Heat Transfer Analysis of Blast Furnace Tuyere through CFD Simulation

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Tuyere Failure Analysis and Improvement through CFD Simulation

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ABSTRACT

Tuyere is a critical component of a blast furnace. It is used to blow hot air into blast furnace. Tuyere failure affects the production of blast furnace directly. Due to the elevated temperature environment, more than fifty percent of the failures are related to thermal effects, such as high radiation absorptivity, low thermal conductivity, inefficient cooling system, and operating parameters. The purpose of this research is to simulate the tuyere cooling system using computational fluid dynamics (CFD) model. The possible reason of tuyere failure is discussed. Through parametric study, the sensitivity of some significant variables would be investigated, including cooling water temperature, cooling water velocity, coating material emissivity, blast pressure and mass flow rate, etc. Also, suggestions would be provided for improving the tuyere reliability.

Keywords: Blast Furnace, Tuyere, CFD, Cooling System, Tuyere Reliability

1. INTRODUCTION

In the iron-making industry, Blast Furnaces (BF) are widely applied. Tuyere is the equipment blowing hot blast air into BF for providing oxygen for fuel combustion. In the tuyere, the chemical combustion of various types of fuel takes place, such as pulverized coal, oil, natural, and so on. Hence, tuyere is working in an extremely hot environment. As one of the important equipment of BF, tuyere failure could directly impact the liquid iron production of BF.

The tuyere failure is not a simple problem, but a complicated one, because of the complex conditions. From literature reviews, many things would cause tuyere failures. Farkas and Móger (2013) [1] claimed that most of the tuyeres utilized in BFs are cooled by water flow. The material used for tuyere is copper, which could have a sufficient cooling and low cost. They have summarized several reasons for tuyere erosion.

- Direct abrasion: the hot material directly contacts the surface of tuyere, including liquid metal or slag, and coke breeze.
- Erosion consequences of metallographic processes: liquid iron penetrates into the copper without a hard face protection. This would decrease the thermal conductivity of tuyere and lead to tuyere failure.
- Inadequate water cooling of tuyeres.
- Non-optimal tuyere structure: such as welding and casing.
- Insufficient number of tuyeres as compared to the size of blast furnace.

Li et al. (2008) [2] investigated the effects of the incrustation scale and copper impurity by using numerical simulation method. Copper impurity has relatively minor effects on temperature distribution of tuyere. The formation of incrustation scale in the tuyere could cause an inhomogeneous temperature distribution in the tuyere. Also, the maximum temperature in the tuyere increases. Copeland and Street (2013) [3] have done a series of studies to improve their tuyere working lifetime. They did both practical experiments and numerical simulations. Their study indicated some practical methods for avoiding tuyere failure.

- No recirculation in the tuyere design: low water velocity and flow eddies would cause hot spot.
- Hard surface is required to prevent from Fe penetration.
- Nut coke (small size of coke) should not be close to the wall: otherwise, direct abrasion occurs.

Zhao et al. (2005) [4] have completed an investigation of tuyere nose failure by using Computational Fluid Dynamic (CFD). They figured out that water flow temperature and velocity had minor effects on improvement of tuyere reliability. Absorptivity is relatively critical but this value is highly dependent on surface condition and environment temperature. The absorptivity could be in a wide range from 0.18 to 1.0. This paper also uses CFD technology to numerically simulate the tuyere nose cooling system. Through parametric study, the important parameters that are helpful for improving tuyere reliability are examined.

2. APPROACH

The studied specific tuyere is spiral. This tuyere is cooled by two water flows. One is cooling the tuyere body, and the other is cooling the tuyere nose. The simulation is focusing on the tuyere nose cooling system, since the hot spots exist at the tuyere nose region. The commercial software Fluent is utilized. First, according to industrial drawings and operating conditions, a baseline case is set up. The results of the base case can provide a general understanding of the cooling system, such as temperature distribution, hot spots locations, water flow streamlines and water temperature increment. Second, a parametric study is conducted for investigating the effects of several parameters, like water velocity and temperature, hard facing thickness and emissivity or absorptivity, in order to determine whether they are sensitive for tuyere cooling or not. From the temperature increase of water flow through the tuyere and the temperature distribution of tuyere, the effects of each parameter are discussed. The tuyere reliability could be improved by adjusting these parameters.

