Section-by-section, Step-by-step, Integration

Validation & verification

3-D interactive multiple platforms (immersive VR environment, AR, PC, mobile, or web versions)
3D SIMULATION AND VISUALIZATION OF BLAST FURNACE

Issues:
- Furnace campaign life
- Energy efficiency
- Pollutant emissions
- Furnace downtime
- Training

Outcome (since 2002):
- Virtual blast furnaces
- Copyrighted software packages
- Multimillion dollars savings
- Significant downtime reductions
- Best Paper awards

Collaborators: AISI, AIST, ArcelorMittal USA, ArcelorMittal Dofasco, AK Steel, Stelco, Tata Steel U.S. Steel, and Union Gas
COMPUTATIONAL FLUID DYNAMICS (CFD)

Eight-Step Approach

Geometry Creation → Mesh Generation → Boundary Conditions → CFD Models

Optimization ← Validation ← Visualization & Analysis ← Iterative Calculation
3-D BLAST FURNACE MODELS

Comprehensive 3-D Blast Furnace CFD Models
- 3D CFD software packages
- Graphic User Interfaces (GUI)
- VR visualization

- Flux Reaction
- Cohesive Zone
- Coke Gasification
- Ore Reduction
- Interphase Heat Transfer
- Fuel Lance/s & Tuyere
- Raceway Size/Shape
- Combustion
- Flow and Heat Flux
- Erosion
- Liquid Level
BLAST FURNACE CFD MODELS

Shaft Model:
- Burden distribution
- Chemical reactions
- Iterative method for cohesive zone shape and location
- Iterative method for coke rate

PCI-Raceway Model:
- Multiphase reaction turbulent flow
- Iterative method for raceway shape
- Coal combustion (devolatilization, surface combustion)
- Coke combustion (kinetic/diffusion model)
- Gas combustion (eddy dissipation model)
- P1 radiation model

Hearth Model:
- Coupled CFD with inverse Heat Transfer for Skull/Erosion Profile
- Conjugate heat transfer
- Real geometry (skulls, refractories, ram, shell…)
- Variable properties
- Liquid Level
CFD HEARTH MODEL

- GUI preprocessor
- 3-D
- Real geometry including deadman, blowing layer, skulls, refractories, ram, and shell
- Velocity, pressure, species, hot metal and refractory temperatures
- Inner profile
- Liquid level and tapping
- VR visualization
METHODOLOGY

3-D CFD model

1-D heat transfer model

Hot face temperature

Inner profile

Predicted TC temperature

1-D fine tuning model

Inner profile
VALIDATIONS

➢ CFD results were compared with the following measured data:

• Velocity and streamlines 1/10th scale water model at PUC

• Species distribution in a 1/50th scale warm water model at PUWL

• Refractory temperatures of the Mittal No. 7 blast furnace (both old and new geometry)

• Refractory temperatures of the US Steel No. 13 blast furnace
EXAMPLES OF VALIDATIONS

U-velocity at 0-Degrees

-40 -30 -20 -10 0 10 20 30

Y-Position(mm)

Velocity(m/s)

EXP
BFH

June 8.69%
USE OF CFD HEARTH MODEL

- Visualize flow patterns
- Predict inner profiles
- Design monitoring systems for refractory temperatures
- Investigate the impacts of operating and geometrical conditions on the campaign life of hearth
- Troubleshooting
- Design new furnaces
BF RACEWAY CFD MODEL

➢ CFD Raceway Models:
  • Lance
  • Raceway
  • Combustion

➢ Recommendations:
  • Strategies for high PCI & CH₄ rate
  • Guidance for lance design and protection
  • Solutions for troubleshooting
  • Evaluation of new alternative fuel injections
METHODOLOGY

(a) Simulation of NG+Coal inside a tuyere

(b) Obtain the raceway shape and size

(c) Schematic of Raceway combustion
LANCE AND TUYERE

➢ Fluent is used
  • 3-dimensional, Turbulent
  • Heat transfer
  • Multiphase flow
  • Multispecies reactions
  • Coal combustion
  • Natural gas co-injection
  • Oxygen enrichment

➢ Cases studied for
  • Coal devolatization in the lance; Effects of PCI rate, PCI carrier gas flow rate, Oxygen lance flow rate, and blast air temperature, etc; Lance arrangements; Maximize PCI rate; Lance failure; Tuyere failure, etc.
RACEWAY FORMATION KINETICS

