EXPERIMENTAL INVESTIGATIONS OF TUBE CONFIGURATION IN HORIZONTAL SURFACE CONDENSER

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Abstract— This study presents the analyses of the effect of the arrangement of tubes in a tube bundle in a horizontal, two-pass condenser on the amount of heat transferred to the circulating water in the tubes. The tube bundle is assumed to act as a staggered tube bank in cross-flow with downward superheated steam on the steam-air mixture velocity profile used. The most heat transfer occurs in the tubes rows where the steam-air mixture velocities are the highest. Furthermore, the magnitude of the velocity profile is proportional to the magnitude of the change in circulating water temperature.

INTRODUCTION

The saturated circulating water is assumed to be turbulent flow. Previously defined relationships for heat transfer through tube banks, including condensate inundation, vapor shear, and the effect of tube surface geometry are used in analyzing six tube configurations todetermine the largest change in temperature of the circulating water. The heat flux in the system is defined as a function of the condenser and tube material properties, tube geometry, tube spacing, condensate inundation and steam velocity. Numerical modeling of the six tube configurations using a Reynolds-averaged Navier-Stokes (RANS) approach is presented to confirm the analytical results results from the six configurations examined provide the optimal tube arrangement for maximum heat transfer to the circulating water. It is found that the circulating water temperature is dependent1.2 FUNCTION OF STEAM CONDENSER The function of a surface condenser is to create the lowest possible turbine or process operating back pressure while condensing steam. The condensate generated is usually recalculated back into the boiler and reused. Both of these operations are accomplished at the best efficiency consistent with the ever-present problem of economy. Surface Condenser also provides a convenient point for make up water entry and expelling point for non condensable gases.

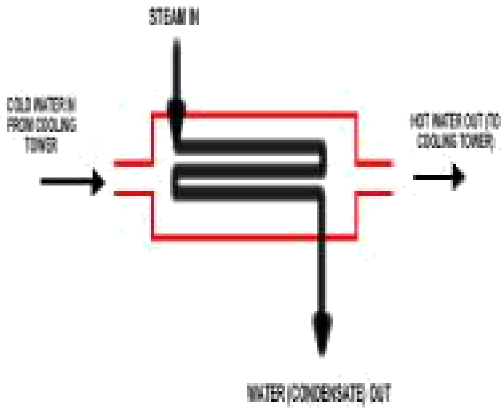

Fig.1.2 Function of Steam Condenser

1.3 CLASSIFICATION OF CONDENSERS Heat removed from a product during the refrigeration process must be disposed of. This heat can be dumped as iste or reused for space,

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water, or process heating. The section of a refrigeration system that accomplishes heat rejection is the condenser. Two types of condensers are currently available:

1.3.1 Direct Type Condenser
1.3.2 Surface Condenser

2. LITERATURE REVIEW

Several papers has been written providing heat transfer, vapor velocity, film condensation and pressure drop correlations over horizontal tube banks based on experimental results and detailed simulations using computational fluid dynamics (CFD) models.

An analysis of a two-pass condenser is performed by Malin [1] using a CFD model simulating flow and heat transfer. In Malin's work, a single-phase approach for the steam-air mixture flow within the condenser is used to calculate the performance of a condenser with a superheated steam supply.

The simulated condenser employs the use of two tube bundles of parallel staggered tubes with the first-pass entering the lower bundle and exiting the condenser through the upper tube bundle.

Browne and Bansal [2] examined variations in experimental observations made in over 70 papers to provide an overview of condensation heat transfer on horizontal tube bundles for downward flowing condensing vapor. The effects of surface geometry, condensate inundation, vapor shear and gravity are studied.

Wilson and Bassiouny [3] provided results for laminar and turbulent flow of air across a single tube row as well as staggered and in-line tube banks. The effects of flow and tube geometry on the Nusselt number, friction factor, velocity and turbulence kinetic energy profiles are presented therein.

Mehrabian [4] evaluated the heat transfer and pressure drop of air over a single, circular tube and over a tube bank based on experimental results. Additionally, a relationship between the velocity distribution of air in cross flow and pressure drop over horizontal tubes is provided.

3. PROBLEM DESCRIPTION:

The objective of this project is to analyze different tube configurations in a tube bundle to determine the best arrangement for the maximum amount of heat transferred to the circulating water in a horizontal, two-pass condenser. The six configurations shown below will be examined.

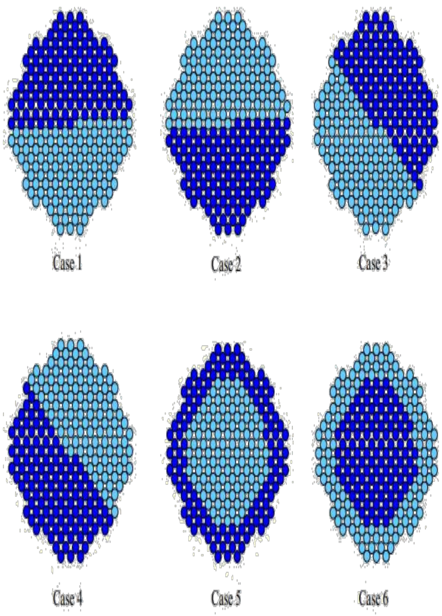

Fig. 2.1 Cross-Sectional View of Tube Configurations

The dark blue and light blue portions of the cross-sectional views in Fig. 2.1 represent the cold first-pass and warmer second-pass in the tube bundle, respectively.

