Susceptibility of CANDU® Steam Generator Preheater to Cavitation Erosion

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ABSTRACT

In 2009, Darlington Steam Generator (SG) tube inspections revealed some tubes had degraded in the preheater. The tube degradation occurred at the clearance gap between the tube and the preheater baffle and reached up to 50% through-wall depth at the baffles in the middle portion of the preheater. The general pattern of the damage and the elemental composition analysis suggested that the degradation was the result of a hydrodynamic process, such as cavitation erosion.

Cavitation erosion occurs when vapour bubbles exist or form in the flowing liquid and then these bubbles collapse violently in the vicinity of the wall. These bubbles collapse when steam bubbles contact water that is sufficiently subcooled, below the saturation temperature. In the gap between the tube and the preheater baffle, low flow will exist due to the pressure difference across the baffle plate. In addition, heat transfer occurs from the primary-side fluid to the secondary-side fluid within this clearance gap that is driven by the primary-to-secondary temperature difference. Factors, such as the tube position in the baffle hole and fouling, influence the local conditions and can cause subcooled boiling that result in cavitation.

This paper presents a study of flow and heat transfer phenomena to determine the factors contributing to cavitation erosion in SG preheaters. The analysis used the THIRST[1] code for a 3-dimensional thermalhydraulic simulation of the steam generators and the ANSYS FLUENT®[2] code for detailed calculations of flow and heat transfer in the clearance gaps. This study identifies that tubes in the preheater region are susceptible to cavitation erosion and indicates that this area should be part of the station inspection program because, regardless of preheater design, some tubes may experience the thermalhydraulic conditions and undergo degradations similar to those observed for the tubes in Darlington SGs.

1. INTRODUCTION

Inspections in 2009 showed that tubes were degraded in the SG preheater of the Darlington Nuclear Generating Station (DNGS) [1]. Tube wall thickness was reduced at elevations of the baffle plates in many regions of the preheater. The degradation occurred on the outside of the tube, near the top surface of the baffles and reached up to 50% through-wall. The tube degradation coincided with the clearance gap between the tube and the preheater baffle hole. In this gap, there is low flow due to the low pressure difference across the baffle plate which reduced the efficiency of the preheater heat transfer. Also, in the clearance gap, heat transfer occurs between the primary side fluid (heavy water) and the secondary side fluid (light water) and is driven by the primary-to-secondary temperature difference.

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1 THIRST stands for the ThermalHydraulic In Recirculating Steam Generators.

2 ANSYS FLUENT® is a registered trademark of ANSYS, Inc.

The SG preheater increases the thermal output of the SG by heating the feedwater while cooling the primary water before it returns to the reactor. The DNGS preheater consists of 1 thermal plate and 10 windowed baffle plates. In the preheater, the feedwater is heated from 177ºC to saturation temperature (265ºC for 5.09 MPa)[3] while the heavy water is cooled from 278ºC at the top of the preheater to 265ºC at the thermal plate elevation. Under certain heat transfer conditions, boiling may occur on the outer tube surface and the resulting steam bubbles may move up through the gap. Because the steam bubbles mix with the colder secondary side fluid in the gap or just above the baffle plate, condensation of the bubbles occurs, possibly resulting in cavitation and cavitation erosion.

Cavitation erosion occurs when vapour bubbles exist in the flowing liquid and then collapse in the vicinity of the wall. Bubbles collapse if the ambient pressure around them is greater than the vapour pressure or if steam bubbles mix with water that is sufficiently subcooled. Material damage occurs when the bubbles collapse in a very short time, which could be of the order of hundreds of microseconds, and form liquid microjets that hit the surrounding solid surface at high speed. According to recent measurements, the velocities can be as high as 500 m/s [2]. In subcooled boiling, cavitation erosion is usually negligible because the driving force, or temperature difference, for bubble collapse is small. However, under high heat flux conditions, subcooled boiling was reported to result in erosion [3].

This paper presents a numerical analysis of flow, heat transfer phenomena in the preheater and the clearance gap to examine the possibility of cavitation and cavitation degradation in the Darlington SG preheaters with windowed baffles. Since other CANDU® SGs have segmented baffles in the internal preheater or external preheaters, in which this "tube to baffle plate" gap also exists, the evaluation if these preheater are susceptible to cavitation are also performed. The THIRST code was used to predict the flow field, pressure drop, and primary and secondary side temperature distributions in the SG, including the preheater. The ANSYS FLUENT code [4] was used to obtain a detailed temperature distribution in the gap that was used to conclude if subcooled boiling could occur by comparing the local fluid temperature with the saturation temperature. The ANSYS FLUENT cases use boundary conditions from the THIRST calculations.

