning which can be done after a few years for large equipment using inhibitors. Different types of inhibitors can be used like Benzotriazole, Sodium nitrate, Sodium benzoate, etc.

V. CONCLUSIONS

Shell and tube heat exchangers are commonly used in refrigeration, air conditioning, and the food industry as refrigerants to water condensers. And they often suffer from severe fouling issues.

- In this work, shell and tube heat exchanger was experimentally investigated as well as stimulated in ANSYS software.
- Its thermal conditions were compared with fouling and without fouling condenser coil. Parameters like heat transfer and COP were calculated. The heat transfer of fouled condenser coil was 12%less than that without the fouling condenser coil.
- As well the COP without fouled condenser was 9 % more than the fouled condenser coil.
- Material selection, Exchanger design, and fluid velocity are the factors that can lead to fouling.
- Manual cleaning as well chemical cleaning of the coil can be done by use of inhibitors to avoid fouling to some extent.

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