ASME 2018 POWER CONFERENCE
JUNE 24-JUNE 28, 2018
BUENA VISTA, FLORIDA, USA

POWERENERGY2018-7148

CONDENSING TURBINE EXHAUST STEAM IN A STEAM SURFACE CONDENSER USING MULTIPLE SOURCES OF COOLING WATER

Ranga Nadig, Ph.D.
Maarky Thermal Systems Inc.
1415, Route 70 East, Suite 604
Cherry Hill, NJ, 08034, USA

ABSTRACT

Scarcity and restrictions in the use of cooling water has prompted power plant developers to explore multiple sources of cooling mediums to condense turbine exhaust steam in a steam surface condenser. The cooling mediums can have different chemistries dictating selection of different tube and tubesheet materials. The flowrate, inlet temperature and temperature rise for the cooling mediums can be different. Some cooling mediums may not be available during certain times of the year. The resulting steam surface condenser will include multiple smaller tube bundles of various sizes operating with different flowrates and temperatures.

The challenges in designing a condenser that employs multiple sources of cooling medium with different chemistries, flowrates and inlet temperatures are enormous. To ensure reliable operation a number of thermal, hydraulic and mechanical design issues must be carefully evaluated. Determining performance of the entire condenser at off-design conditions with variations in flowrates and inlet temperatures of one or more cooling water streams (or absence thereof) can be complicated.

This paper highlights the major concepts that need to be addressed while designing a steam surface condenser that employs multiple sources of cooling medium to condense the turbine exhaust steam. Critical thermal, hydraulic and mechanical design issues that can impact the performance and reliability of the overall condenser are addressed.

INTRODUCTION

The standard steam surface condenser uses a single source of cooling medium to condense the turbine exhaust steam. The cooling medium can be cooling tower water, water from lake or river, sea water, gray water, water from abandoned mines or from other sources. A single source of cooling water at a given flowrate, inlet temperature and temperature rise condenses the entire turbine exhaust steam. The tube and tubesheet material are selected to be compatible with the single cooling medium. The waterboxes are designed for a single operating and design pressure. The waterboxes can have a divided or non-divided construction. The condenser can be designed with one, two, three or four passes. The thermal, hydraulic and mechanical design of the condenser, with single source for cooling water, is relatively straight forward. Performance at off design operating points with varying turbine exhaust steam flow rates, cooling water flowrates and inlet temperatures for condenser with single source for cooling water are relatively easy to compute.

Multiple sources of cooling medium introduce numerous complexities into the thermal, hydraulic and mechanical design of steam surface condenser. Cooling mediums can have different water chemistries dictating the use of different tube and tubesheet materials. The operating and design pressures for each medium can be different leading to complications in the mechanical design of a single tubesheet. The flowrates and inlet temperatures for each medium may be different. This creates challenges in allocating heat transfer areas for each cooling medium. The tube bundle for each cooling medium may have different tube outer diameter, thickness and different number of passes. These variations make the thermal, hydraulic and mechanical design complicated and challenging.

Calculating the condenser performance at off design conditions is extremely complicated. Variations in flowrates, inlet temperatures of cooling mediums, absence of certain cooling mediums during certain times of the year lead to complex calculations to determine the overall thermal performance of the condenser.

To illustrate the complexities in thermal, hydraulic and mechanical design a steam surface condenser with three different sources of cooling water is selected. The design concepts can be easily extrapolated for an increase or decrease in cooling medium sources.

THERMAL, HYDRAULIC AND MECHANICAL DESIGN CONSIDERATIONS

Distribution of Heat duty

The multiple sources of cooling medium will have to condense the entire turbine exhaust steam in the condenser. The condenser will include multiple tube bundles. Each tube bundle is designed to operate with a given cooling medium. The size and configuration of each tube bundle will depend on the cooling medium chemistry, flowrate, inlet temperature and temperature rise. The length of tubes in each tube bundle will be the same.

Selection of Tube Material

Tube material selection will be based on the chemistry of each cooling medium. The cooling mediums may require different tube material. For example, first cooling medium may require 304 stainless steel tubes, the second may require 316 stainless tubes and the third cooling medium may require Duplex 2205 tubes. The steam surface condenser can be designed with different tube material for different tube bundles.