2. FACTORS AFFECTING FLOW AND HEAT TRANSFER IN CLEARANCE GAP

The orientation of the tube in the baffle hole affects the flow and heat transfer through the clearance gap. Manufacture, assembly and operating conditions can cause the tube eccentric, even to touch the baffle plate, or at any location within this hole with a small inclination angle as shown in Figure 1, away from the exact concentric geometry. For eccentric or inclined tubes, the heat flux can be increased locally in the certain region and then increases the likelihood of boiling in comparison to a concentric tube.

[3] This value is approximate for the preheater as the saturation temperature depends on the local pressure.

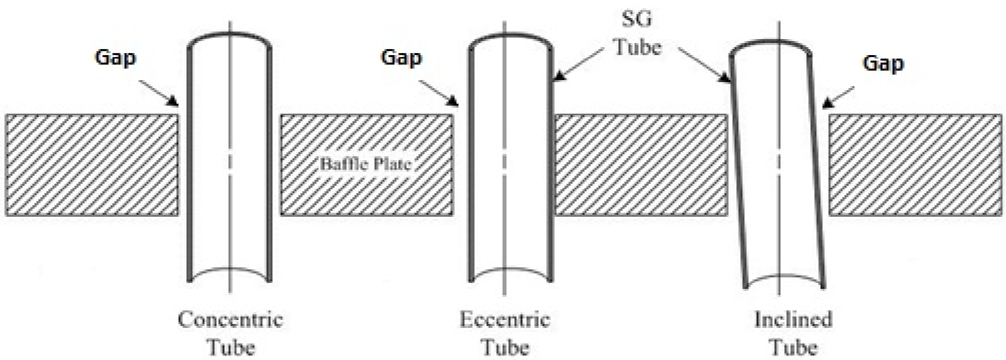

Figure 1. Tube alignments in clearance gap.

Fouling also plays an important role in the flow and heat transfer in the gaps. Fouling particles can deposit on the inner surface of the tube or the outer surface of the tube or on the baffle plate surface. Fouling on the tube reduces the heat flux through the wall and, therefore, reduces the likelihood of boiling while fouling on the baffle hole surface reduces the flow rate through the gap, and therefore, increases the likelihood of boiling. Reference [5] reports that secondary side fouling occurs on tube support plates, rather than on the tubes and suggests that fouling deposits occur near the gap entrance where the flow gets into gap and are caused by the electrical forces created by the flow in the clearance gap. In the extreme case, secondary-side fouling can block the gap completely and flow is reduced to zero thus eliminating the possibility of cavitation in the gap.

It is of great interest to know whether the observed degradation is self-limiting, proceeds at a constant rate, or the rate accelerates with time. Plant evidence suggests the degradation it is self-limiting. First indications of degradation come from tube inspections in 2001 [6]. This example suggests that the cavitation erosion rate is not high and may be self-limiting. Fouling, which continues over time, reduces the flow rate through the gap and can block the flow, thus, eliminate boiling. Without boiling in the gaps, there is no cavitation and no cavitation erosion. This hypothesis can explain the temporal behaviour of the degradation at the station but needs further verification.

3. NUMERICAL ANALYSIS

The THIRST code was used to analyze the thermalhydraulic conditions in the SG with a finer mesh of the preheater. This finite difference code solves the conservation equations for continuity, momentum, and energy inside the SG shell between the tubesheet and the separator deck. Three-dimensional distributions of pressure, velocity, temperature, steam quality, and void fraction are provided for the whole SG. However, THIRST cannot model flow and heat transfer in the baffle clearance gaps. The code assumes the hydraulic resistance of the baffle that is a function of the clearance width, but ignores individual clearances. Therefore, THIRST provides the local conditions in the preheater that can be used as boundary conditions for the thermalhydraulic calculations inside the clearance gap by ANSYS FLUENT.

ANSYS FLUENT is a commercial Computational Fluid Dynamics (CFD) code based on finite volume method [4]. It can solve the governing equations of continuity, momentum, and energy for the flow and heat transfer under various conditions. In the present analysis, the code was used to determine whether boiling can occur in the clearance gaps under various scenarios such as different degree of fouling inside the tube and outside the tube, tube eccentricity, and tube inclination angle. Also, the code was used to analyze the gaps in various baffles at various locations using boundary conditions provided by THIRST results.