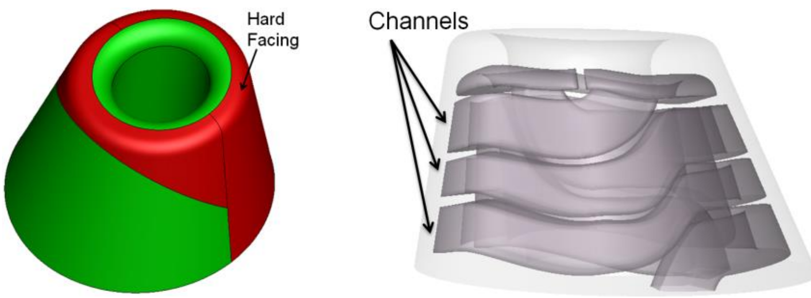


Figure 1. Geometry of tuyere nose cooling system

The geometry of the tuyere is shown in Figure 1. The tuyere is protected by a hard facing layer of FeCr, which covers the red surface. To simplify the simulation, the assumptions are made as following:

1. To avoid simulating the combustion of fuel in tuyere and BF. The raceway adiabatic flame temperature is used as the gas temperature of the tuyere outside surface. The blast temperature is used as the environment temperature of the tuyere inside surface. As shown in Fig 3. The heat transfer coefficients of convection are from a reference [5].
2. Since the temperature of the environment around tuyere is very high, the emissivity of materials is hard to measure. For the baseline condition, the worst condition is assumed with the emissivity/absorptivity as 1.0.

3. RESULTS AND DISCUSSION

3.1. Base case results

Figure 2 shows the external surface temperature distribution on tuyere. The temperature at tuyere tip is much higher than the other region. That means in this region the tuyere requires more cooling than other region. At the hard facing rims, there is an obvious temperature jump, especially at the tuyere tip. The temperature is over 1340F. The detailed analysis of the base case is referred to the paper published at IHTC [6]. From the base case, it is concluded that:

- The hot spots location of simulation results matches the industrial observation.
- The thickness of tuyere tip should be a sensitive and significant parameter.
- The water flow may not a limiting parameter for the tuyere cooling.

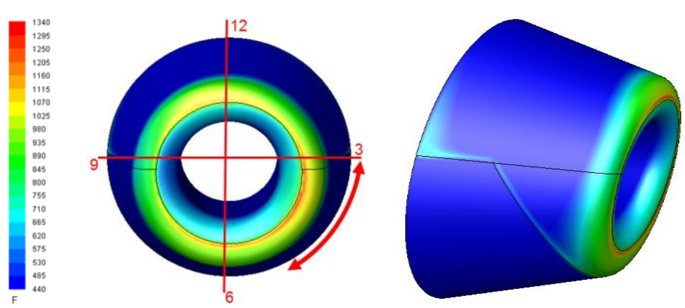


Figure 2. Temperature distribution of external surface of tuyere

3.2. Steady cases of specific operating conditions

At plants, except normal operation, two other operations are frequently applied: shutting down operation and emergency water operation. Therefore, the simulations of these conditions are conducted. The operation conditions for each case are listing in Table 1.

Table 1. Three operation conditions

	Temperature of Water (F)	Mass Flow Rate of Water (lbm/s)	Hot Facing Temperature (F)
Normal Operation	T_w (base)	MFR (base)	T_{HF} (base)
Shutting Down Operation	T_w - 5	MFR	T_{HF} + 629
Emergency Water Operation	T_w – 24	MFR - 15	T_{HF}

3.2.1. Shutting Down Operation

From Figure 3, it can be seen that the tuyere nose cooling system is not sufficient. The temperature is much higher at the tuyere tip in comparison to the tuyere body. At the hard facing edges, the temperature jump is more obvious. In Figure 4 both (a) and (b), the hot spots are at the same location from 3 o'clock to 6 o'clock for both operations. Temperature distribution of shutting down operation is higher than normal operation.