➢ Fluent is used

- 3-D transient gas-particle flow simulations
- Eulerian approach
- A multi-fluid granular model is used to describe the flow behavior of the fluid-solid mixture.
Main Features of In-House CFD Code

- 3-dimensional
- Turbulent
- Multiphase flow (gas, pulverized coal, and coke particles)
- Heat transfer
- Multispecies reactions
- Coke combustion
- Coal combustion (moisture evaporation, volatilization, Char combustion)
- Natural gas co-injection
- Coke combustion rate
- Natural gas combustion rate

RACEWAY COMBUSTION
Example: High Rate Natural Gas Injection in Blast Furnace

➢ Issue:
  ▪ Unstable operation at both full and low production with high natural gas injection.

➢ Outcomes:
  ▪ Established good practice of natural gas lance selection to better suit the furnace production rate.
  ▪ Stable and controllable operation.
  ▪ Eliminated production loss caused by high blast pressure at full production rate.

Collaborators: John D’Alessio, U.S. Steel Canada
**Fast Lance**

**Straight Lance**

---

### Pressure Drop Across Tuyere

**High Production**

- **Fast Lance**: Unsuitable
  - Pressure drop too high for stable operation
  - Plant cannot supply enough wind to maintain high production

- **Straight or Bored Lance**: Suitable
  - Increased combustion provides higher tuyere velocity
  - Helps to avoid the practice of tuyere plugging

### Low Production

- **Fast Lance**: Suitable
  - Plant can supply enough wind due to the lower pressure drop

- **Straight or Bored Lance**: Unsuitable
  - Tuyere velocity too low due to reduced combustion
Example: Troubleshooting Blast Furnace PCI Lance

**Issues:**
- Lance failures
- Lance performance

**Outcomes:**
- Significant downtime avoidance by half due to fewer lance failures
- A coke rate savings of 15 lbs./NT hot metal was realized
- $8.5 million per year cost savings

*Collaborator:* John D’Alessio, U.S. Steel Canada
Example: ArcelorMittal Dofasco Case

Objective:
• To increase coal combustion efficiency
• To optimize NG injection location and rate

Outcomes:
• Parametric effects on coal combustion efficiency with 11 cases
• Recommended NG injection configurations and injection rate

Collaborator: Dave Pomeroy, ArcelorMittal Dofasco
Effects of NG Injection Location on Gas Temperature

Possible overheating tuyere tip

Case A1: NG from lance

Case B1: NG from gas port

Gas Temp. (°C)
Effects of NG Injection Location and Rate on Coal Burnout

<table>
<thead>
<tr>
<th>Case</th>
<th>NG from Lance</th>
<th>NG from Gas Port</th>
<th>Coal Combustion Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>$R_{NG}$</td>
<td>0</td>
<td>80.5%</td>
</tr>
<tr>
<td>A2</td>
<td>$1.5 \times R_{NG}$</td>
<td>0</td>
<td>85.0%</td>
</tr>
<tr>
<td>A3</td>
<td>$2.0 \times R_{NG}$</td>
<td>0</td>
<td>90.1%</td>
</tr>
<tr>
<td>B1</td>
<td>0</td>
<td>$R_{NG}$</td>
<td>78.9%</td>
</tr>
<tr>
<td>B2</td>
<td>0</td>
<td>$1.5 \times R_{NG}$</td>
<td>78.6%</td>
</tr>
<tr>
<td>B3</td>
<td>0</td>
<td>$2.0 \times R_{NG}$</td>
<td>79.8%</td>
</tr>
</tbody>
</table>

Note: Coal Combustion Efficiency is the total coal burnout percentage in raceway.

- The coal combustion efficiency increases when the NG is injected from the lance.
- As rate of NG from lance increase, the total coal burnout increases.
Example: Co-Injection of NG and PCI

➢ **Issue:**
  - Need efficient replacement rate of coke by PC and NG
  - Improve combustion efficiency of injected fuels

➢ **Outcome:**
  - Identified improvements in combustion efficiency
  - Possible enhancement of production by 2.5% if implemented

**Collaborators:** Stuart Street, AK STEEL (Former SEVERSTAL, Dearborn)
Results & Discussion

➢ Unexpected explanation for industrial failures
   – NG combustion in tuyere near upper wall
   – High thermal stress and wear
Example: Testing Unplanned Loss of PCI

➤ **Issue:**
  - Co-injection blast furnace loses PCI capability for one of a number of reasons
  - To maintain production, pure NG operation is required