3.1 DNGS preheaters: THIRST calculation

The thermalhydraulic performance of Darlington SGs for 100% reactor power is simulated using the THIRST code. The DNGS preheater consists of 1 thermal plate and 10 windowed baffles as shown in Figure 2 (left). In this paper, the thermal plate is labeled P01 and baffle plates are labeled P02, P03, etc., up to P11.

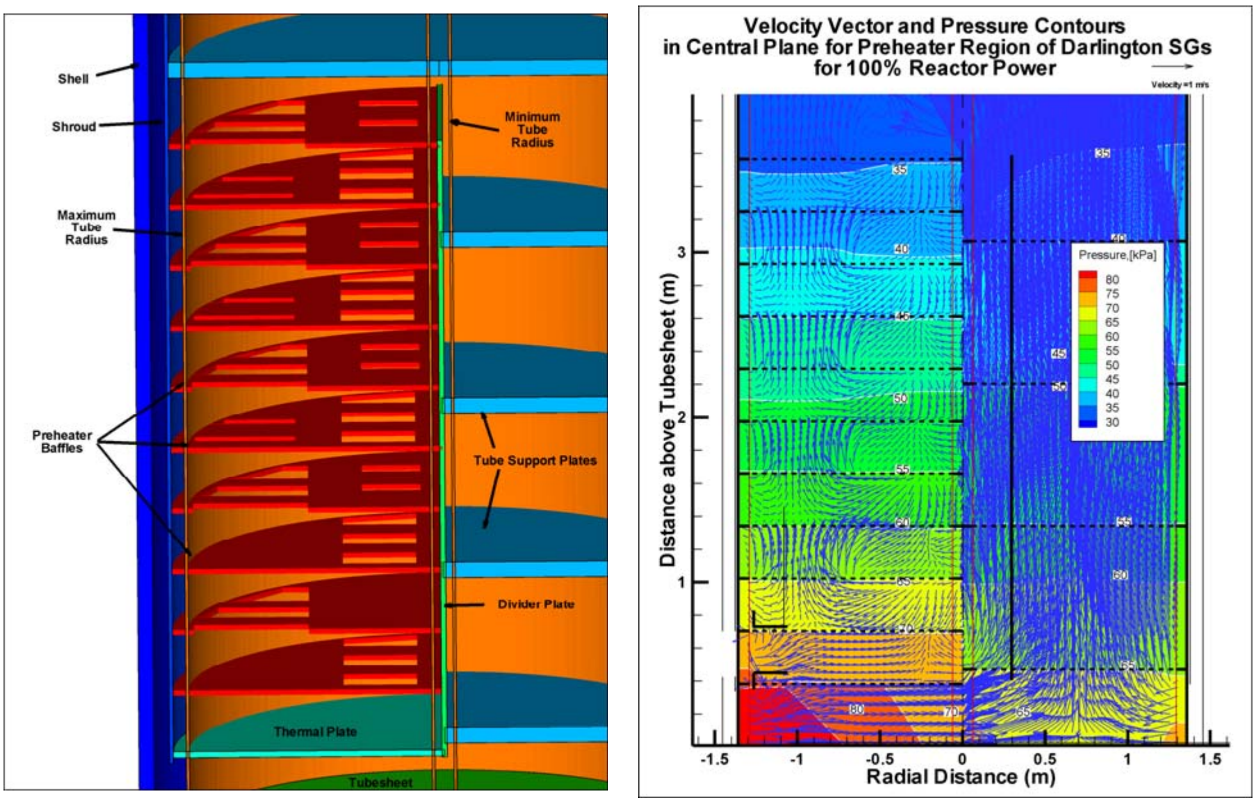

Figure 2. Darlington SG geometry (left) and velocity and pressure results from THIRST (right).

The velocity vectors and pressure[4] contours of the DNGS preheater are obtained from THIRST calculation and given in Figure 2 (right), showing the SG plane of symmetry with the focus on the preheater. For easier reference, the major geometrical structures, such as baffles, shroud, shell, and inlet nozzle, are drawn. The pressure reduces from the inlet of the preheater to the exit as the flow passes through the baffles. A recirculation zone, shown by downward flow, is seen between every second baffle - P02 and P03, P04 and P05, P06 and P07, P08 and P09, and P10 and P11. Despite the fact that the flow at the central plane in the recirculation zones is

[4] The plotted pressure is relative to the pressure at the reference. This reference point is at the plane of symmetry in the downcomer at an axial elevation equal to the elevation of the primary separator deck.

downward, the flow through the gap clearances is upward. These zones exist mostly at the central plane of the SG and do not exist at locations further away from this central plane.