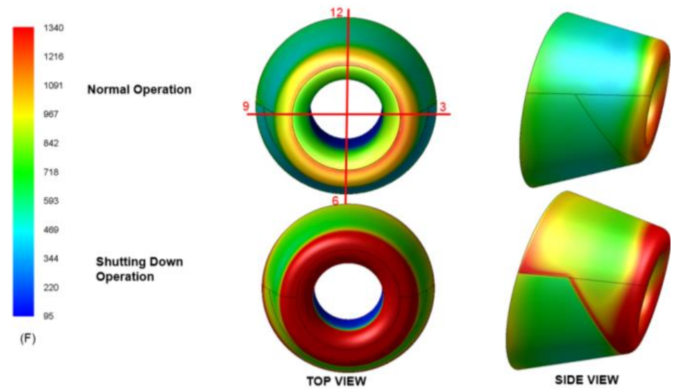
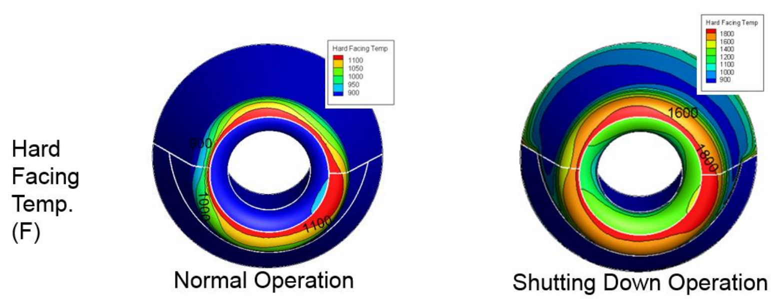
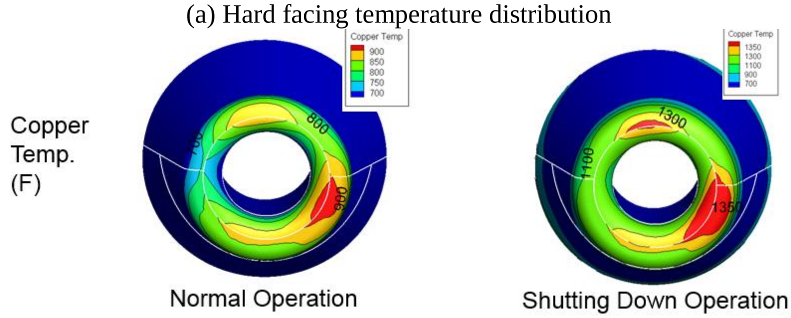


Figure 3. Temperature distribution comparison between Normal Operation and Shutting Down Operation



(a) Hard facing temperature distribution



(b) Copper temperature distribution

Figure 4. Temperature distribution comparison between Normal Operation and Shutting Down Operation

3.2.2. Emergency Water Operation

From Figure 5, the tuyere nose cooling system is less sufficient. The temperature is much higher at tuyere tip compared to the tuyere body. At the hard facing edges, the temperature jump is even more substantial. In Figure 6 both (a) and (b), the hot spots are at the same location from 3 o'clock to 6 o'clock for both operations. Temperature distribution of shutting down operation is once again higher than normal operation.

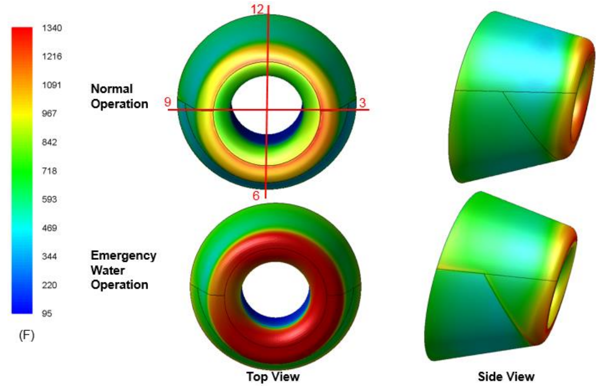
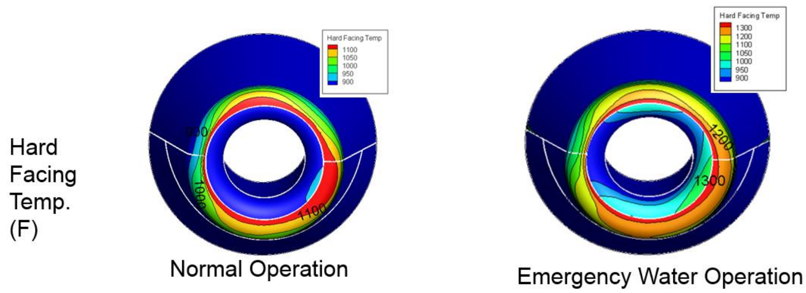
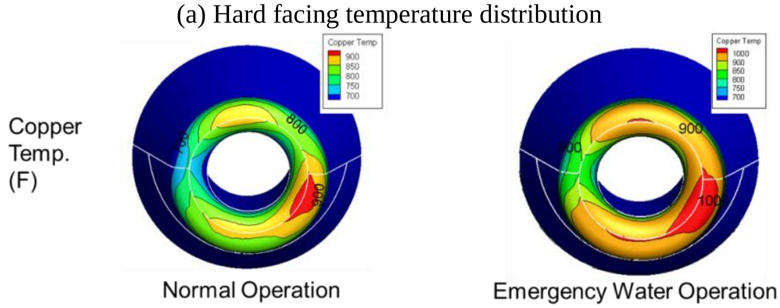


