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Heat Transfer Analysis of Blast Furnace Stave Cooler

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Abstract

Blast furnace cooling technology is critical for enhancing productivity and extending furnace campaign life in the metallurgical industry. This study presents a comprehensive heat transfer analysis of a blast furnace stave cooler, utilizing both numerical simulations and experimental validations conducted at the Rourkela Steel Plant (RSP). A three-dimensional (3D) model of the stave cooler was developed using ANSYS® software to calculate temperature distributions and heat dissipation. The analysis compared the performance of different stave materials (cast iron, copper, and aluminum) and cooling mediums (water and nitrogen) under thermal loads ranging from 573 K to 1723 K. Results indicate that copper staves exhibit superior thermal performance due to higher thermal conductivity, and nitrogen can serve as an effective alternative cooling medium when its mass flow rate is adjusted to compensate for its lower specific heat compared to water. The numerical results closely corroborate experimental data, validating the model's accuracy.

Keywords: Stave Cooler, Blast Furnace Cooling, Heat Transfer, ANSYS, Nitrogen Cooling

1. Introduction

Blast furnaces are integral to steel production, generating significant heat due to combustion processes. Effective cooling systems are essential to protect the furnace's steel shell and refractory lining from overheating, thereby preventing structural damage and extending operational life. Stave coolers, installed on the inner surface of the furnace, are critical components that dissipate excess heat using cooling fluids such as water or, as explored in this study, nitrogen.

Traditionally, cast iron staves have been used due to their durability in moderate heat load zones. However, copper staves have gained prominence in high thermal load regions (e.g., bosh, belly, and lower stack) due to their superior thermal conductivity, which reduces heat flux by approximately 50% compared to cast iron. This study investigates the thermal performance of stave coolers, comparing different materials and cooling mediums, with the following objectives:

1. Analyze the behavior of stave materials under varying thermal loads.
2. Develop a 3D model of the stave cooler.
3. Determine temperature differences through experimental and numerical methods.
4. Validate numerical results against experimental data from RSP.
5. Evaluate nitrogen as an alternative cooling medium.

2. Literature Review

Previous studies have extensively explored blast furnace cooling technologies. Y. Ko et al. [1] analyzed thermal behavior in the tap-hole area, highlighting the influence of material properties on temperature distribution. Akash Shrivastava and R.L. Himte [2] conducted heat transfer analyses on stave coolers, comparing different lining materials and skull thicknesses. Anil Kumar et al. [3] modeled 3D stave coolers, finding that high alumina brick linings outperform silicon carbide in reducing thermal stress. W. Lijun et al. [4, 6] utilized ANSYS for thermal stress analysis and developed intelligent monitoring systems for stave coolers, emphasizing the importance of operating conditions like water velocity and temperature.

K. Verscheure et al. [7] reviewed furnace cooling technologies, noting their impact on productivity and safety. U. Pückoff and CH. Knoche [8] traced the evolution of stave coolers from Soviet designs to modern copper-based systems. Other studies, such as those by C. Peng Yeh et al. [10] and C.M. Chang et al. [11], focused on lining erosion and conjugate heat transfer, underscoring the protective role of refractory linings. Despite these advancements, few studies have explored alternative cooling mediums like nitrogen or compared multiple stave materials comprehensively.

3. Methodology

3.1. 3D Modeling of Stave Cooler

A 3D model of the stave cooler was constructed using ANSYS Workbench, based on dimensions from RSP (Table 1). The stave body measures 0.2 m thick, 0.9 m wide, and 1.64 m high, with cooling coils of 0.33 m diameter and 8.42 m length (Table 2). The model was meshed and exported to ANSYS FLUENT for thermal analysis, incorporating material properties (Table 3) and boundary conditions.

