Predictive Tools and Innovations in the Ventilation of Cooling Beds

Digital technologies are transforming industry at all levels. Steel has the opportunity to lead all heavy industries as an early adopter of specific digital technologies to improve our sustainability and competitiveness. This column is part of AIST's strategy to become the epicenter for steel's digital transformation, by providing a variety of platforms to showcase and disseminate Industry 4.0 knowledge specific for steel manufacturing, from big-picture concepts to specific processes.

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A number of recently executed U.S. projects were used as examples of innovations in the fundamental application of a developed system and method of ventilator selection to match cooling bed requirements. This is key to mill function, interior working conditions and reducing steelmaking cost. Specific tools have been optimized to predicatively demonstrate, coupled with traditional calculations and physical modeling, ventilation performance and heat exhaust of cooling beds, assuring that the proper solution is in place for the complete life cycle of the process equipment and manpower.

As obvious as any statement could ever be, the purpose of a long products cooling bed is the cooling of beams, rails, reinforced bars and other long products through air convection after their production in the hot mill, rolling, finishing and potentially quenching process areas of a long products steel mill. Three opposing needs and determining the most effective solution render this study relevant and compelling: cost, quality and plant safety. The practical application of natural gravity ventilation, which includes but would be not limited to the use of gravity roof ventilators, usage and placement of inlet louvers for process exchange air, the placement of the process itself, the size and shape of the mill building envelope, and the time and length of the cooling bed to allow for long products to cool, can produce a process result that is most efficient in terms of cost and time, while delivering or exceeding grade quality specification to the long products being produced all while optimizing plant safety.

As all of the work conducted under this study occurred with long-standing confidentiality agreements in place, the specific results and applications must remain undisclosed, as the actual rates of cooling for specific sizes and alloys might allow the reverse engineering of a steelmaker's use of particular tools and innovative techniques at making better steel more efficiently. The authors believe that the general methods can be applied to other applications and are repeatable and verifiable.

Discussion

Practical Purpose of Cooling Beds —

The practical work of Sir Henry Bessemer and its application, which flows through 19th-century pioneers such as Carnegie and Scranton to the innovative practices of 21st-century mini-mill producers, was mainly at the front end of the hot mills. This is to produce metal cheaply while maintaining a required quality level consistent with a particular type of steel. No process can effectively handle the daily throughput volume if the product cannot be cooled and handled in a timely manner, while ensuring a quality level that allows mill certification grade rating of finished goods by the American Standards for Testing and Materials (ASTM). Improperly handled or cooled material in quenching and as well in air convective cooling phases can present steel with many defects even after the best practices are applied through the hot mill. Defects in steel products are defined as deviations in appearance, shape, dimension, macrostructure/microstructure and/or chemical properties when compared with the specifications given in the technical standards or any other normative documents in force. All of the foregoing basically means cracks, inclusions and delamination issues that increase defects are detected either through visual inspection or with the help of instruments and equipment. This creates bottlenecks that hinder what should be effective mill processes and must be avoided as well in order to ensure that the best possible price and grade can be achieved for the end product.

While speed is important, at the same time it is important to allow the long product to cool below the critical rate of cooling. A cooling process that pushes the steel to cool too rapidly or does not allow for even cooling may be the cause for numerous defects in finished products as well, therefore hindering the finished product from making the desired ASTM grade. There is a need for a balanced and considered approach to arrive at a best practice case in the ventilation of long products cooling beds. The microstructure of steel is responsible for the macrobehavior of steel or, in other words, steel's material properties. And once a cooling bed process is in place, it is difficult or expensive to make changes. The small cost difference between the well-considered and well-designed ventilation system of a cooling bed and an ill-conceived system can be huge in time spent with non-destructive testing, metallurgical repairs, frustration and steel grade (and its value in the global steel marketplace).

Cooling beds consist of drive systems that cycle fixed and moving rakes. The rakes then "walk" the product across the cooling bed as it cools at a pre-determined rate. Unequal heat release generally results in stresses in the produced materials. By having moving rakes, the metal is turned, avoiding parts of the profiles to be in continuous contact with the bed supports, causing differences in the rate of cooling. Cooling beds for rails and blooms may not have a rake pattern but utilize chain transfers. The long product mill cooling bed generally sits between the finishing mill and cut-to-length shears and heat treating facilities and the straightening, cold shear transfer and inspection stations. If properly cooled, throughput at later process stages is increased, the costs required at these stages are mitigated and grade standard is improved.