Figure 5. Temperature distribution comparison between Normal Operation and Emergency Water Operation



(a) Hard facing temperature distribution



(b) Copper temperature distribution

Figure 6. Temperature distribution comparison between Normal Operation and Emergency Water Operation

3.3. Parametric Study

Through the research, a series of parametric study is conducted.

Table 2 shows the list of cases. Some essential parameters are considered, such as water flow rate and temperature, hard facing thickness, hard facing absorptivity and reduced tuyere tip thickness.

Table 2. Parametric Study Case List

	Water Flow Rate	Water Temperature (F)	Hard Facing Thickness	Reduced Tuyere Tip Thickness (inch)	Hard Facing Absorptivity
Base Case	R_w (base)	T_w (base)	T_{hk} (base)	0.0	1.0
Case 1	$R_w \times 1.25$	T_w	T_{hk}	0.0	1.0
Case 2	$R_w \times 1.5$	T_w	T_{hk}	0.0	1.0
Case 3	R_w	$T_w - 36$	T_{hk}	0.0	1.0
Case 4	R_w	$T_w - 18$	T_{hk}	0.0	1.0
Case 5	R_w	$T_w - 9$	T_{hk}	0.0	1.0
Case 6	R_w	T_w	Thk × 1.15	0.0	1.0
Case 7	R_w	T_w	T_{hk}	1.15	1.0
Case 8	R_w	T_w	T_{hk}	1.35	1.0

Case 9	R_w	T_w	T_{hk}	1.55	1.0
Case 10-18	R_w	T_w	T_{hk}	0.0	0.1-0.9
Case A1-A5	Effects of Refractory Profile				

3.3.1. Effects of water flow rate and temperature

Figure 7 shows the effects of water flow rate. As increasing the water flow rate, the maximum temperature in tuyere decreases slightly. That implies the water flow rate is high enough for tuyere cooling. In
Figure 8, it shows that increasing water temperature would also increase the temperature of tuyere. However, these two effects are insignificant. As expected, the effect of changing water flow rate and temperature is very limited on reducing maximum temperature of tuyere. Even the water temperature is reduced by 420 F the temperature of tuyere decreases about 420 F. The water temperature variation is proportional to the change of maximum temperature on tuyere.

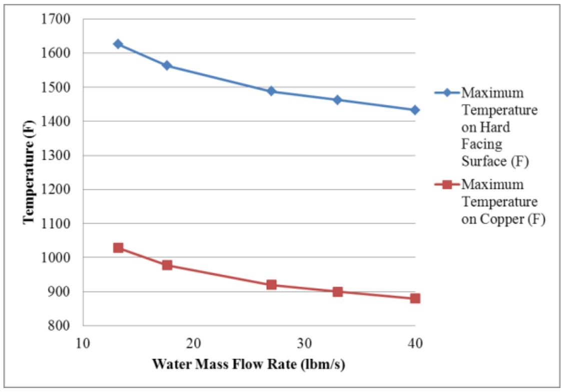


Figure 7. Effects of water flow rate

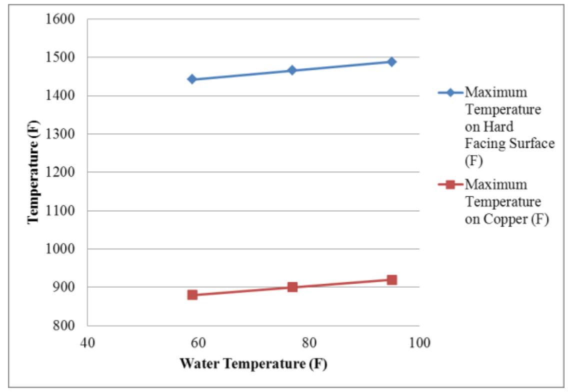


Figure 8. Effects of water temperature

3.3.2. Effects of hard facing layer thickness

From Figure 9, one can tell that increasing the thickness of hard facing can only raise the hard facing temperature, but not reduce temperature of copper or water. However, the hard facing is functional for preventing from liquid iron penetrating into tuyere. Therefore, theoretically the thickness of hard facing is supposed to be as small as possible; while practically, the hard facing should be able to isolate liquid iron from tuyere. Otherwise, the efficiency of tuyere cooling system would be impacted.