In the preheater for 100% power, the feedwater is heated from 177ºC to saturation temperature (265ºC for 5.09 MPa)[5] where the flow is determined by the structure of the windowed baffles. The heavy water is cooled from 278ºC at the top of the preheater to 265ºC at the thermal plate elevation. The primary and secondary temperature distributions predicted by THIRST are presented in Figure 3. Under certain heat transfer conditions, boiling may occur on the outer tube surface and the steam bubbles move up through a clearance gap of 0.26 mm width. Because the steam bubbles mix with the colder secondary side fluid in the gap or just above the baffle plate, condensation of the bubbles occurs, possibly resulting in cavitation and cavitation erosion.

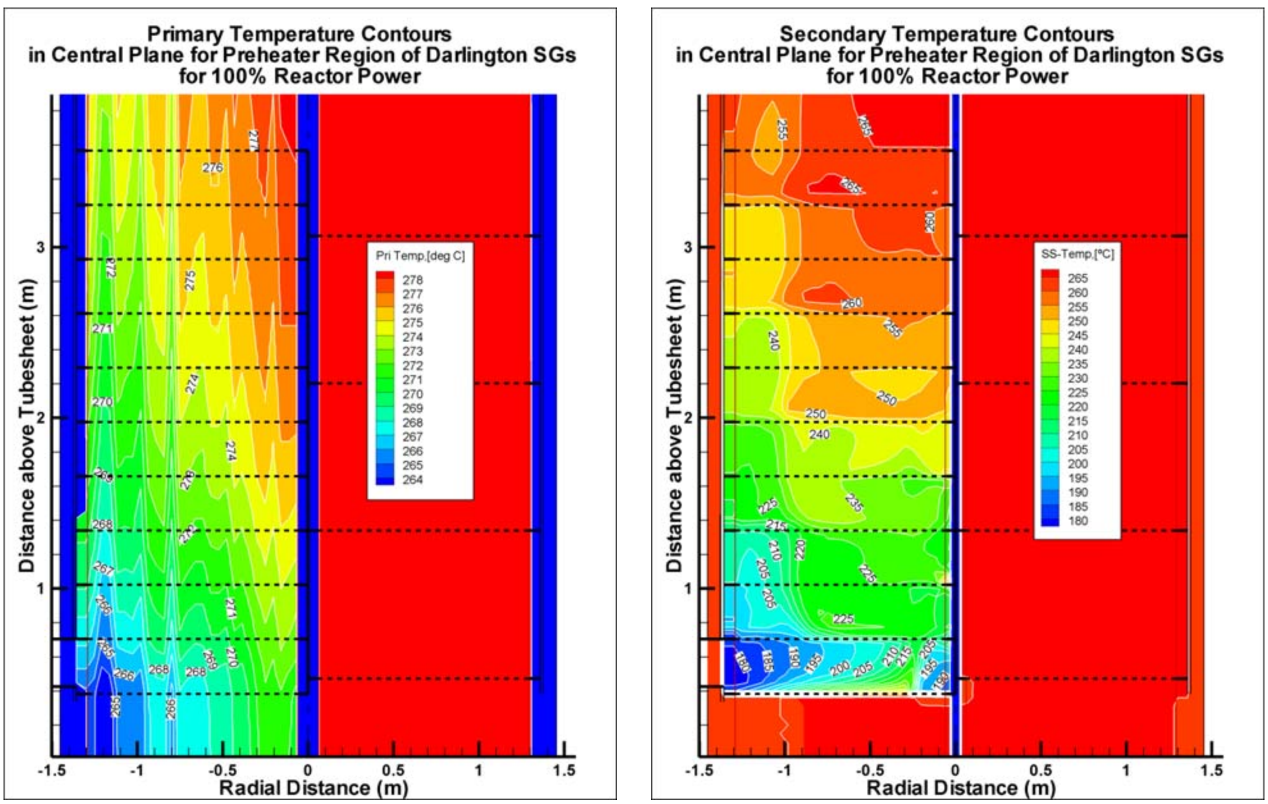

Figure 3. Primary (left) and secondary (right) temperature distributions predicted by THIRST

5 This value is approximate for the preheater as the saturation temperature depends on the local pressure.

3.2 Clearance gap: FLUENT calculation

ANSYS FLUENT was used to analyze the temperature distribution within the gap clearance to identify the onset of boiling as a function of mass flow rate, primary and secondary side tube fouling, and tube eccentricity and inclination. For the present model, the flow is assumed single phase and steady state. The assumption of single phase is used because the objective of this analysis is to detect the onset of boiling.

