Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 29-30, 2015

Condenser Design for the Proposed AM600 NPP

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1. Introduction

Analysis of global electric markets shows that the electrical grid size of many developing countries (e.g., Bangladesh, Kenya, Vietnam, Egypt) is too small or too distributed to accommodate Nuclear Power Plants (NPP) with large unit sizes (e.g., >1000 MWe). Thus a modern NPP design with a smaller output (~600 MWe) is of interest. The 'AM600' represents the Balance of Plant (BOP) turbine cycle for such a unit. The condenser design for the proposed AM600 is addressed here. The design goals are to make the condenser more robust and compact with a reduced component count. The AM600 condenser design also has new features as described below.

Considering that the minimum heat sink temperature for potentially emergent nuclear countries is on the order of 21^{o}C or higher, a turbine design with a single low pressure rotor can be considered without sacrificing thermal efficiency. The condenser back pressure range for the considered markets is on the order of 2 to 3 in-HgA. With these boundary conditions, the AM600 condenser duty can be met with a single pressure zone design with a total of eight (8) titanium tube bundles (four (4) per pass) divided into four isolable sections. Due to the compact design (i.e., accepting exhaust from only one low pressure cylinder), both axial ends of the condenser are unobstructed and available for attachment of extended flash chambers, diverting inflows away from the tube bundles. This design permits all drains and bypass steam to be fed into these chambers, reducing hotwell flow and allowing for isolation of individual sections of the condenser in the event of a tube leak.

A steam surface condenser is a type of heat exchanger in which vapors are converted into the liquid state by removal of latent heat via condensation on water filled tube surfaces. Such condensers are typically designed with one or two passes. Two-pass condensers have the potential for a higher temperature range but require greater transfer surface for equal performance of the single-pass. The two-pass condenser is generally more economical in a closed loop cooling application while the single-pass is frequently selected for once through installations. Utility scale condensers designed with more than two-passes are usually uneconomical. Typical arrangements for the condenser and circulating water cooling system are illustrated in Fig.'s 1 and 2.

Selection of condenser tube material represents a critical design decision. Material impacts not only heat transfer, fouling, and long term reliability but it also can affect steam generator degradation. For example in the case of copper tubing, copper transport from the condenser to other steam cycle components, can permanently reduce plant output and impact the life of major components.

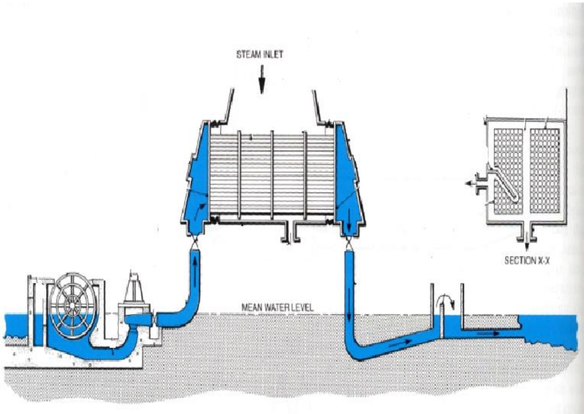

Fig. 1. Steam surface condenser – once through [1]

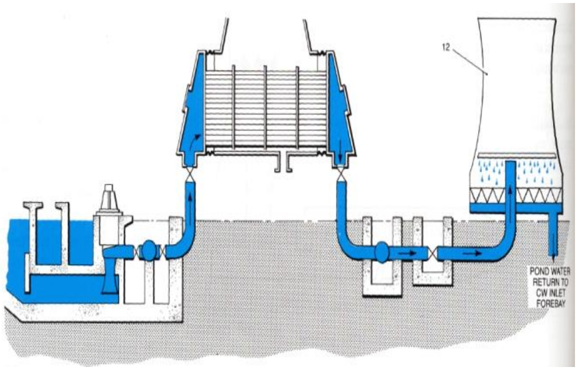

Fig. 2. Steam surface condenser – closed loop [1]

The hotwell of a condenser is designed to collect the condensed steam. The AM600 hotwell is divided into four sections. Each section is independently monitored for tube leaks (i.e., chlorides) and can be isolated on such an indication. The AM600 hotwell volume is designed for a minimum of three minutes of rated condensate flow [2].