Determination of Heat Generation — Designing a properly conceived cooling bed for steel and its interior environment is a convergence of metallurgy, thermodynamic engineering and specific U.S. Occupational Safety and Health Administration (OSHA) standards. Like all generalities, it is easier said than done and, as steelmakers have known through the ages, the devil is indeed in the details.

Once a steel mill's annual production and maximum hourly throughput is established, it is a matter of properly sizing a cooling bed and locating it within the mill for best possible utility and ventilation. Create a building envelope that allows for OSHA-required air changes per hour, efficient proximity of inlet openings to the bed (fresh air intake louvers) and heat exhaust above the cooling bed (gravity roof ventilator).

"Scala graduum Caloris. Calorum Descriptiones & signa." in *Philosophical Transactions,* 1701 (only 320 some years ago!), gave the steelmaking practitioner Newton's Law of Cooling, which describes the cooling of a warmer object to a cooler temperature. This law is written as:

$$T(t) = T(e) + (To - Te)\ e^{kt} \qquad \text{(Eq. 1)}$$

where

To = temperature of metal arriving a t cooling bed,
T = temperature of cooled metal (end of cooling bed),
Te = ambient temperature and
K = 1/RC.

where

R = thermal resistance between steel and environment,
C = caloric capacity of the object and
C = c * m.

where

c = specific heat (in the steel of steel 502 joules/kg * k (a constant) and
m = mass of object (weight of steel being cooled).

As the mechanical engineering reader can remember from school, this can be restated as the Fourier Law:

$$\frac{dQ}{dt} = -h \cdot A \cdot \left(T(t) - T_{env}\right) = -h \cdot A\Delta T(t) \qquad \text{(Eq. 2)}$$

where

Q = the thermal energy (SI unit: joule),
h = the heat transfer coefficient (assumed independent of T here) (SI unit: W/(m^2 K)),
A = the heat transfer surface area (SI unit: m^2),
T(t) = the temperature of the object's surface and interior (SI unit: K),

T(env) = the temperature of the environment, i.e., the temperature suitably far from the surface (SI unit: K) and

T(t) = the time-dependent thermal gradient between environment and object (SI unit: K).

All this to say in practical terms that specific alloys in specific sizes (which have a specific mass) cool at a specific rate which can be determined as calculable, verifiable and repeatable. What the formulas do not provide is the optimal rate of air convective cooling to achieve the optimal result in term of cost of result and grade of material.

These values can also now be verified for a specific shape and alloy utilizing a software package from ANSYS, which allows computerized fluid dynamic (CFD) modeling, finite element modeling (FEM) and finite element volume modeling (FVM), each of which are topics too large to discuss here.

Ferrous long products have a tradition of utilizing cooling beds, with significant innovative and modernizing work having been carried out by engineer John Johnston and his team at United States Steel Corporation's engineering offices in the 1930s. This allows the current steel works practitioners the ability to compare calculations and modeling with the proven results of operating facilities and utilize the comparison in physical modeling experimentations prior to executing on any given process equipment.

However, as the steelmaker will know how much steel they are producing, how much heat the material gives off in a particular rate of cooling and how long it should generally take to cool to achieve the desired result, the steelmaker has the information to know how long (in length) a cooling bed is required for the tonnage of steel produced in a set period. The next steps are to determine the proper building envelope, inlet and outlet to achieve the desire air convection for cooling and air exchange for an acceptable interior safety standard.

Natural Ventilation Determination of Heat Extraction

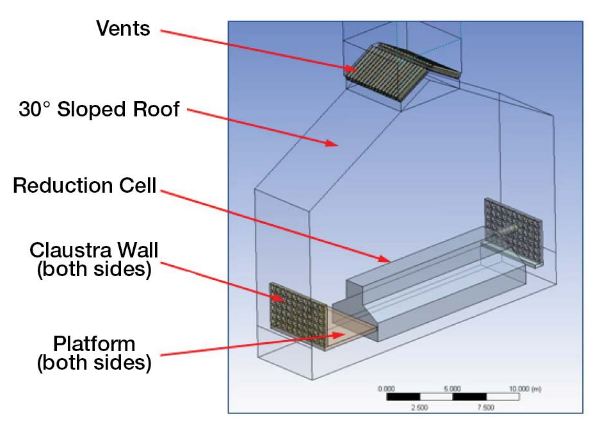
For the hot process building of a steel mill to function, heat has to be extracted from the inside of the building. This is as true for the cooling beds as it is for furnace area, rolling mills, quenching stations and other heat-producing areas of the mill. This is done by having air inlets at the bottom of buildings and outlets at the apex of buildings. The reason for this is to maximize the potential chimney effect. When using stack (buoyancy) effect ventilation, the process heat becomes the driver and therefore increasing this distance (height) improves the ability of the heated airstream to utilize basic gravity for acceleration of the heat/airflow. This allows a regular number of air changes per hour within the plant environments all while ensuring that the process environment remains weather resistant under process operating conditions.