➤ **Outcome:**
  - Examined the impacts of a switch to pure NGI
  - Potential avenues for higher NGI rates highlighted (preheating)

**Collaborators:** Stuart Street, AK STEEL (Former SEVERSTAL, Dearborn)
Results & Discussion

➢ Resulting RAFT is **11%** lower than baseline, at **1,994 K**
  - Temperature drop due to abundance of $\text{H}_2\text{O}$ and $\text{CO}_2$
➢ Raceway gas temperature distribution is also dramatically different
➢ Highest temperatures correspond to locations of NG combustion
➢ Little recirculation of combustion products within raceway
Impacts of PCI Loss and Pure NGI

- Nearly all injected fuel is consumed within raceway
- While CH$_4$ combustion provides heat, byproducts of CH$_4$ combustion result in endothermic reactions
- These results shine light on the quenching effect observed in industrial furnaces at high NG rates
- Limiting factors for furnace stability include condensation in BF (impacted by O$_2$ in blast) and RAFT for furnace heat
- O$_2$ can increase heat, but drops top temp. Max NGI rate is typically near 150 kg/mthm
- Potential to address this problem by pre-heating injected natural gas to maintain RAFT without impacting top temperature
Example: Preheating Natural Gas

Issues:
- High NG injection to replace coke is desired to improve energy efficiency and emissions
- Furnace unstable at high NG rates due to quenching effects on raceway flame T

Potential Solution:
- Preheating NG may:
  ✓ Increase sensible heat input
  ✓ Increase NG injection velocity (enhanced mixing/combustion)
  ✓ Counter reduction in raceway flame temperature

Research:
- Use CFD to determine effects of NG preheating on coke rate and energy efficiency
Effects of Pre-heated NG

- Blast furnace coke rate decreases as natural gas temperature is increased.
- Preheating natural gas from 300 K to 600K can provide a drop of **8.7 kg/thm in furnace coke consumption (2.3%)**
- Assuming a coke price of $275/ton, for a BF operating at 6,500 thm/day, **~$5.88M will be saved annually**

<table>
<thead>
<tr>
<th>NG T</th>
<th>Coke Rate (kg/thm)</th>
<th>Coke Rate Δ</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 K (base)</td>
<td>392.1</td>
<td>0 kg/thm</td>
<td>0%</td>
</tr>
<tr>
<td>350 K</td>
<td>389.3</td>
<td>-2.8 kg/thm</td>
<td>0.7%</td>
</tr>
<tr>
<td>400 K</td>
<td>388.6</td>
<td>-3.5 kg/thm</td>
<td>0.9%</td>
</tr>
<tr>
<td>450 K</td>
<td>387.5</td>
<td>-4.6 kg/thm</td>
<td>1.2%</td>
</tr>
<tr>
<td>500 K</td>
<td>386.0</td>
<td>-6.1 kg/thm</td>
<td>1.6%</td>
</tr>
<tr>
<td>550 K</td>
<td>385.0</td>
<td>-7.1 kg/thm</td>
<td>1.8%</td>
</tr>
<tr>
<td>600 K</td>
<td>383.4</td>
<td>-8.7 kg/thm</td>
<td>2.3%</td>
</tr>
</tbody>
</table>
Example: HPC4Mfg

- Sponsors: DOE/AMO, LLNL
- Goals:
  - Significantly reduce computational time
  - Improve resolutions
  - Develop integrated blast furnace simulators for process control, optimization, design, troubleshooting, and workforce training
- Results:
  - Total of ~1000 cases run to analyze various operating conditions
  - Significant reduction in amount of time required to run large scale studies using capabilities of HPC
    - Time to run on HPC: 144 hours (1 week)
    - Time to run on PC: 6,048 hours (9 months)
BF ‘Simulator’ – Data Analytics

- New methodology for CFD data analytics
- Using CFD results from HPC parametric studies, develop interactive application to predict BF operation outputs
  - Functions at any data point inside data range
  - Will extrapolate for points outside range
- Predict TGF, FTA, coke rate, gas utilization, and shaft ΔP based on input conditions
  - Accuracy matching CFD models (in ideal operation) w/o needing a new run for each condition
- Future Goals:
  - Accessible from SMSVC website
  - Ability to import result sets from any BF
  - Addt’l variables could easily be added to expand the .CSV database
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Example: Blast Furnace Tuyere Nose