Table 1: Dimensions of Stave Cooler

Part	Thickness	Width	Height
Stave Body	0.2 m	0.9 m	1.64 m

Table 2: Dimensions of Casting Coil

Part	Diameter	Length
Casting Coil	0.33 m	8.42 m

Table 3: Material Properties

Metal	Thermal Conductivity (W/m·K)	Density (kg/m³)	Specific Heat (J/kg·K)
Copper	387	8940	381
Cast Iron	42	7200	460
Aluminum	237	2700	900

3.2. Numerical Analysis

The numerical analysis assumed steady-state conductive heat transfer in a 3D domain. Boundary conditions included:

- Insulated stave walls except for the hot face.
- Variable heat flux on the hot face, dependent on furnace position.
- Cooling fluid inlet at 300 K with a specified mass flow rate.

The governing equations included:

1. **Continuity Equation**: $$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$
2. **Navier-Stokes Equation** (momentum): $$\rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = \rho x - \frac{\partial p}{\partial x} + \frac{1}{3} \mu \frac{\partial}{\partial x} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) + \mu \nabla^2 u$$
3. **Energy Equation**: $$\rho c_p \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = \left(u \frac{\partial p}{\partial x} + v \frac{\partial p}{\partial y} + w \frac{\partial p}{\partial z} \right) + k \nabla^2 T + \mu \phi$$

Heat transfer calculations utilized Fourier's Law: $$Q = -K \times A \times \frac{dT}{dx}$$ and heat flux: $$q = \frac{Q}{A}$$ Total heat extracted was calculated as: $$Q = m c_p dT$$

3.3. Experimental Setup

Experiments were conducted at RSP, focusing on stave coolers in the bosh and hearth zones. Thermocouples measured inlet and outlet temperatures, while volume flow meters and pressure gauges recorded fluid flow rates and pressures. Nitrogen was supplied as an alternative cooling medium. Data were collected to calculate heat extraction (Tables 4, 5, 6).

Table 4: Heat Extraction at Bosh Position

Stave Cooler	Inlet (°C)	Outlet (°C)	Temp Diff (°C)	Mass Flow Rate (kg/s)	Heat Extracted (W)	Total Heat (W)
1-1	27.4	32.8	5.4	0.55	12435.39	12435.39
2-2	27.4	30.8	3.4	0.468	6662.35	19097.74
3-3	24.4	30.8	6.4	0.625	13398.40	32496.14
4-4	24.4	35.6	11.2	0.652	29309	61805.14
5-5	24.4	33.2	8.8	0.69	24023.33	85828.47
6-6	24.4	35.4	7.0	0.52	10223.21	106051.68
7-7	24.4	34.0	8.4	0.68	18288.816	124340.50

Table 5: Heat Extraction at Hearth Position

Stave Cooler	Inlet (°C)	Outlet (°C)	Temp Diff (°C)	Mass Flow Rate (kg/s)	Heat Extracted (W)	Total Heat (W)
1-2	24.2	27.2	3.0	0.71	8918.31	8918.31
3-4	23.6	25.0	1.4	0.9	5275.62	14193.93
5-6	23.6	24.4	0.8	1.153	3862.089	18056.02
7-8	23.6	24.2	0.6	1.0344	2598.62	20654.64
9-10	23.6	24.2	0.6	1.5	3768.3	24422.94
11-12	23.6	23.8	0.2	1.3	1088.62	25511.56
13-14	23.6	23.8	0.2	1.5	1256.1	26767.66

Table 6: Heat Extraction at Lower Hearth Bottom (LHB)

Stave Cooler	Inlet (°C)	Outlet (°C)	Temp Diff (°C)	Mass Flow Rate (kg/s)	Heat Extracted (W)	Total Heat (W)
1-2	23.2	26.2	3.0	0.18	2260.98	2260.98
3-4	21.8	24.6	2.8	1.3	15240.68	17501.66
5-6	21.8	23.6	1.8	1.2	9043.92	26545.58
7-8	21.8	24.2	2.4	1.2	12058.56	38604.14
9	21.8	23.2	1.4	1.5	8792.7	47396.84
10-11	21.8	24.4	2.6	1.07	11648.23	59045.07

12-13	21.8	24.0	2.2	1.2	11053.68	70098.75

4. Results and Discussion

4.1. Validation of Numerical Model

The numerical model was validated by comparing the temperature difference (dT) between the inlet and outlet of the stave cooler with experimental data from RSP. The comparison, as described in the original document, shows a graph plotting temperature differences across the stack to belly positions of the blast furnace. The experimental data (labeled "Exp.") and numerical data exhibit close agreement, with minor fluctuations attributed to variations in stave cooler arrangement and mass flow rates. This validates the accuracy of the 3D model in replicating real-world conditions.