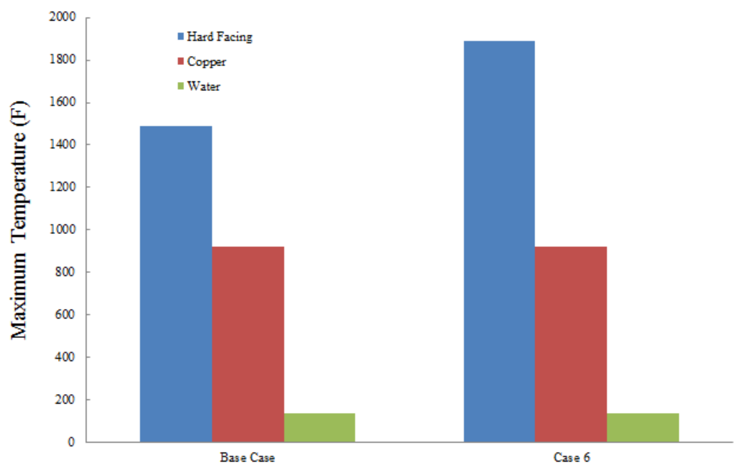


Figure 9. Comparison of maximum temperature of tuyere and cooling water

3.3.3. Effects of copper layer thickness at tuyere tip

Figure 10 and Figure 11 show decreasing the tuyere tip thickness could effectively reduce tuyere maximum temperature and improve tuyere reliability. As discussed in 2D theoretical analysis, the resistance of FeCr and copper are greater than water. That implies these two materials are controlling factors. In case 7-9, the thickness at tuyere tip is reduced from 0.3 in to 0.7 in. Figure 10 illustrates that decreasing tuyere tip thickness has a great effect on temperature distribution on tuyere surface. The temperature distribution at tuyere tip can be significantly reduced. From the summarized results in Table 3, the maximum temperature of hard facing and copper in Case 9 are reduced by 54 F and 195 F respectively by comparing with the base case. From the point of view of heat transfer, reducing the thickness of copper at tuyere tip is an effective way to reduce the tuyere temperature at the tip.