To simplify the design it is prudent to use the highest grade material for all cooling mediums. This step would simplify the design but lead to higher cost. Selecting different genres of tube materials for different cooling mediums would complicate the design even further. For example selecting Admiralty tubes for the first cooling medium, duplex 2205 stainless steel tubes for the second cooling medium and titanium tubes for the third cooling medium will lead to additional challenges in the condenser design. Restricting the tube material to a single genre such as stainless steel (304 SS, 316 SS, 317 SS, duplex 2205, Sea Cure etc.) or copper based alloys (Admiralty, 90:10 Cu:Ni, 70:30 Cu:Ni) or titanium would simplify the condenser design.

Tube Thickness

Tube material thickness is specified by the end user and is dependent on the tube material, water chemistry, operating conditions and maintenance schedules. Typical industry standard recommend the following tube thicknesses for condensing zone tubes for various tube materials:

- Admiralty Tubes: 18 BWG
- 90:10 Cu:Ni Tubes: 18 BWG or 20 BWG
- 70:30 Cu:Ni Tubes: 18 BWG or 20 BWG
- Stainless steel: 22 BWG
- Titanium: 24 BWG/25 BWG

The tube thickness in the air cooling and impingement zones can be same or thicker than that in the condensing zone. For titanium tubes it is common industry practice to use 22 BWG tubes in the impingement zone.

Dummy Tubes or Rods

Including two or three rows of 14 BWG dummy carbon steel tubes or rods in the impingement zone is mandatory. The dummy tubes or rods extend from the first support plate to the last support plate, prevent a direct line of sight between the turbine exhaust steam (or bypass steam) and the tubes. The dummy tubes or rods protect the active tubes during erection and from steam impingement during normal and bypass operation.

Tube length

The length of tubes in each tube bundle will be the same. The condenser will include smaller tube bundles for each cooling medium. The size of the tube bundle will depend on the flowrate and inlet/outlet temperature for the given cooling medium. The heat transfer surface for each cooling medium tube bundle will be different. The heat transfer surface and the tube bundle size have to be manipulated to yield a constant tube length. This can be accomplished by varying the tube velocity, tube outer diameter and the number of tube passes. The tube diameters can range anywhere from 0.75” to 1.5”. The tube velocities can vary between 6.0 ft./sec to 10.0 ft./sec depending on the tube material. The number of tube passes can vary from one pass to four pass. With the above noted variations it is, in most instances, possible to design tube bundles for multiple cooling mediums with the same tube length.

Tubesheet Design Considerations

In cylindrical condensers, as shown in Figure 1, it is typical to use a single tubesheet for all cooling mediums. The tubesheet will be in contact with multiple sources of cooling medium. The tubesheet must be compatible with the chemistry of all cooling mediums. Each cooling medium will have its own operating and design pressure. The mechanical design of the tubesheet must be based on the highest design pressure. Different cooling water operating pressures and temperatures must be accounted for in calculating the tubesheet thickness and tube-tubesheet joint pull out load. Variations in operating pressures, operating temperatures, tube material, tube diameter, differential thermal expansion between shell and tube will cause complex stress distribution in the tubesheet. These stresses should be quantified and should be in compliance with specified industry guidelines.

In cylindrical condensers, waterbox dividers that separate various cooling mediums must be firmly bolted or welded to the tubesheet and waterbox cover to ensure leak tightness. The design must prevent mixing of the cooling mediums in waterboxes.

In rectangular condensers, as illustrated in Figure 2, it is possible to include stand alone tube bundles and waterboxes for each cooling medium. This design permits the use of different tubesheet material for different cooling mediums. The tube and tubesheet material could be of different genres. For example it is possible to use copper based tubes and tubesheets for one cooling medium, stainless steel tubes and tubesheets for the second cooling medium and titanium tubes and tubesheets for the third cooling medium. The stress distribution in the tubesheet is simple when compared to that for a circular tubesheet. Separate water boxes for each cooling medium eliminate the possibility of mixing of cooling medium.