4. NUMERICAL ANALYSIS - MODELING USING RANS SOLVER

FLOW3D, CFD software developed by Flow Science Inc., is used to simulate the condenser for each of the six cases. The condenser geometry, initial conditions, operating parameters and assumptions made in the heat and mass transfer algorithm, are used to create the FLOW3D models. Analyzing the condenser and tube bundle using FLOW3D generated a steam-air mixture velocity profile, which is used to confirm the velocity profile created in the heat and mass transfer algorithm.

A numerical mesh is created for each of the six cases. A large grid is generated that included the entire cross-section of the condenser. A smaller, denser grid embedded within the larger grid is created for the tube bundle. This nested grid permitted greater resolution around the individual tubes. The first-pass tubes and second-pass tubes are grouped into separate subcomponents within the nested grid. These tube regions are further arranged into separate subcomponents for Cases 3 through 6 in order to group together the tubes exhibiting similar heat fluxes and circulating water temperatures, which varied as a result of the

tube configurations. Since the subcomponents are treated as having the same properties, smaller subcomponents had properties closer to the actual properties of the individual tubes that made up each subcomponent. The average circulating water temperature and overall heat transfer coefficient is calculated for each subcomponent. In order for FLOW3D to treat the tubes as having a constant circulating water inlet temperature, fixed surface heat transfer coefficients are applied to the tubes, thus assuming the tubes are maintained at a constant temperature. This is necessary to prevent the tube inlet

circulating water temperature from converging to a higher temperature with the steam inlet temperature, preventing any heat transfer from occurring.

5. ANALYTICAL DISCURSION

The six tube configurations presented and analyzed to determine the outlet circulating water temperature using the mathematical model described. Since the tube bundle contains an odd number of tubes, the number of tubes has been divided as equally as possible in the first and second-passes to prevent the number of tubes in a particular pass from influencing the circulating water temperature

The mathematical model, based on the work of Malin [1], employs an iterative solution method to solve for the heat flux, and subsequently for the outlet circulating water temperature. Applying the algorithm to the six cases yielded values for the heat flux from the steam-air mixture to the circulating water, the outer tube wall temperature, the interface temperature and the circulating water temperature for every row of tubes in the tube bundle. The heat flux distribution through the tube bundle is analyzed by graphing the change in circulating water temperature for each row along the length of the tubes in the first and second-passes. The six cases are compared by evaluating the average circulating water temperatures of the first-pass and second-pass tubes.

An energy balance is performed for each case to validate the algorithm results. The results of the energy balance for Case 1 are provided and are representative of the results obtained from each case since the methodology presented in followed for all six cases.

The six tube configurations are modeled in FLOW3D, which provided the velocity of the steam-air mixture. The FLOW3D velocity profiles are used in the algorithm to calculate circulating water temperatures. Comparisons between the initial results from the algorithm using velocity profiles based on Mehrabian [4] and those obtained using FLOW3D data are presented

FLOW3D Velocity Magnitude Contours

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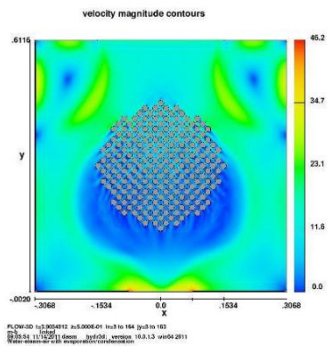
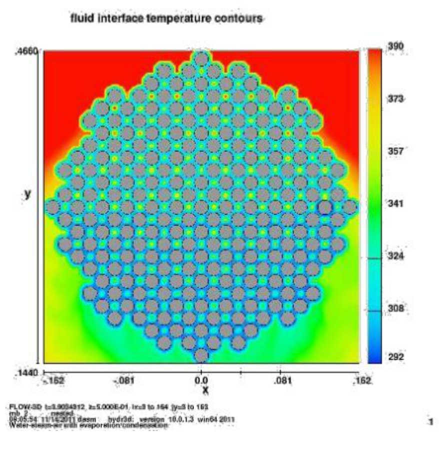


FLOW3D Mixture Temperature Contours



6.CONCLUSION

Table.5.1 Steam-Air Mixture Velocity Profiles

Steam-Air Mixture Velocity Profiles (m/s)