Therefore, the results of the analysis are valid for cases where the boiling region is small and will not have significant effect on the overall single phase flow. The fluid in the gap is light water. Boiling begins when the tube surface temperature exceeds the saturation temperature by 2ºC of wall superheat [7]. Because the models assume single phase flow in the gap, the results are correct for water flows including the onset of boiling. Where there is boiling, cavitation is possible.

A tube located in the bundle periphery adjacent to the central-tube-free lane at P05 was selected for this analysis as a reference case, since this location had tubes with significant degradation [1]. The analysis is focused on flow and heat transfer in the clearance gap with the concentric tube and its geometry and boundary conditions are sketched in Figure 4 (left). The geometry conditions are,

Table 1. Geometrical input data.

Parameter	Unit	Value
Baffle Thickness	mm	25
Tube Outer Diameter	mm	15.9
Tube Inner Diameter	mm	13.7
Tube Pitch	mm	24.5
Diameter of Tube Hole	mm	16.4

For the pressure boundary condition, the outlet relative pressure is set to zero, and the inlet relative pressure is the pressure difference across the baffle as calculated by the THIRST code and included the effect of elevation. Both 2-dimensional (2-D) and 3-dimensional (3-D) models were used as 2-D axis-symmetrical models are simpler for concentric hole-tube cases with various degree of fouling while the 3-D models focused on the effect of tube eccentricity and tube inclination. All of the thermal hydraulic parameters used for the FLUENT calculations, including pressure difference across the baffle plate, primary and secondary temperatures, are obtained from THIRST results, and listed in Table 1.

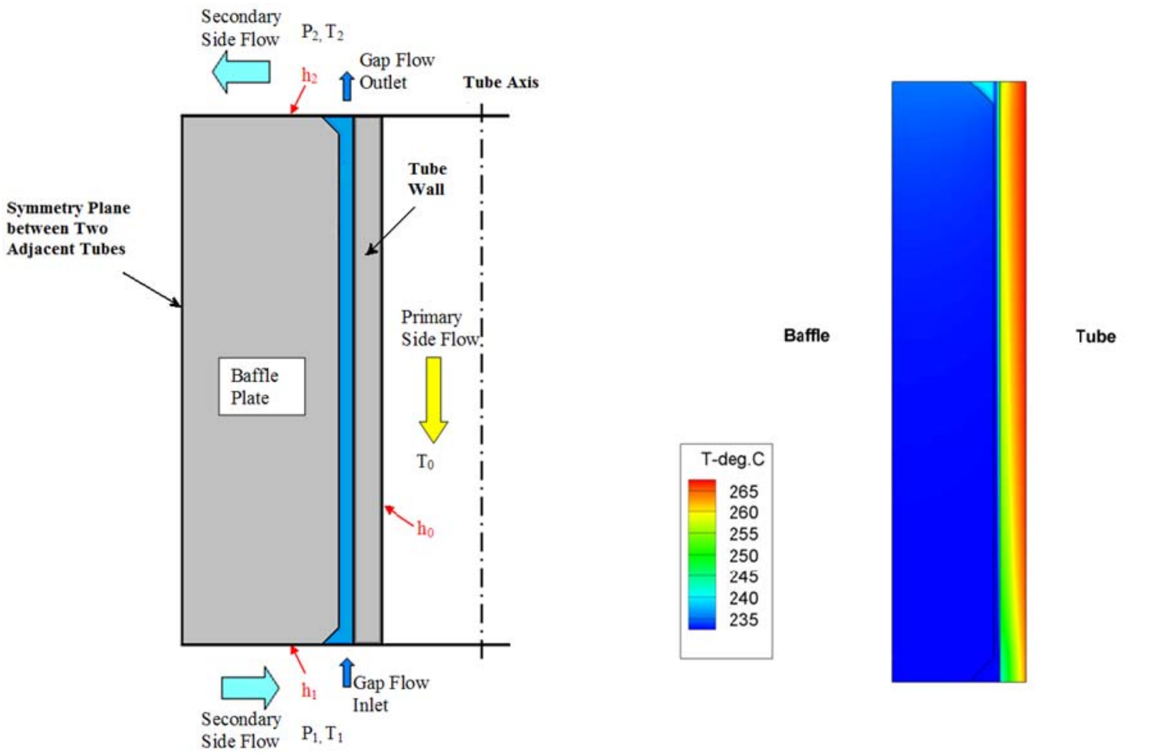

Figure 4. Geometry and boundary conditions (left, not to scale) and temperature distribution (right)

Table 2. Input parameters for reference case.