➢ Issues:
  • Tuyere failures
  • Downtime and maintenance cost

➢ Outcomes:
  • Identified insufficient cooling in between the nose inlet and the outlet pipe causing tuyere failures
  • 2005 AISI Institute Medal Award

Collaborator: Yongfu Zhao, U.S. Steel Research
Example: Tuyere Failure Analysis

➢ Issue:
  • Unknown reason of tuyere failure

➢ Outcomes:
  • Identified the cause of failures
    ▪ Thickness at the tuyere tip is significant (The thicker, the higher the temperature at the tip surface.)
    ▪ Water temperature and velocity are not critical

Collaborator: Sergey Trenkinshu, ArcelorMittal
Example: IH4 Blowpipe Redesign

**Issue:**
- Blowpipes having short life expectancy
- Refractory cracking, shell hot spots

**Outcomes:**
- Length of thermal paper extended, reducing thermal stress
- Refractory changed to wall-cast, nearly doubling current strength

Collaborator: Dale Goodloe, ArcelorMittal
Features of CFD Shaft Model

- GUI preprocessor
- 3-D
- Burden distribution
  - Falling curve
  - Stock line profile
  - Burden descending
  - Mix layer
- Velocity, pressure, species, gas and burden temperature
- Chemical Reaction (Total 9 reactions considered)
  - Shrinkage un-reacted core model
  - Grain model
Features of CFD Shaft Model

- Cohesive zone shape and location
  - Uniform liquidus temperature
  - Non-uniform liquidus temperature (as a function of burden composition)
- Reduction degree, Coke rate
- CO and H₂ Gas utilization
- Coal ash distribution in shaft
- VR visualization
BURDEN DISTRIBUTION MODEL

❖ Predict burden distribution from a given charging matrix
VALIDATION

➢ Measurement of the impact location for different chute angle

➢ Measurement of first layer profile
CHEMICAL REACTIONS

❖ Indirection reduction by carbon monoxide:
  \[3\text{Fe}_2\text{O}_3 (s) + \text{CO (g)} \rightarrow 2\text{Fe}_3\text{O}_4 (s) + \text{CO}_2 (g)\]
  \[\text{Fe}_3\text{O}_4 (s) + \text{CO (g)} \rightarrow 3\text{FeO (s)} + \text{CO}_2 (g)\]
  \[\text{FeO (s)} + \text{CO (g)} \rightarrow \text{Fe (s)} + \text{CO}_2 (g)\]

❖ Indirection reduction by hydrogen:
  \[3\text{Fe}_2\text{O}_3 (s) + \text{H}_2 (g) \rightarrow 2\text{Fe}_3\text{O}_4 (s) + \text{H}_2\text{O (g)}\]
  \[\text{Fe}_3\text{O}_4 (s) + \text{H}_2 (g) \rightarrow 3\text{FeO(s)} + \text{H}_2\text{O (g)}\]
  \[\text{FeO (s)} + \text{H}_2 (g) \rightarrow \text{Fe (s)} + \text{H}_2\text{O (g)}\]

❖ Decomposition of flux:
  \[\text{MeCO}_3 (s) \rightarrow \text{MeO (s)} + \text{CO}_2 (g) , \text{Me}=\text{Ca, Mg}\]

❖ Coke gasification:
  \[\text{C(s)} + \text{CO}_2 (g) \rightarrow 2\text{CO (g)}\]
  \[\text{C(s)} + \text{H}_2\text{O (g)} \rightarrow \text{CO (g)} + \text{H}_2 (g)\]

❖ Water gas shift reaction:
  \[\text{CO(g)} + \text{H}_2\text{O (g)} \leftrightarrow \text{CO}_2 (g) + \text{H}_2 (g)\]

❖ Direct Reduction:
  \[\text{FeO (l)} + \text{C (s)} \rightarrow \text{Fe (l)} + \text{CO (g)}\]

Gas Solid Reaction Model
- Un-reacted Core Model
- Grain Model
- Kinetic Model

Un-reacted Core Model

Kinetic Diffusion Model

Assume Equilibrium When T>900 °C

Kinetic Model
Iterative Methodology

- Step 1: Assume a cohesive zone (CZ) to initialize the burden structure for CFD simulation.
- Step 2: Obtain the burden temperature distribution using the converged CFD results.
- Step 3: Determine the new CZ using isothermal lines from CFD results with the softening temperature of iron ore (upper boundary) and the liquidus temperature (lower boundary).
- Step 4: Feed back the updated CZ to update the burden structure and conduct simulation.
- Step 5: Repeat the Step 2-4 until the shape of cohesive zone converge.
VALIDATION

We appreciate USS for providing the measurements data for our validation.
EFFECT OF NATURAL GAS RATE

Solution loss

- Plant measurements are from literature: J.C. Agarwal et al., 1992 Ironmaking Conf. Proc.