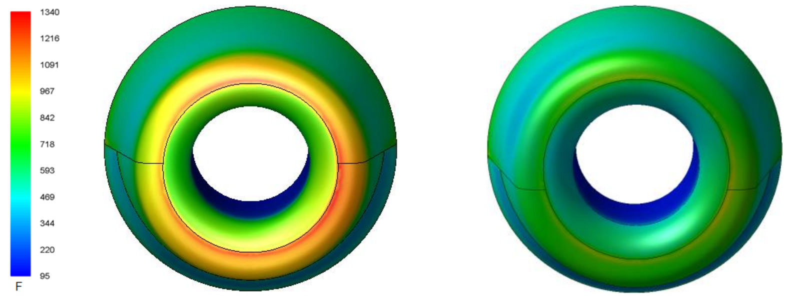


Figure 10. Comparison of temperature distribution of base case and Case 9

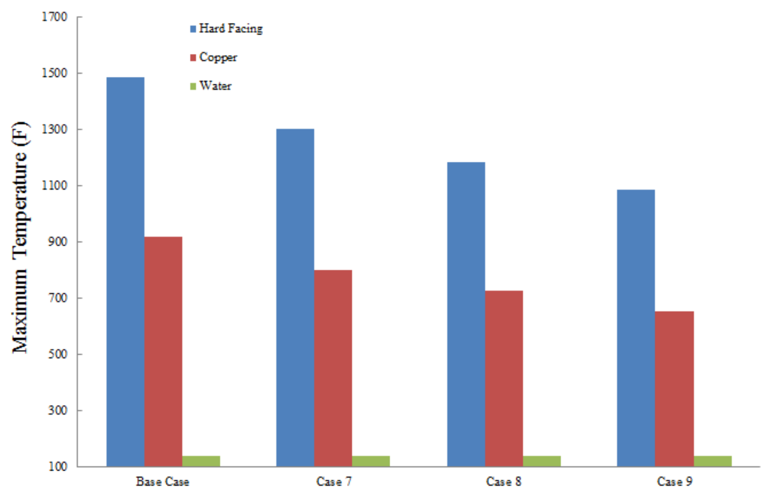


Figure 11. Comparison of maximum temperature of tuyere and cooling water

3.3.4. Effects of hard facing absorptivity

Table 3 and Figure 12 show the great effects of hard facing absorptivity to tuyere temperature. From Figure 16 one can observe that when absorptivity is greater than 0.3, the absorptivity and maximum temperature have a linear relationship. In reality, the absorptivity could be decreased by polishing the surface. However, once the tuyere is inserted into a blast furnace, the absorptivity is uncontrollable. The surface could probably be abraded by pulverized coal or other particles; high temperature environment would also impact its absorptivity. To minimize the absorptivity of hard facing is really an effective way to reduce tuyere maximum temperature for enhancing the tuyere reliability. Figure 13 is the comparison of temperature distribution between base case and Case 10. Obviously, the hard facing temperature is greatly reduced. From the point of view of heat transfer, the radiation absorption is the greatest heat source of the tuyere cooling system, which is even more critical than convection and conduction. Effectively reducing the radiation absorption is a good way to avoid tuyere failure.

Table 3. Summary of effects on tuyere maximum temperature

	Base Case	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14	Case 15	Case 16	Case 17
Hard Facing (F)	1490	1300	1185	1085	752	813	876	953	1117	1205	1277	1396
Copper (F)	920	802	728	654	629	645	671	698	762	798	838	879

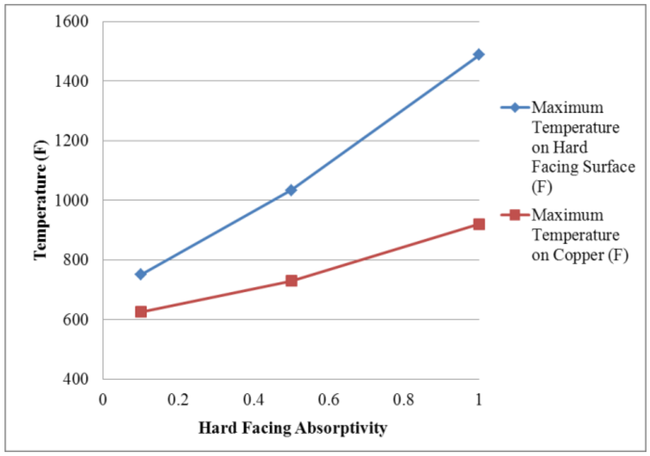


Figure 12. Comparison of maximum temperature of tuyere and cooling water

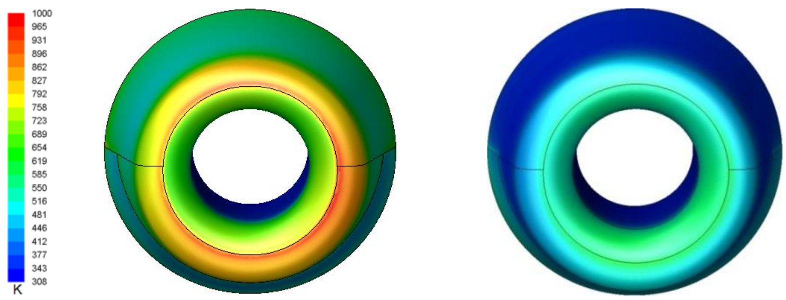


Figure 13. Comparison of temperature distribution between base case and Case 10

3.4. Welding Effects

This specific tuyere is welded by two separate parts. The study of tuyere body has been conducted concentrating on the temperature profile affected by the welds. The tuyere body section has been extended from the existing nose model. The detailed body cooling water channel such as the channel shape and baffles are not included in this model. Instead, a convective boundary is set at the body inner surface. The convection heat transfer coefficient is assumed as the averaged value from the baseline case results. The body exterior surface is set as exposed to the flame which is coincident with the nose. Convection and radiation between the body exterior surface and the hot raceway gas has been considered. The weld is added in the body section and the dimensions are shown in Figure 14 and Figure 15. The weld length outside of the body exterior surface is 0.6 in. The weld thickness between coppers is estimated as 0.2 in. Thermal conductivity of copper is set as 224 Btu/h.ft.F, and thermal conductivity of weld is assumed to be 69.3 Btu/h.ft.F.