This process has been understood at least from the time King Charles I of England decreed in 1600 that castle rooms should have 10-foot ceilings and that windows should be taller than wider to allow better smoke extraction. In 1914, the American Society of Heating and Ventilation Engineers (the predecessor of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, or ASHRAE) published that 50 m^3 of air per hour per human was a minimal standard. The 2004 ASHRAE/ANSI standard 621989[1] has been optimized to 42.4 m^3 of renewed or fresh air per hour per human. This ASHRAE standard relies on the National Ambient Air Quality Secondary Standard for airborne particulate at 60 μg/m^3 with a mean 24-hour maximum of 150 μg/m^3.

Natural ventilation occurs by two different means: first, wind-driven natural ventilation, where the topography of the building is studied to create a building shape where, either by pressure or suction, the warm air within the building is drawn to the exterior. This system is reliant on a particular constant minimal wind factor (Cw), which can generally not be assumed for most industrial building applications. Second, stack effect natural ventilation, where the differential of temperature and pressure between two bodies of air creates buoyancy in the airstream of the air body within the process building. This sort of system must work in all wind conditions, including under zero wind conditions, as shown in Fig. 1.

Within the building there exists a neutral plane. Below this line, air is drawn into the building; above this line, air is exhausted. The larger the distance between in the ingress and egress, the greater the chimney effect. Therefore, the greater the velocity of

Figure 1



General layout of process building.

air and therefore the total quantity of heat that can be extracted from the inside of the process building. Gravity ventilation is a form of stack effect ventilation that requires no power source. It is also a static process, which means no parts making additional noise or vibration. This is a large benefit in an environment where there is already sufficient noise and vibration in the interior and ambient environments.

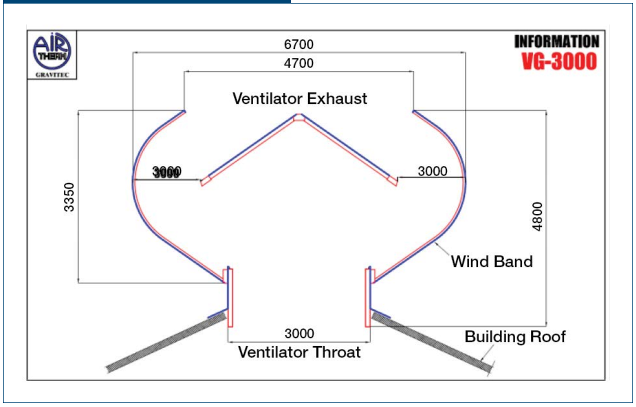
Heat from the air convective heat release of the cooling bed fills the interior space within the occupied building and a very high quantity of heat (as described in kilowatts or British thermal units) is produced and must be exhausted to conform to state and national building standards and, in a number of cases, state and national hygiene standards. The purpose of this ventilation system (air inlet, grating and gravity ventilators) is for the extraction of heat by means of air exchange. Control and abatement of process-released gases and particulate should be handled by advanced process equipment defined as the gas treatment center.

Air-Therm's tulip-shaped gravity roof ventilator is called the VG Gravitec. It consists nominally of a 100% free area throat stack, a covered central roof section and two specialized designed asymmetrically rounded wind bands sections that are open to at least the throat's 100% free area, as can be seen in Fig. 2. The tulip design consists of a structural frame, corrugated cladding and internal gutters made of light-gauge sheet metal. The frames can be reclad if required, giving the steel mill buildings an extended life cycle. Each application design is dependent on specific location variables, however overall height of the ventilators tends to be nominally 150% of throat opening.

Air-Therm has developed a series of low-profile design ventilators dating back to the 1960s. These ventilators consist of sheet metal boxes with a series of baffles and gutters that allow for nominally 50% free area all while being weather resistant under positive smelter operating conditions. If the low-profile module begins corroding due to the mill environment, it may require complete replacement of the affected modules. The low-profile designs are nominally 500 to 900 mm in height (Fig. 3).