Mehrabn FLOW3D

R Ca Ca Ca Ca Ca
o CAse se se se se se
w Cases 1-6 1 2 3 4 5 6

1	48.20	26.74	26.74	26.77	26.72	26.82	26.68
2	68.16	26.93	26.80	26.79	26.81	26.76	26.85
3	83.48	25.58	25.84	25.84	25.84	25.79	25.87
4	96.40	23.26	23.57	23.58	23.57	23.52	23.59
5	107.78	25.33	30.17	30.14	30.12	30.18	30.24
6	118.06	24.33	24.37	24.31	24.32	24.36	24.31
7	127.52	24.01	24.04	24.01	24.01	24.07	24.10
8	136.33	19.41	19.62	19.61	19.64	19.64	19.72
9	144.60	18.92	17.43	17.34	17.38	17.33	17.08
10	152.42	18.71	18.76	18.82	18.75	18.87	18.84
11	159.86	13.71	13.93	13.98	13.91	14.03	13.98
12	166.97	13.77	13.75	13.78	13.70	14.00	13.94
13	173.78	10.49	10.57	10.46	10.48	10.72	10.69
14	180.34	10.98	11.05	10.96	10.96	10.94	10.87
15	186.67	9.79	9.90	9.72	9.74	9.75	9.62
16	192.80	9.56	9.64	9.53	9.51	9.34	9.27
17	198.73	7.64	7.80	7.60	7.61	8.23	8.23
18	204.49	7.19	7.93	7.82	7.80	8.35	8.34
19	210.09	6.19	6.77	6.54	6.55	6.87	6.81
20	215.55	6.04	6.16	6.01	6.03	6.63	6.27
21	220.87	5.28	5.85	5.53	5.49	5.97	5.93
22	226.07	4.63	5.37	5.16	5.14	5.73	5.37
23	231.15	4.77	5.12	4.72	4.67	5.18	5.12
24	236.13	4.39	4.72	4.37	4.33	5.05	4.65
25	240.99	4.64	5.08	4.49	4.48	5.18	4.90

Six unique tube configurations in a horizontal, two-pass condenser are analyzed in an iterative heat and mass transfer algorithm to determine the outlet circulating water temperature through the tubes. The algorithm considers the heat transferred from the steam-air mixture to the interface between the mixture and condensate, through the condensate, through the tube wall and into the circulating water. The algorithm also takes into account the latent heat produced by the condensate forming around the tubes. A steam-air mixture velocity profile is established using the approach taken by Mehrabian. The outlet circulating water temperature for each first-pass row is calculated and using a weighted average, a new inlet circulating water temperature is created for the second-pass tubes, from which an exit circulating water temperature is calculated.

The results using the assumed Mehrabian-based steam-air mixture velocity profile in the heat and mass transfer algorithm show that all six cases has higher outlet circulating water temperatures for the second-pass tubes than for the first-pass tubes. More heat is transferred to the first-pass tubes when these tubes are located on the bottom of the tube bundle, such as in Cases 2 and 4. Case 2 resulted in the most heat transferred to the first-pass tubes, resulting in the warmest circulating water at the outlet of the first-pass, with a temperature of 25.996°C. Case 1 resulted in the largest change in circulating water temperature from the first-pass to the second-pass with a change of 4.786°C. Overall, Case 3 resulted in the most heat transferred to the circulating water, with an average second-pass outlet temperature of 29.758°C.

The Mehrabian steam-air mixture velocity profile that is used in the algorithm could be more accurate and closer to the actual velocity in the condenser, similar to the velocity profile seen in the FLOW3D simulations, by using a different correction factor. The Mehrabian [4] approach directly increases the pressure drop, and consequently, the row velocity with each successive row, which significantly increases the velocity at higher rows. The steam-air mixture velocity profiles obtained from FLOW3D simulations of the six cases decreases as the steam-air mixture moves downward through the tube bundle, due to the tubes obstructing the mixture flow path. This velocity profile is opposite from the assumed profile based on Mehrabian. The FLOW3D velocity profiles obtained for each of the six cases are relatively similar and exhibit symmetry. Comparable to the results using the Mehrabian-based velocity profile, the results using FLOW3D data shows an increase in circulating water temperature in both the first and second-passes. Case 1 has the hottest circulating water temperature of 22.380°C at the outlet of the first-pass tubes. Case 2 has the largest change in temperature between the first and second-passes of 1.322°C. Case 5 has the hottest second-pass circulating water temperature of 23.216°C.

In comparing results calculated from the Mehrabian and FLOW3D steam-air mixture velocity profiles in the algorithm, the heat flux and circulating water temperature are found to be proportional to the velocity. As the velocity increases, the heat flux and circulating water temperature increases, consistent with thermodynamic principles. The first-pass tubes that experience the highest velocity, which are the lowest tube rows with a Mehrabian-based velocity profile (Cases 2 and 4) and the highest tube rows with a FLOW3D-based velocity profile (Cases 1 and 3), has the most heat transfer to the tubes. The tubes where the highest velocities result in the highest outlet circulating water temperature. Therefore, the velocity is proportional to the circulating water temperature.

The FLOW3D models may be refined to more accurately compare the results of the algorithm with those employing the Mehrabian approach to the steam-air mixture velocity. The FLOW3D grid that is generated is relatively coarse and the flow is assumed laminar in order to expedite simulating all six cases. A higher grid resolution and assuming a turbulent steam-air mixture flow through the bundles would each increase the predicted maximum velocity through the tubes. A grid sensitivity and/or closure model sensitivity analysis could be performed to further validate the results obtained herein.

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