An added feature of the AM600 design is the inclusion of large flash chambers on each end along the axis of the turbine. This is possible since the low pressure turbine is designed with only a single cylinder. All the drains, vents, bypasses, and dumps from various services within the turbine cycle are routed to these chambers. Retained water after these inflows flash is confined within the chambers and routed directly to the suction header for the condensate pump, bypassing the main condenser hotwell. Flashed steam is routed to the condenser bundles through the sparger end of these chambers.

Air removal for the AM600 condenser design is proposed as standard design using vacuum pumps. Since this approach is well proven it is not given further consideration in this paper.

Erosion and corrosion failures of tubing can represent a concern with operating condensers. However, the AM600 uses the industry standard specification of Titanium (Ti) tubing. Therefore, these issues do not require review here.

The specification for support plate spacing requires tube vibration analysis. Over the years, many different vibration methodologies have been developed to calculate a "safe span" that results in no tube damage due to fretting fatigue or midspan collisions. HEI [3] considers two methods, with the first referred to as the tube spacing (ligament) method. In the tube spacing method, it is assumed that the steam will achieve sonic velocity (either due to very cold heat sink temperatures, or due to shutting down a waterbox, etc.), resulting in tube vibration. The tube span between support plates is adjusted to keep the vibration amplitude equal to or less than one-third of the interstitial tube spacing. This design criterion ensures that a minimum clearance of one-third of the ligament is maintained preventing tube-to-tube collisions. The second method, extracted from the MacDuff and Fegler method (M-F) compares the natural frequency of the tube versus that associated with vortex shedding and fluid elastic whirling. To be conservative, the designer should use the shorter of the two spans.

The spacing of tube support plates depends on analysis of tube vibration, but in practice the maximum dimension should not exceed 60 tube diameters. Due to the extreme resistance of Ti tubing material to corrosion, it is industry practice to specific very thin tube walls (e.g., 23 to 25 ga.). In fact the limiting tube wall is typically associated with handling and fabrication of bundles and not with internal pressure or corrosion or erosion allowance. From this consideration, the recommended maximum spacing for Ti tubes can be as low as 35 tube diameters. This will often satisfy the criteria for freedom from fundamental frequency vibration for both machine and steam-flow-induced sources [4]

In an alternative method, tube vibration is analyzed by computing the severity factor (maximum value for safe operation is 1) according to Peak [5] and Coit [6]. Both results show nearly identical results. The AM600 exhaust flange velocity for backpressures of 1.5 in-Hg and 3 in-Hg are 1014 ft/sec and 590 ft/sec, respectively. A tube span (i.e., support plate spacing interval of 30-in) results in a severity factor which meets all criteria.

2. Physical Arrangement and the Bundle Layout

The physical arrangement of the condenser bundles is shown in the following figures. The schematic orientation with other interfacing systems and components is shown in Fig. 3. The tube bundles and tube sheets are shown in Fig.'s 4 and 5, respectively. Fig.'s 6 and 7 show the condenser tube bundles with the interfacing flash chambers.