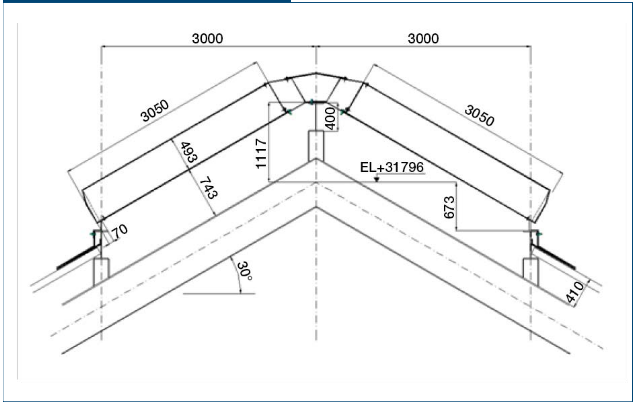
A driving factor in the decision to construct new steel mills is the reduction in total installed construction costs. Low-profile ventilators are less expensive (supply cost) and have significantly lower dead and live load forces on the building's structure, therefore requiring significantly lighter and less-expensive building roof structure.

Figure 2



Configuration of tulip-shaped ventilator.

Figure 3



Configuration of low-profile shape ventilator.

Methodology

Computational fluid dynamics involves the discretization of the solution domain into finite volumes (control volumes) and the subsequent solving of the Navier-Stokes equation (conservation of momentum), conservation of mass and conservation of energy equations. In addition, in this case, the buoyancy forces are also being considered. The commercial CFD software Fluent version 13.0.0 – SP2 was used for the analysis. Fluent is a well-known CFD solver that has been benchmarked for many types of problems.

Based on the positive results utilizing this system, the CFD solver is being upgraded to the next level, called CFX.

Testing and Understanding CFD Simulation as a Relevant Tool

This research project has been carried out utilizing a quantitative research methodology. After an audit of available resources and the creation of a pilot project (one-shot experimental case study), which would give rapid prognosis, and observing the strong potential for a successful result, a pre-test–post-test control group design for a complete project roll-out was executed.

By assuming that all engineering technologists and engineers are equal, the manpower required for the study was randomized in equal groups. Due to the nature of the particular project, it was possible to have a control group working side by side with the group implementing the experimental system. It was immediately obvious who was part of the experimental group and who was not.

One group had access to internal and external CFD resources and finite element testing resources and the other did not. Being in an engineering office together, both teams immediately recognized that management was implementing a test system. From an engineering standpoint, this meant assembling the required information and specification, designing a system specific to the proposed application, implementing the system, and then verifying the performance using empirical data. The assumption was that the CFD and FEM model would give a more precise and visual result, which should be comparable to hand calculations and physical model research.

Model Description

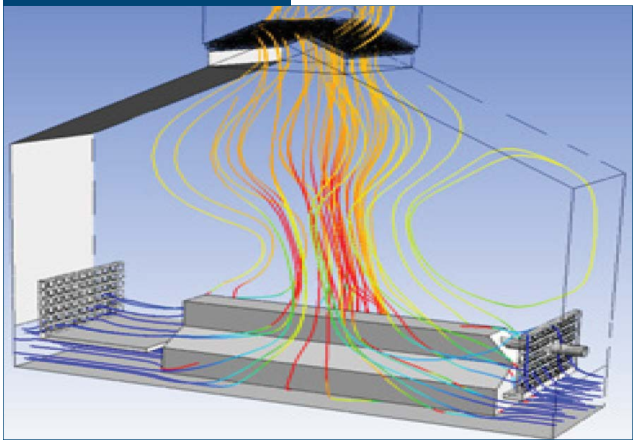
In this particular comparative application, Air-Therm VG-Series ventilator and a number of Air-Therm Low Profile models were positioned at the top of the cooling bed application with a particular height from ground to ventilator inlet (throat). The dimensions are identified in Fig. 3. Fig. 4 shows the details of the potential Air-Therm ventilators. In the CFD model, the ventilators were simplified in order to keep the mesh size reasonable; however, the important dimensions such as flow areas were maintained similar to those of the actual ventilators. Sitting on top of the same building, with the same height roof pitch, process conditions and external ambient conditions of both ventilation configurations were simulated.