Item	Parameter	Symbol	Value	Unit
1	Primary fluid temperature	T_0	274.2	°C
2	Heat transfer coefficient at the inner surface of the tube	h_0	30700	W/m^2K
3	Secondary fluid temperature at the gap inlet	T_1	230.8	°C
4	Heat transfer coefficient at the lower surface of the baffle plate	h_1	3000	W/m^2K
5	Secondary fluid temperature at the gap outlet	T_2	240.1	°C
6	Heat transfer coefficient at the upper surface of the baffle plate	h_2	3000	W/m^2K
7	Pressure difference across the clearance gap	ΔP	508	Pa

The obtained temperature contours in Figure 4 (right) indicate that the highest temperature in the gap appears near the outlet at the tube surface. The temperature variation along the gap at the tube outer surface is plotted in Figure 5 (see the light-blue dash line). For the reference case of ΔP = 508 Pa, the surface temperature increases in the gap because of the heating from the primary side. Near the outlet, the temperature reaches a maximum value of 257ºC that is lower than the nucleation boiling temperature, 267.8ºC. This reference case did not consider any fouling at primary and secondary sides, so the result indicates that under the no-fouling conditions, boiling, and hence, cavitation does not occur. For simplification, the varying mass flow rate through the clearance gap versus fouling was modeled by reducing the pressure drop across the baffle plate that reduces the flow rate. The varying mass flow rate through the gap simulates fouling of the clearance gap as fouling reduces the cross-sectional area available for flow. In the SG, with the pressure drop across the baffle plate remaining the same, the mass flow rate is reduced due to the reduced flow area by fouling. Figure 5 shows the effect of mass flow rate on the onset of boiling. Only the lowest mass flow rate, 0.64 g/s, results in boiling inside the gap. The mass flow rate with boiling reaches maximum when boiling occurs at the gap exit and is determined from interpolation of the results at 0.82 g/s.

The effect of fouling was studied by adding three fouling layers to the reference case includes:

- A layer of primary fouling on the inner tube surface with 90 µm thickness;
- A layer of secondary fouling on the tube side with 5 µm thickness; and
- A layer of secondary fouling on the baffle side with 25 µm thickness (estimated).

Fouling on the primary side increases the thermal resistance, hence, decreases the likelihood of boiling. When secondary side fouling is present, it can be on the tube, on the baffle or on both. Two factors influence the onset of boiling. If the fouling layer is on the tube outer surface, the thermal resistance for heat transfer increases, therefore, reduces the likelihood of boiling. If fouling is on the baffle side, it reduced flow area and reduced mass flow rate in the gap, so the likelihood of boiling within the gap increases. The possibility of boiling in the gap clearance depends on which mechanism prevails.