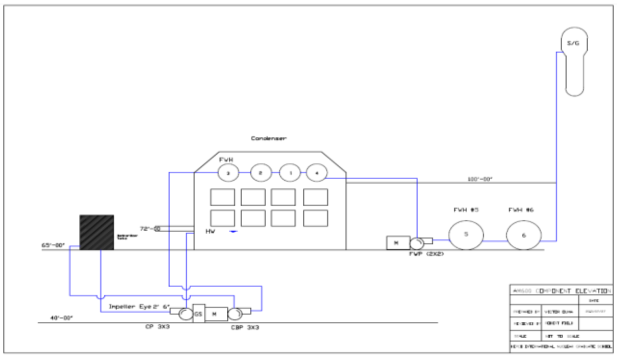

Fig. 3. Schematic arrangement of the AM600 condenser

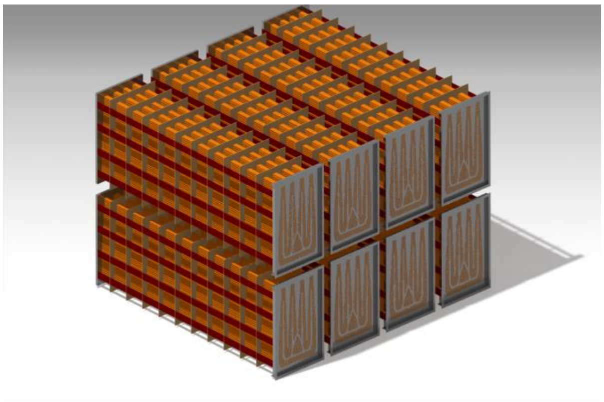

Fig.4. Condenser tube bundle layout

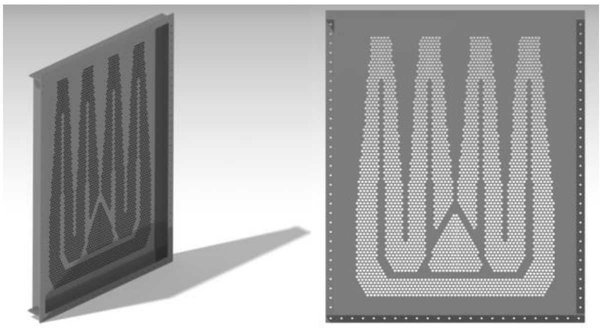

Fig. 5. Condenser tube sheet hole pattern

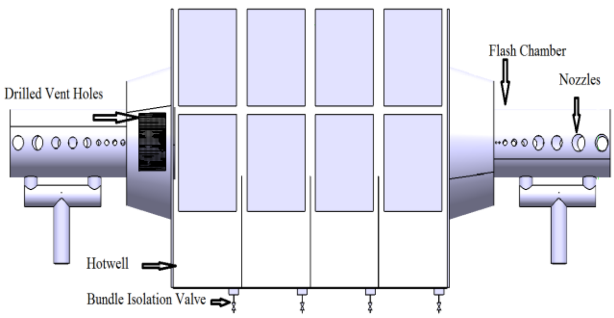

Fig. 6. Condenser with flash chamber extensions

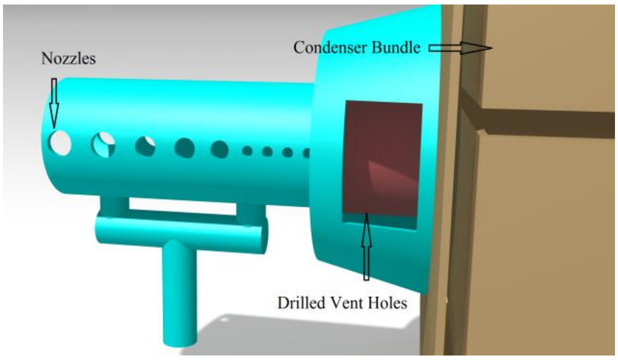

Fig. 7. Flash chamber with main sparger, drilled vent holes

It is expected that all dumps, bypasses, drains, and vents will be routed to the flash chambers. This will result in the following advantages:

(i) simplified fabrication with improved design for nozzle reinforcement,

(ii) simplified erection,

(iii) reduced component counts, including a reduced number of impingement plates and spargers,

(iv) reduced potential for high velocity steam flows due to these sources,

(v) ability to isolate condenser zones in the event of a tube leak,

(vi) reduced potential for Subcooling (i.e., slight potential for superheat in 1^{st} point heater drains flow to condensate pumps),

(vii) improved flow distribution to condensate pump suction header, and

(viii) simplified access, maintenance, and inspections.

The flash chambers are designed to be flush with the condenser outer wall where they are capped off with a solid end plate. Flashing steam leaves the flash chambers through a drilled, full diameter sparger segment [Fig.7]. This end segment is enclosed within a conical extension of the condenser outer wall to turn and introduce the steam flow leaving the sparger to the tube bundles.

3. Results and Analysis

Key parameters related to condenser design include:

(i) condenser heat load,

(ii) desired condenser backpressure,

(iii) cold water temperature,

(iv) water velocity inside condenser tubes,

(v) condenser tube diameter,

(vi) condenser tube length,

(vii) tube material and thickness, and

(viii) condenser tube cleanliness factor.

The heat load calculation and sizing is based on the methods per HEI [3].

The design heat load is taken from the AM600 maximum calculated heat balance.