Detecting Tube Leaks

Tube bundles are typically not subjected to full tubeside hydrotest pressure in condenser manufacturer's facility. It is common practice to bolt the waterboxes together and hydrotest at the tubeside hydrotest pressure. The tube bundles are not hydrotested. Improperly rolled tubes, damage during transit, improper erection, transient or abnormal operation can lead to tube leaks. In such events it is imperative to determine the location of the tube leak and plug the leaking tube.

Location of leaking tubes can be determined by installing a conductivity sampling trough under each tubesheet and analyzing the conductivity of the condensate in the trough with a conductivity sampling meter. The trough with the spiking condensate conductivity identifies the location of the tubesheet with a tube leak. The exact tube leak can be detected by shutting the circulating water flow to the tube bundle with the tube leak, entering the waterbox and discharging smoke from a smoke gun on to the tubesheet. It should be noted that the shellside is still under vacuum. The tube that draws the smoke is the leaking tube and can be plugged.

Alternatively Helium can be introduced on the tubeside of the condenser. Helium detection at the vent connection of the evacuation package will indicate the location of the tube leak. Based on the restriction in access and power plant safety guidelines other tube leak detection techniques can be deployed.

Tubesheet-Waterbox Connection-Cylindrical Shells

It is a common industry practice to bolt the waterboxes to tubesheets. This design permits the removal of waterboxes to gain full access to the tubesheets. In cylindrical condensers with multiple cooling mediums operating at different pressures and temperatures the tubesheet is subject to complex set of loadings. Prolonged operation under such varying operating conditions could lead to leaks in the tubesheet-waterbox flange. A welded waterbox-tubesheet joint would eliminate the leaks and stiffen the tubesheet. Bolted covers could be installed on the waterboxes to provide access to tubes.

Welding of waterbox to tubesheet is not necessary in rectangular condensers as each cooling medium has its own waterbox. The tubesheets for a given cooling medium see only one set of pressures and temperatures.

Tube-Tubesheet Joints

In cylindrical condensers employing multiple cooling mediums, the single tubesheet is subject to complex set of stresses from the varying operating pressures and temperatures of the different cooling mediums. The complex bending and movement of tubesheet causes uneven loads on the tube-tubesheet joints. The stresses in the tubes should be quantified to ensure that the tube-tubesheet joint loads are within the limits specified by ASME Section VIII code. Rolled and seal welded tubes-tubesheet joints offer the highest permissible tubes-tubesheet joint load. For cylindrical condensers using multiple cooling mediums, to ensure maximum reliability, it is prudent to roll and seal weld the tube-tubesheet joint.

Support Plate Spacing

Support plate spacing is a function of tube geometry (outer diameter, thickness and material), condenser pressure and turbine exhaust steam flow and size. Support plate spacing is typically calculated per the guidelines in the HEI standards. If the tube bundles employ tubes with different diameters, thickness and materials, then the support plate distance for each tube bundle will be different. In such an event the lowest calculated support plate spacing shall be used for all tube bundles. This will ensure that the tubes across the condenser in all tube bundles are firmly supported and resistant to flow induced vibration. It is prudent to perform a vibration analysis and demonstrate that under all operating conditions the actual cross flow velocity is 50% of the critical cross flow velocity. This ensures that there is 100% margin in resistance to flow induced vibration.

Differential Thermal Expansion Between Shell and Tubes

Usage of tubes with different materials and operating temperatures will result in uneven differential thermal expansion between shell and tubes. The flexible element located on the shell neck absorbs the differential thermal expansion between the shell and the tubes. In cylindrical condensers with single set of tubesheets, the differential thermal expansion between the shell and the tubes will be distributed between the tubesheet and the flexible element. The flexible element must be carefully analyzed to quantify the distribution of the differential thermal expansion and ensure that the resulting stresses are within allowable limits.

In rectangular condensers, each cooling medium is equipped with its own tubesheets and waterboxes. As a result the differential thermal expansion for each cooling medium is absorbed by its own flexible element in the corresponding shell neck. The stresses in the tubesheet are not as complex as that in the single set of tubesheets in cylindrical condensers.

Condenser Pressure

The condenser design, at the design point, is based on the specified turbine exhaust flowrate, condenser pressure, flowrates and inlet temperatures for various cooling mediums. At other operating cases with higher flowrate of one or more cooling mediums, lower cooling medium inlet temperatures or lower turbine exhaust steam flow rates, the condenser pressure could be substantially lower than the design point pressure. The condenser pressure could be well below 1.0“ HgA.