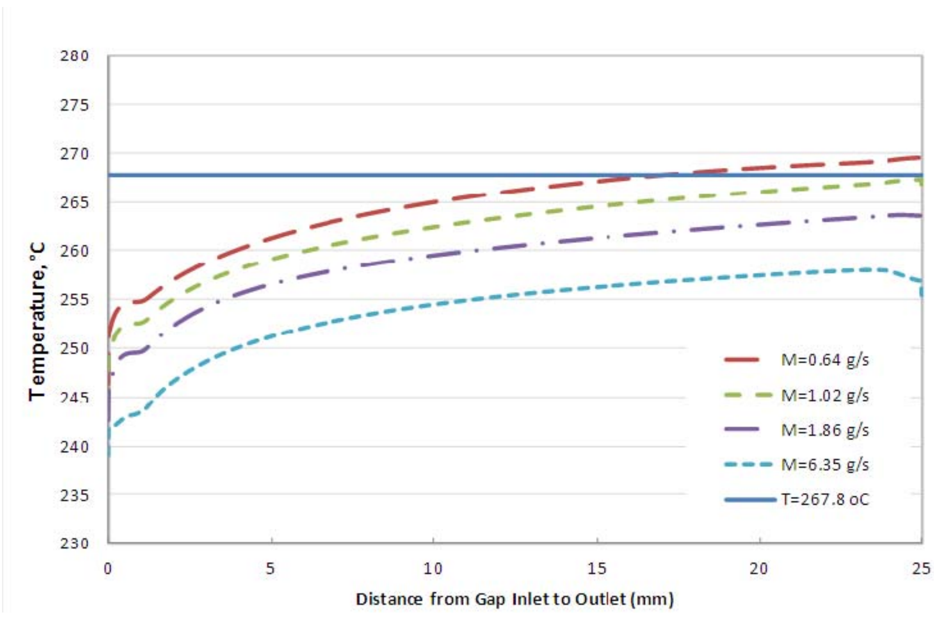

Figure 5. Temperature distributions at tube outer surface for various mass flow rates.

Inclined and eccentric tube alignments in the baffle hole can significantly influence the flow and heat transfer in the clearance gap based on the 3-D FLUENT model results. The inclined tube case is analyzed where a tube is inclined 0.8° to the vertical in the hole. The temperature contours at the tube surface are shown in Figure 6 (left). As expected, the temperature distribution is not axis-symmetrical, and the maximum temperature occurs at the wide side of the gap near the exit. This temperature reaches 267.8ºC when the mass flow rate in the gap is 1.8 g/s. The result indicates that the likelihood of cavitation increases when compared to the reference case. The eccentric tube case is analyzed in which the tube outer surface touches the hole surface. The temperature contours at the tube surface are shown in Figure 6 (right). When compared with the reference case, the temperature is higher at the contact side of the gap because of the direct heat conduction from the tube to baffle plate. The maximum fluid temperature reaches 267.8ºC near the exit with the mass flow rate of 7.1 g/s, which is much higher than the mass flow rate for a concentric tube, 0.82 g/s. This result indicates that the eccentric tube increases significantly the likelihood of cavitation. However, it needs to mention that it is impossible to predict tube location in the hole in the SG during operation because the location results from manufacturing tolerances and assembling practices. In addition, during operation, the fluid drag force affects the tube location and thermal expansion changes the relative locations. Even though inspection techniques could determine the tube location within the baffle hole, it may change under operation.

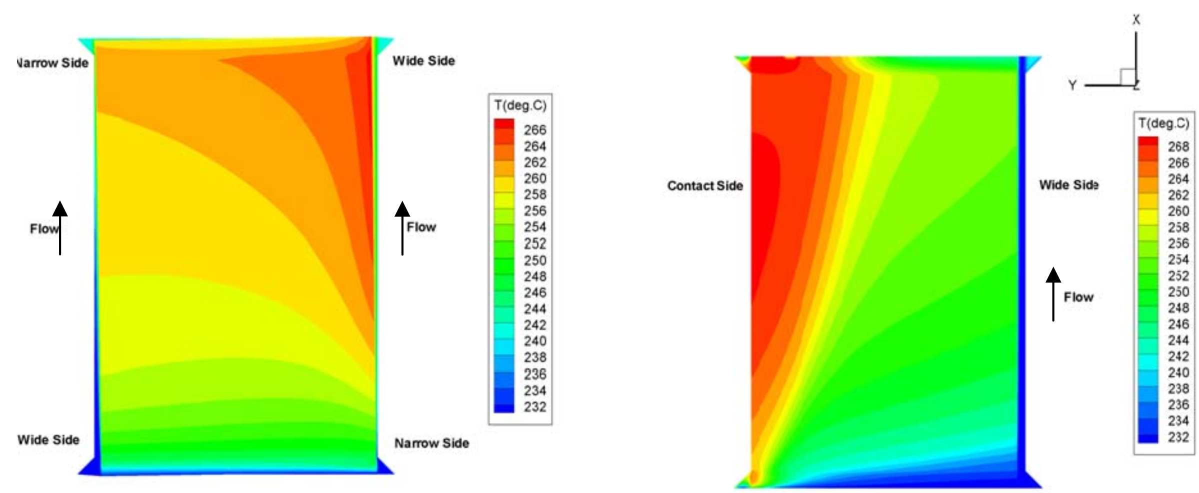

Figure 6. Temperature contours for inclined tube (left) and eccentric tube (right)

Tube degradation at the upper baffle plates, P07 through P11 was also calculated and analyzed. Based on the numerical results, the cavitation is not as severe as that presented at P05 and P06. These upper baffles are not as thick with a thickness of 16 mm in comparison to 25 mm for lower baffles. Even more important, at these upper baffle plates, the secondary water temperature is closer to the saturation temperature, so that the subcooling is not low enough to cause high condensation rates when steam bubbles mix with the water above the plate. However, lower plates, e.g., P03, can experience cavitation erosion in regions with low cross flow and high fouling even though the secondary water temperature is low for typical operation conditions and boiling in the gaps does not occur. Under low cross flow above the plate (stagnant zone) and fouling conditions, as analyzed in Figure 5, boiling can possibly occur and then cavitation erosion is likely because the steam bubbles mix with the cold (subcooling) water above the plate. The mixing results in fast direct condensation and cavitation damage is likely.