- High NG Case
  - Baseline Case
  - High NG Case

- Low NG Case
  - Baseline Case
  - High NG Case

Reduction degree

<table>
<thead>
<tr>
<th>Case</th>
<th>Coke Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>High NG Case</td>
<td>411 kg/MTHM</td>
</tr>
<tr>
<td>Low NG Case</td>
<td>423 kg/MTHM</td>
</tr>
</tbody>
</table>

NG rate $\uparrow$ solution loss $\downarrow$ coke rate $\downarrow$
BLAST FURNACE SHAFT SIMULATOR (BFSS)

1. Start
2. Input blast furnace geometry
3. Input burden materials
4. Input tuyere conditions

- BURDEN DISTRIBUTOR
- PRE-PROCESSOR

BLAST FURNACE SHAFT CFD SOLVER

Output

Post-processing and VR visualization
BLAST FURNACE SHAFT SIMULATOR

**Diagram**

- **Throat**
  - Height $H_1$ (m): 2
  - Diameter $D_1$ (m): 9

- **Shaft**
  - Height $H_2$ (m): 13
  - Diameter $D_2$ (m): 13

- **Belly**
  - Height $H_3$ (m): 2
  - Diameter $D_3$ (m): 13

- **Bosh**
  - Height $H_4$ (m): 2
  - Diameter $D_4$ (m): 11

- **Lower Bosh**
  - Height $H_5$ (m): 4
  - Diameter $D_5$ (m): 11

- **Tuyere Level**
  - Height $H_6$ (m): 3

**Dimensions**

- **Throat** $H_1$: 2 m
- **Shaft** $H_2$: 13 m
- **Belly** $H_3$: 2 m
- **Bosh** $H_4$: 2 m
- **Lower Bosh** $H_5$: 4 m
- **Tuyere Level** $H_6$: 3 m

**Set BF Geometry**

- **Shaft Angle** $a$: 81.25°
- **Volume** $V$: 2248.6 m$^3$

**Calculated Results**

- **Height** $H_{RF1}$: 3.3 m
- **Height** $H_{RF2}$: 4.4 m
- **Height** $H_{RF3}$: 9.9 m

**Shaft Points**

- Above Tuyer
- Above-Burden Probe 2
- In-Burden Probe 5

**Unit Conversion**

- **Height** $t$: 13.67 m
- **Height** $t$ Above Tuyer: 18.12 m
EFFECT OF BURDEN DISTRIBUTION
VIRTUAL BLAST FURNACE

➢ Multiple versions of training package
  – PC, Web, Mobile
  – 3D TV
  – 3D Immersive Virtual Reality (VR)
  – Augmented Reality (AR)

➢ Taught in industrial training and short courses world wide

➢ Used for problem solving for design, troubleshooting and optimization with multimillion savings and cost avoidance
U.S. Steel Blast Furnace Ironmaking Academy  
Total 20 Participants

<table>
<thead>
<tr>
<th></th>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neutral</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td>The VBF simulator was <strong>beneficial</strong> as a visual learning aid in this training course.</td>
<td>95%</td>
<td>5%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>The VBF simulator enables me to <strong>better visualize</strong> the blast furnace and its equipment in a way that is difficult for me to do with presentation slides or text alone.</td>
<td>85%</td>
<td>15%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Training courses on <strong>other process</strong> (i.e., cokemaking, steelmaking, etc.) should develop similar simulations in the futures as a learning aid.</td>
<td>80%</td>
<td>20%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

"excellent training tool; great problem-solving capabilities"; "This interactive model helped me visualize the material flowing through the process. It was very helpful in understanding the flow"
Comprehensive CFD modeling and visualization provide important tools for blast furnace process/product design, optimization and troubleshooting to address issues on energy, environment, productivity, quality, and training.

The integration of CFD simulation and VR visualization provides innovative ways to create virtual worlds of real problems for cost-effective solutions.
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➢ U.S. Dept. of Energy HPC4Mfg Program
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➢ American Iron and Steel Institute
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  ▪ All industrial collaborators
  ▪ CIVS staff & students

centers.pnw.edu/civs
www.steelconsortium.org