In the case of the VG tulip model, there was a static pressure drop of approximately 4.5 Pa. In the case of the low-profile designs, there was a pressure drop of approximately 16 Pa. Simulations were carried out multiple times and due to modeling factors there are always nominally different results; however, all simulations demonstrated very similar characteristics with similar effects and pressure drops. Considerations reviewed were location of the stack relative to flow separations, building stack height and the design slope of the building roof. For the purpose of this study, the cooling bed buildings were considered the tallest surrounding structures.

Based on the volume of metal being produced, an ability to calculate the heat released per duration and the duration required for the optimal economically viable steel grade, it was possible to ascertain the required ambient air inlet and natural ventilated heat exhaust for any particular cooling bed application with the previously used calculations and then either verify the results with computer modeling and already in-place results, or alternatively ensure that computer models have been correctly carried out by hand to verify computer models. Any variance in results should give pause to reverify both sets of calculations.

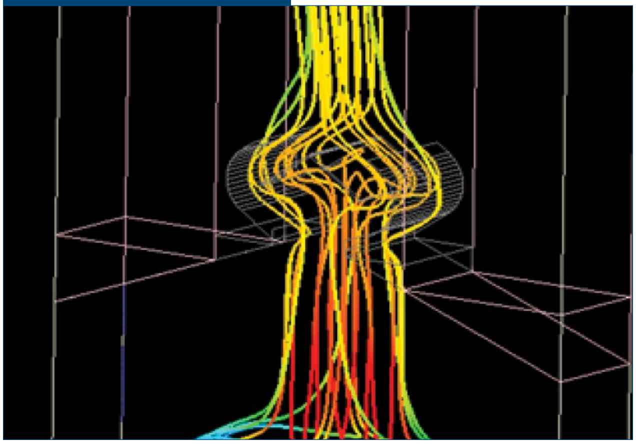
Limitations — Computational fluid dynamic (CFD) models that attempt to resolve airflow around buildings by solving Navier-Stokes are able to give accurate internal and in-flow models. However, it is more difficult to utilize CFD models to accurately predict airflows in a mixed open environment. Computational wind engineering (CWE), due to the size of the models, remains a tool for general guidance. This is due to

Figure 4



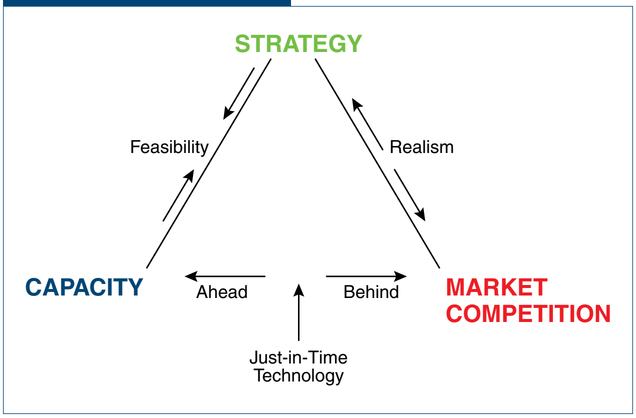
Low-profile simulation.

Figure 5



Tulip-shaped simulation.

Figure 6



Dynamic situation triangle.

variance and prediction inaccuracies. Direct numerical simulation (DNS) requires significant computing capacity and due to its complexity is not an available tool for the designing practitioner. Large eddy simulation (LES) and detached eddy simulation (DES) will eventually be other tools to understand the potential re-entrainment of exhausted gases.

Combining CFD simulation with physical modeling experimentation, hand calculations and field measure of existing smelter facilities will give the engineering practitioner the best approach to optimizing their ventilation design, allowing for the reasonable and feasible application of available information and science.

Conclusion

With the advent and availability of affordable and practical CFD solutions, optimization in design is possible in the early stages of project planning that allows for better understanding of safety concerns, possible design optimization and backup of empirical calculation and physical modeling results. It has been found that in its current state, CFD technology can be considered a "just-in-time" technology for the design, health, safety and environment, as explained in Fig. 6. However, results should always be viewed critically and reverified with other means to ensure the correctness of results.

This study demonstrates that beyond the historical and correct use of empirical calculation and physical modeling, affordable and available technologies are improving engineers' ability to deliver needed information and produce the best possible engineered result.

A design team can now request to see different sizing, types and locations of ventilators and inlet louvers for their cooling bed applications to gauge the potential results, can adjust and move the location of air inlets, and can even potentially adjust the location of process equipment to improve air guidance performance for man, machinery and the making of steel.

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