Similarly, higher turbine exhaust steam flow, higher bypass steam flow rates, lower flowrates or absence of a cooling medium, higher inlet temperatures of cooling mediums could yield condenser pressures which are substantially higher than that at the design point.

The operating conditions that lead to low and high condenser pressures should be identified and the range of condenser pressures encountered should be carefully evaluated.

At lower condenser pressures the steam turbine should not choke. In addition, the evacuation package must be able to evacuate the non-condensible gases from the condenser at the lower range of condenser pressures.

The highest possible condenser pressure should be lower than the trip setting for the steam turbine to ensure that the steam turbine does not trip during operation. In addition the evacuation package must be able to evacuate the non-condensible gases from the condenser at the higher range of condenser pressures.

Cathodic Protection

For cylindrical condensers there will be one set of tubesheets. The tubesheet material will be common for all cooling mediums. The selected tubesheet material should be suitable for all cooling medium water chemistries. There could be instances where the tubesheet and tube material are different in a given tube bundle. In such instances, the waterbox internals should be coated with high solid epoxy, 100% solid epoxy or rubber lined. Cathodic protection (sacrificial anodes or impressed current system) should be installed, as appropriate, to protect the tubes and tubesheet. It should be noted that the design of the cathodic system could be different for different tube bundles.

Design of Air Channel and Subcooling of Air Vapor Mixture

Tube bundle for each cooling medium should be equipped with its own air cooling zone and air outlet connection. The air cooling zone should be located in the cold pass. The number of tubes in the air cooling zone for a given tube bundle should be proportional to the turbine exhaust steam condensed by the tube bundle.

The purpose of the air cooling zone is to subcool the air vapor mixture by 7.5°F. Variations in cooling medium inlet temperature will lead to varying subcooling of the air vapor mixture in the air cooling zone. Air outlet connections from different tube bundles will discharge air vapor mixture at different temperatures. The resultant air vapor mixture temperature after mixing must be calculated. The evacuation package should be designed to evacuate the air vapor mixture from the condenser at the resultant temperature. Alternatively, the evacuation package could be designed to evacuate the air vapor mixture at the highest temperature or the lowest amount of subcooling.

Removing Non-Condensible Gases from the Condenser

The condenser is equipped with multiple tube bundles. At any given time one or more cooling medium may not be available as a result one or more tube bundles may not be in operation. Each tube bundle must be equipped with its own air channel and an air outlet connection. Each air outlet connection must be equipped with an isolation valve. The isolation valve must be closed when tube bundle is not in operation.

The air outlet connections from different tube bundles should be manifolded into a single connection and routed to the evacuation package. The pressure drop in the air outlet piping from the condenser to the evacuation package should not exceed 0.1” Hg.

Steam jet air ejector packages or liquid ring vacuum pumps can be used to evacuate non-condensible gases from the condenser. The evacuation package must be designed to evacuate the non-condensible gases from the condenser over the entire range of operation.

For condensers with multiple cooling mediums, steam jet air ejector packages are recommended as they are independent of the circulating water flowrate, chemistry and inlet temperature. The hotwell condensate flowing through the inter and after condenser condenses the steam from the steam-air mixture discharged from the first and second stage ejectors.

The evacuation capacity of the vacuum pump is dependent on the condenser pressure and the cooling medium inlet temperature. The cooling medium which is anticipated to be available permanently or most of the time should be used to cool the seal water in the seal water heat exchanger. The vacuum pump design should be based on the permanently available cooling medium inlet temperature, the minimum subcooling of the air outlet mixture and the minimum condenser pressure.

CONCLUSION

Turbine exhaust steam can be condensed in a steam surface condenser using multiple sources of cooling medium. Provisions can be incorporated so as to permit the condenser to operate with one or more sources of cooling mediums out of service. Extreme care must be exercised in designing the shell side and tubeside internals so as to accommodate differences in flowrates, inlet temperatures and the chemistry of cooling mediums. All operating scenarios must be evaluated. Removal of non-condensible gases from the condenser by the evacuation package must be carefully addressed. Proper startup, operating, trouble shooting and maintenance guidelines must be established to ensure that the condenser operates reliably under the specified range of operating scenarios.