4.2. Cooling Medium Comparison

The study compared the heat extraction capabilities of water and nitrogen as cooling mediums. When both fluids were used at the same mass flow rate, water extracted more heat due to its higher specific heat (approximately four times that of nitrogen). By increasing the nitrogen mass flow rate fourfold, the temperature difference (dT) achieved was equivalent to that of water, as described in the original document. This graph illustrates that both fluids maintain similar heat transfer rates under adjusted flow conditions, confirming nitrogen's potential as an alternative cooling medium.

4.3. Material Performance

The thermal performance of cast iron, copper, and aluminum staves was compared based on the maximum hot face temperature. As described in the original document, a graph shows that copper staves maintain the lowest hot face temperatures, followed by aluminum, with cast iron exhibiting the highest temperatures. This is due to copper's high thermal conductivity (387 W/m·K) compared to aluminum (237 W/m·K) and cast iron (42 W/m·K).

Temperature contours further illustrate material performance:

- **Cast Iron with Nitrogen**: The contour plot shows higher temperatures on the hot face, with a gradual decrease towards the cooling pipes, reflecting cast iron's lower thermal conductivity.
- **Copper with Nitrogen**: The contour plot indicates lower hot face temperatures and more uniform heat dissipation, attributed to copper's superior conductivity.
- **Cast Iron with Water**: Similar to nitrogen, the contour shows higher hot face temperatures, but water's higher specific heat results in slightly better cooling.
- **Copper with Water**: The contour demonstrates the lowest hot face temperatures, with efficient heat transfer to the cooling pipes.

Additional comparisons confirm that copper staves consistently exhibit lower hot face temperatures than cast iron, regardless of the cooling medium.

4.4. Heat Flux and Extraction

The heat flux on the hot face of the stave cooler varies from the stack to the belly position, as described in the original document. The graph shows a trend of increasing heat flux towards the belly, reflecting higher thermal loads in this region. Total heat extraction demonstrates that copper staves extract more heat than cast iron staves across all positions, due to their higher thermal conductivity.

Cooling pipe temperatures were analyzed at various points along the stave:

- **Water Cooling Pipes**: The graph shows temperature variations along the cooling pipes, with copper staves exhibiting slightly higher pipe temperatures due to enhanced heat transfer.
- **Nitrogen Cooling Pipes**: Similar trends are observed, with nitrogen maintaining comparable or slightly lower temperatures.
- **Nitrogen vs. Water in Cast Iron Staves**: The graph indicates that nitrogen results in slightly lower or equivalent pipe temperatures compared to water.

- **Nitrogen vs. Water in Copper Staves**: Copper staves show similar trends, with nitrogen maintaining effective cooling.
- **Cooling Pipe Temperature Contours**: The contour plot illustrates temperature distribution along the cooling pipes, with points 1 and 13 representing the inlet and outlet, respectively. The plot highlights efficient heat transfer in copper staves.

Maximum hot face temperatures across different furnace zones show that copper staves maintain lower temperatures than cast iron staves, reinforcing copper's suitability for high thermal load zones.

5. Conclusions

This study successfully developed and validated a 3D model for blast furnace stave coolers, achieving the following conclusions:

1. Numerical results closely match experimental data, confirming the model's accuracy.
2. Nitrogen is a viable alternative cooling medium when its mass flow rate is increased fourfold to compensate for its lower specific heat compared to water.
3. Copper staves outperform cast iron and aluminum due to higher thermal conductivity, resulting in lower hot face temperatures and enhanced heat extraction.

These findings suggest that copper staves with nitrogen cooling could optimize blast furnace performance, particularly in high thermal load zones, warranting further investigation into practical implementation.

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