The design value for minimum heat sink temperature has a significant influence on the condenser size and cost. For a given design value for condenser pressure, high heat sink temperatures result in an expected increase in the condenser surface area and thus an increase in the initial investment.

In general, the selection of a longer tube will result in less cooling water required and a decrease in the pumping power. Also, the condenser surface will increase as the tube length increases. One challenge with longer tubes is the unbalanced cooling along the length of the tube. This has resulted in tube vibration damage due to longitudinal flows in some designs.

Cooling water velocity is a prime consideration in condenser design. Water inlet velocities in condenser tubes are usually limited to a maximum 8-ft/s to minimize erosion, and a minimum of 5 or 6-ft/s for optimal heat transfer. Values between 7 and 8-ft/s are most common [7]. For titanium tubing, lower velocities are recommended.

Table I – AM600 condenser design parameters

Parameter	Value
Number of passes	2
Number of bundles	8
Back pressure range	1.5 - 3.0 in HgA
CW inlet temp range	21 - 30^{0}C
Tube velocity	2.1 m/s
Flow rate	79,500 m^3/hr
Ti tube OD	1.25 in
Tube wall gauge	24 BWG
Total number of tubes	28,000
Number of tubes per pass	14,000
Number of tubes per bundle	3,500
Active tube length	12.2 m
Total surface area	34,000 m^2
U_1^*	695.4 BTU/ft^2-^{o}F-hr
F_w / F_m / F_c^*	1.054 / 0.94 / 0.75
Condenser heat load	4.083E+09 BTU/hr
TTD 1^{st} pass/2^{nd} pass (winter)	13.4 / 8.1 ^{0}C
TTD 1^{st} pass/2^{nd} pass (summer)	11.5 / 6.7^{0}C

* For definition of parameters see reference [7]

Historically, nuclear steam cycle condenser tubing has been specified in a range of 7/8 to 1-1/4-in OD. Smaller diameters permit a more compact bundle design, lower circulating water flows, and less pumping power. However, smaller diameter tubes: (i) require more tubes for the required surface area, (ii) are much more subject to blockage, and (iii) have shorter required tube spans. Since most of the targeted locations for the AM600 have access to sea water cooling, circulating water flow is not considered to be a limitation. Thus a high flow, large diameter tube design is considered here. Note that large diameter tubing results in reduced fabrication cost by greatly reducing the number of tubes, reducing the associated drilling and end connections, and through greater stiffness (thus reducing the number of tube support plates).

The most commonly specified cleanliness factor for new condenser design is 85% [6]. Operating performance indicates that this value is achievable but online tube cleaning systems and regular chemical treatment (e.g., biocide) may be required to maintain this level of performance.

3.1 Back Pressure Analysis

Condenser backpressure plays a key important role in determining the efficiency of the plant. Condenser TTD is the difference between the steam side saturation temperature and temperature of the hot circulating water leaving the condenser. The higher the condenser TTD, the higher the condenser backpressure. Condensers designed to interface with once-through cooling systems, particularly in colder climates, are often designed with a high terminal temperature difference (TTD). As the condenser inlet water temperature and consequently the condenser pressure decreases, the steam turbine-generator output increases. However, depending on the turbine design, at some low condenser pressure, the electrical output peaks and may even start decrease with a further reduction in condenser pressure. To avoid operation at these very low exhaust pressures, condensers which are designed for operation in once-through systems are often designed with higher TTDs than condensers designed for operation in closed-loop systems (e.g., cooling tower).

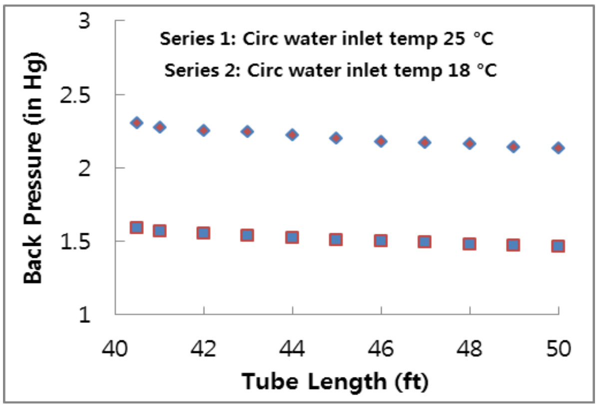

Fig. 8. Condenser backpressure vs. tube length

The effects of tube length (and surface) on back pressure for two different inlet temperatures are shown in Fig. 8. This figure illustrates that condenser backpressure is not overly sensitive to tube length for (and condenser surface area) for the considered range. Thus in the absence of current market pricing for manufactured Ti tubes and vendor bids for fabrication, the tube length is selected as 40-ft, with longer or shorter lengths considered to be cost neutral when considering upfront capital and thermal efficiency.