REFRERENCES

[1] Heat Exchange Institute: Standards for Steam Surface Condensers, Eleventh Edition

FIGURE 1
CYLINDRICAL TUBE BUNDLE DESIGN

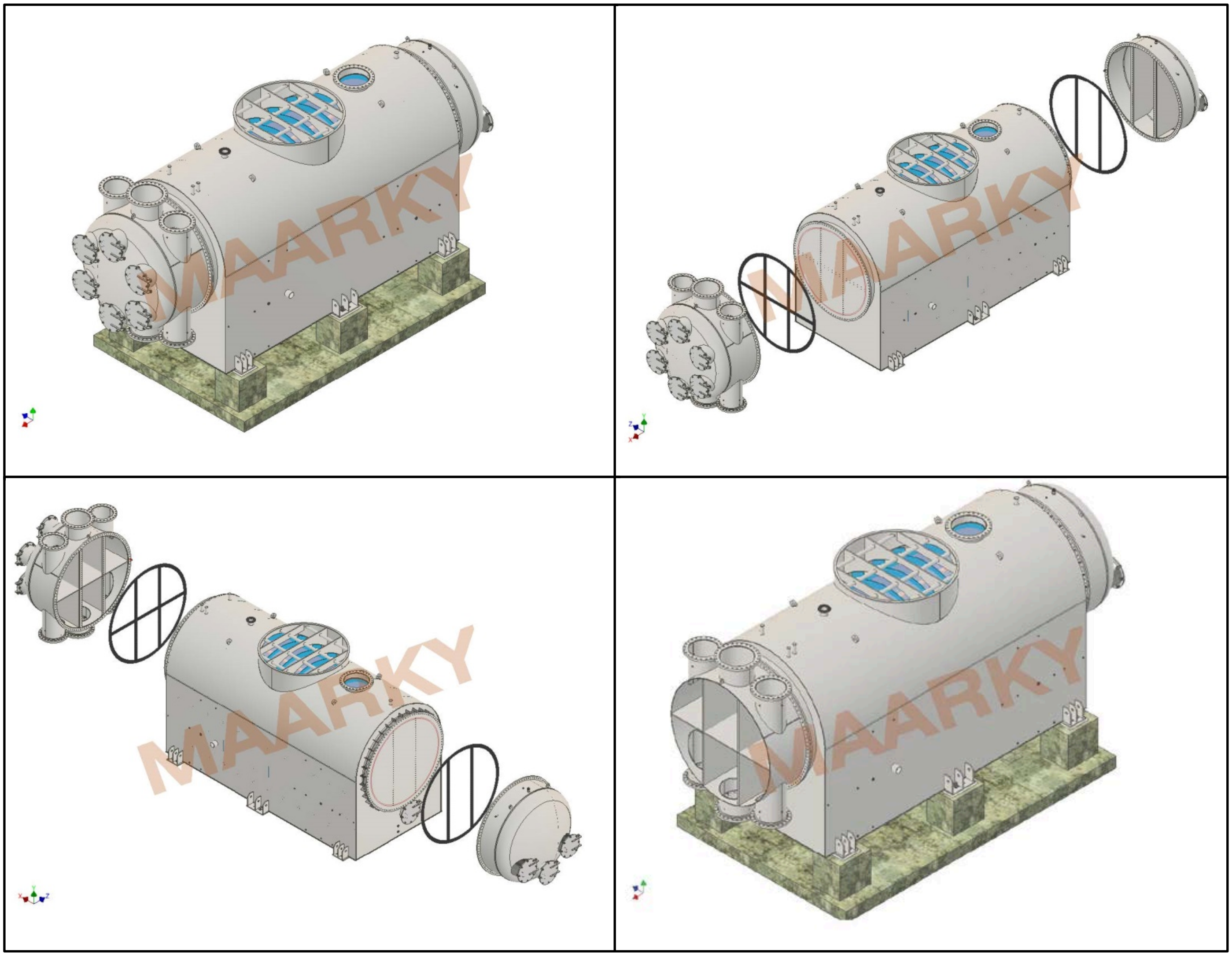

FIGURE 2
RECTANGULAR TUBE BUNDLE DESIGN