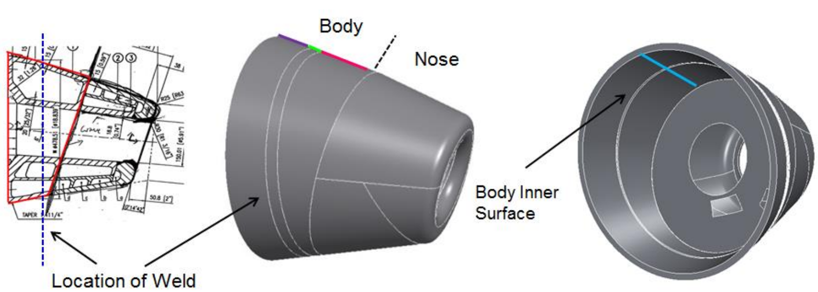


Figure 14. Geometry of Extended Tuyere Body

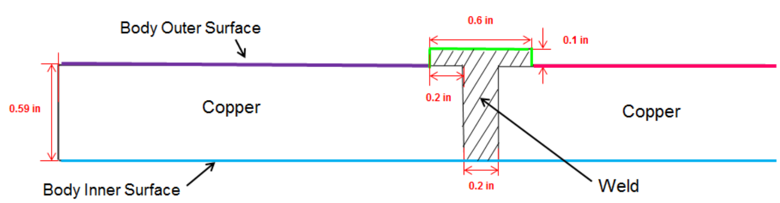


Figure 15. Detailed dimensions of Weld on Tuyere Surface

The refractory may be worn out. Therefore, four cases have been conducted for different refractory profile. For the case A1 the tuyere has no refractory coverage for the entire body, Case A2-A4 has different scales of refractory on the tuyere body with weld. Case A5 has refractory but no weld on the tuyere body. If the area is covered by refractory, it is modeled as an adiabatic boundary with no heat transfer on the surface. If the area is not covered by refractory, it is modeled as exposed to the flame which is coincident with the tuyere nose. The location of the refractory profile for each case is shown in Figure 16.

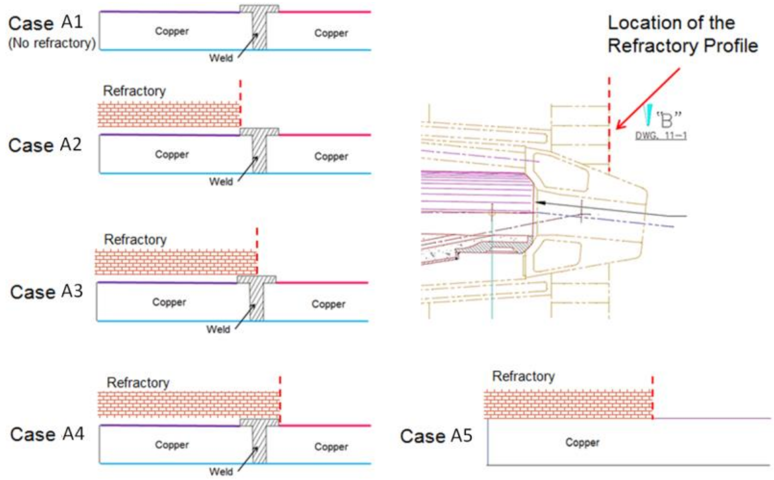


Figure 16. Location of the Refractory Profile

The temperature distribution in the nose and body section for case A1 is shown in Figure 17, the lateral heat transfer (from nose to body) is limited which indicates that the effects of temperature distribution in the nose has negligible effects on the body temperature. Due to the low thermal conductivity of the weld, the temperature of weld area is about 200F higher than the copper area. The temperature difference could induce thermal stress that may lead to tuyere failure.