For the 40-ft tube length and a given circulating water flow, Fig. 9 examines the condenser backpressure versus the number of tubes.

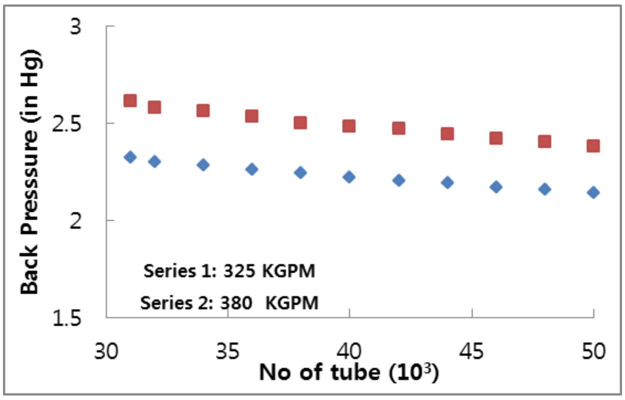

Fig. 9. Changes in back pressure with number of tubes

Fig.'s 10 and 11 illustrate the functional dependence of backpressure for a variation in heat load and circulating water inlet temperature.

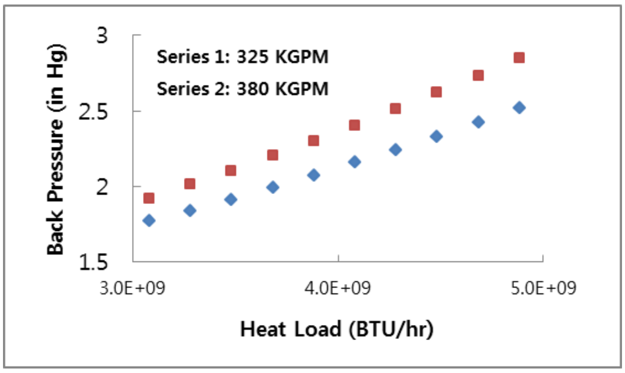

Fig. 10. Changes of backpressure with heat load

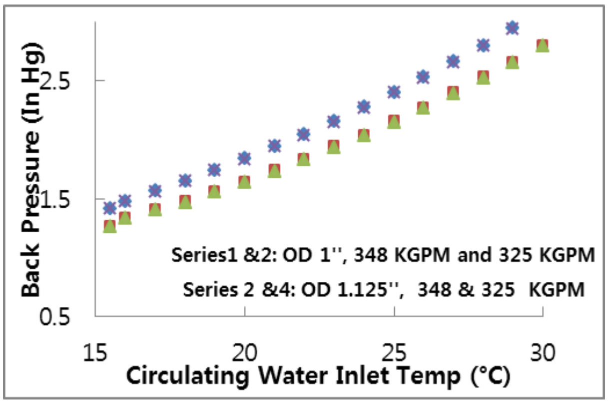

Fig. 11. Variation of condenser backpressure with circulating water inlet temperature

4. Conclusions

By considering load flow on the electrical grid, a smaller size NPP may be more suitable to meet growing demands for electricity in developing countries. From analysis of heat sink temperatures for target countries along with other factors, the AM600 is designed with a single cylinder, two-flow low pressure turbine. For this design, the optimum parameters for the condenser are specified here. The single shell design of this condenser then allows for an innovative design feature, namely the extended flash chambers. This permits the routing of dump, drain, vent, and bypass flows directly to these chambers, bypassing the condenser shell. Within the condenser shell, this design eliminates impingement plates, impingement boxes, and spargers. Failure of these components represents an ongoing source of condenser tube damage in operating nuclear units, requiring significant resources for outage inspections. The extended flash chamber approach also has a number of other advantages as delineated above. These relate to cost, simplicity, reduced inspections, and robust design.

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