3.3 CANDU® Preheaters

Internal and external preheater design have conditions where boiling followed by the rapid condensation of these steam bubbles are present. These conditions may lead to tube cavitation erosion damage similar to the damage that has been observed in DNGS preheaters with windowed baffles. Under this consideration, a CANDU® SG internal preheater with segmented baffle plates was selected and analyzed using the same methodology as in the previous sections for the DNGS SG preheater analysis. Also, a typical external preheater was selected, and then a one-dimensional analytical calculation was used to estimate the local stream velocities and pressures and these parameters were compared to those predicted in the two internal preheaters.

It was found for DNGS preheaters that all baffles can experience cavitation under some conditions but the middle of the preheater (P03 to P05) is likely to be the most susceptible due to the primary and secondary temperatures. The gap clearance between the tubes and the baffle plate for internal and external preheater segmented baffles was 0.15 mm and 0.19 mm, respectively, but both are less than the gap in the DNGS baffle plates (0.26 mm). For DNGS, lower baffle plates have a thickness of 25 mm while upper baffles are 16 mm. In comparison, the lower segmented baffle plates of internal preheaters are 32 mm thick (P02 to P04) while the upper segmented baffles (P05 to P09) are 16 mm thick. The gap and baffle plate thickness both contribute to the pressure drop across the baffle plate. This pressure drop was predicted to be roughly 5 times the value of DNGS preheater at P05 for internal preheaters and 8 times for external preheaters. The higher pressure drop across the baffle plate reduces the susceptibility of this preheater design to cavitation as the flow rate through the gap clearance is proportional to the baffle plate pressure drop in the laminar flow regime. A higher flow rate in the gap means more capability for flow to remove heat and less chance of subcooled boiling occurring. If subcooled boiling does not occur, cavitation will not occur.

These factors make internal and external preheaters less likely to have boiling in the clearance gaps than DNGS. However, as the preheater ages and fouling continues to accumulate on tubes and reduce flow in the clearance gaps, this preheater design (internal and external preheaters with segmented baffles) might also be susceptible to cavitation. However, if cavitation occurs, cavitation degradation is expected to happen because there is a large temperature difference for bubble condensation.

4. CONCLUSIONS

A numerical analysis of flow and heat transfer in the clearance gaps between tubes and baffles in the Darlington SG preheater with windowed baffles has been performed. The analysis focuses on the possibility of cavitation erosion in the clearance gaps based on THIRST thermalhydraulic simulations coupled with ANSYS FLUENT detailed thermalhydraulic simulations of flow and heat transfer in the clearance gaps. The CANDU® internal and external preheaters with segmented baffles were also considered. The following conclusions have been drawn:

- The operating conditions in the Darlington SG preheaters are conducive for cavitation erosion to occur in the clearance gaps between tubes and baffles. Tube damage is more likely in the middle elevation of the preheater with fouling in the clearance gaps as fouling reduces the flow through the gaps and increasing the possibility of cavitation. Lower preheater baffles could experience cavitation erosion if heavily fouled clearance gaps for concentric tubes. In both locations, eccentric and inclined tubes have a greater likelihood of cavitation erosion than concentric tubes.

- Among the factors affecting preheater cavitation, fouling in the clearance gaps is most important, especially fouling deposits on the baffle surface. Fouling on the inner tube surface reduces the possibility of cavitation; fouling on the outer tube surface reduces the possibility of cavitation if the fouling layer has a high thermal resistance and increases the possibility of cavitation if the fouling layer reduces the flow through the gap.
- The operating conditions in internal and external SG preheaters with fouling are conducive for boiling and, therefore, cavitation might occur in the clearance gaps between tubes and baffles. This cavitation may not always result in degradation. In compared to the DNGS preheaters with windowed baffles, internal and external preheaters with segmented baffles should be less susceptible to cavitation because the high cross-flow, which reduces fouling deposition in the preheater.

5. REFERENCES

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