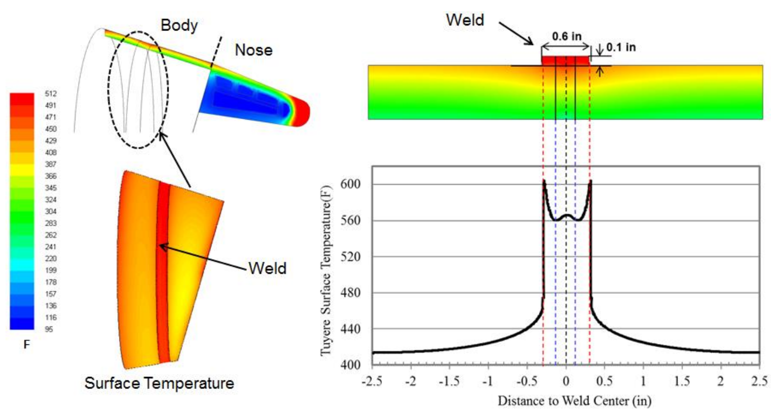


Figure 17. Temperature Distribution on the Tuyere Surface

The Figure 18 and Figure 19 illustrate the parametric study of temperature distribution for all the cases. The significant temperature difference in the weld area is observed if the weld is partially exposed to the flame. The more coverage of refractory on the weld, the lower temperature is at the area. From the comparison of case A3 and case A5 with same refractory, the temperature difference is due to the weld effect (including the shape and thermal conductivity). The temperature difference could be as high as 250F between the Case A3 and Case A5.

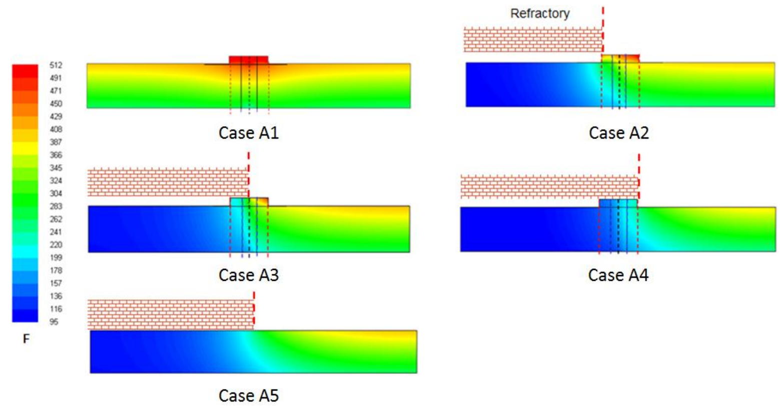


Figure 18. Temperature Distribution affected by refractory

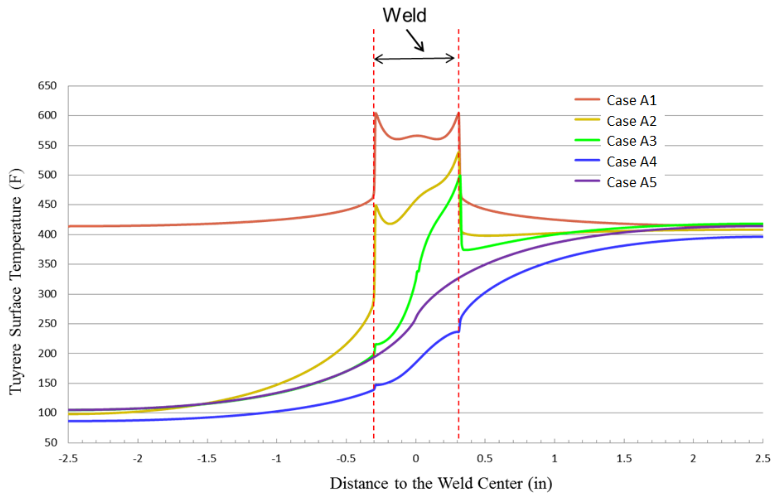


Figure 19. Temperature profile for case A1 to case A5

4. CONCLUSION

A tuyere cooling system is simulated in CFD technology. A baseline case is set up based on the industrial operating condition. To discover the effects of some essential parameters, a list of cases have been conducted. The highest temperature of tuyere surface is at the rims of the hard facing. In all cases, the temperature increase of water flow is very small. Increasing hard facing thickness will raise the temperature of hard facing only. The two effective ways of reducing tuyere temperature are decreasing absorptivity of tuyere by polishing the surface, and reducing the tuyere tip thickness of copper. The radiation absorption is the greatest heat source of the entire cooling system.

The extended tuyere body from the existing nose model has been simulated by using CFD. From the temperature distribution in the nose section and body section, the lateral heat transfer is limited which indicates the effects of temperature distribution in the nose has negligible effects on the body temperature. From the comparison of all the cases, the significant temperature difference in the weld area is observed if the weld is partially exposed to the flame. The temperature difference could induce thermal stress that may lead to tuyere failure.

5. ACKNOWLEDGEMENT

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