BHEL Smart Wall Blowing System: New Product Development in Manufacturing Industry

Abhishek Kumar, R. Dhanuskodi, R. Kaliappan and K. Nandakumar

THE NEED

The head of Research and Development (R&D), Bharat Heavy Electricals Limited (BHEL), Trichy, India was pensive. He looked at the colourful plumage of the peacock that had strayed toward his window and wondered at the stark contrast between the industrial R&D centre and the magnificent bird. He wondered if the presence of the bird was a possible source of creativity necessary to deliver advanced research that would solve a niggling problem. The lower-than-expected heat transfer occurring inside the boiler furnace due to ash deposits on the furnace walls and tube erosions caused due to unnecessary cleaning was an issue that was bothering him. A boiler typically consists of a furnace in which the fuel is fired to produce steam from the water passing through the tube. The tubes create panels that enclose the furnace. As water moves up in the wall panels, it absorbs radiative heat from the products of combustion and gets converted into steam. A lower-than-expected heat transfer due to coal ash deposits in the products of combustion over the wall panels would reduce both the quantity and quality of the steam delivered at the end of the boiler. This significantly affected the efficiency of the plant and caused substantial revenue losses.

The ash deposits were removed by manual operation of all blowers sequentially once in 8 hours to mitigate this problem. However, this was done without understanding the need for cleaning. It is to be noted that the blowers used high pressure and high velocity steam. Cleaning all blowers ritually was a suboptimal solution as the steam jet passing through the non-deposit areas resulted in faster erosion leading to punctures in or bursting of water tubes. This, in turn, caused frequent boiler shutdowns for repair and consequentially a huge financial loss. The R&D head needed a solution that led to automatic cleaning of ash deposits, when essential, to prevent revenue loss due to boiler shutdown.
BHEL: THE HEAVY ELECTRICAL EQUIPMENT GIANT

BHEL, an integrated power plant equipment manufacturer, is one of India’s largest engineering and manufacturing companies. BHEL has represented the core of India’s heavy electrical equipment industry since its incorporation in 1964. BHEL’s growth is considered synchronous with India achieving self-sufficiency in the indigenous manufacturing of heavy electrical equipment, which meets a major part of the country’s power requirement. Of the available 35,000 MW (www.powermin.nic.in) per annum capacity for power plant equipment manufacturing in the country, BHEL constituted nearly 20,000 MW per annum capacity (www.bhel.in).

A widespread network of 17 manufacturing divisions, two repair units, four regional offices, eight service centres, six overseas offices, six joint ventures, and 15 regional marketing centres, and ongoing project execution at more than 150 sites across India and abroad have made BHEL join the elite club of select global giants having an installed capacity of more than 180 GW of power-generation equipment. BHEL had an overseas footprint in 78 countries. The quality and reliability of BHEL products are high since BHEL has adhered to international standards by acquiring and adapting some of the best technologies from leading companies worldwide, including General Electric Company, Alstom SA, Siemens AG, and Mitsubishi Heavy Industries (MHI) Ltd., in addition to the technology developed in its R&D centres.

STRUCTURE AND GROWTH OF RESEARCH AND DEVELOPMENT IN BHEL

BHEL placed a strong emphasis on innovation. With its innovation-based growth strategy, BHEL ranked among the country’s highest R&D spenders in the engineering and manufacturing segment. BHEL spends an average of greater than 2.5% of its turnover on R&D. It has filed 475 patents and copyrights in the last year thus enhancing the company’s intellectual capital to 3,915, which includes patents, copyrights, and design registrations. The Corporate R&D division at Hyderabad leads BHEL’s research efforts through 14 Centres of Excellence (Exhibit 1) and four specialized institutes, namely Welding Research Institute (WRI) at Tiruchirappalli, Ceramic Technological Institute at Bengaluru, Centre for Electric Traction (CET) at Bhopal, and Pollution Control Research Institute (PCRI) at Haridwar. The Amorphous Silicon Solar Cell Plant at Gurgaon conducted R&D in photovoltaic applications.

Exhibit 1. Fourteen Centres of Excellence of BHEL.

| S. No. | Centre of Excellence for | Unit |
|--------|-------------------------|------|
| 1      | Simulators              | Corporate R&D, Hyderabad |
| 2      | Computational fluid dynamics | |
| 3      | Permanent magnet machines | |
| 4      | Surface engineering     | |
| 5      | Intelligent machines and robotics | |
| 6      | Machine dynamics        | |
| 7      | Compressors and pumps   | |
| 8      | Nanotechnology          | |
| 9      | Ultra-high voltage      | |
| 10     | Advanced transmission systems | |
| 11     | Power electronics and IGBT and controller | Electronics Division, Bengaluru |
| 12     | Control and instrumentation | |
| 13     | Advanced fabrication technology | High-Pressure Boiler Plant, Trichy |
| 14     | Coal research           | |

Source: BHEL documents.

The R&D department of BHEL has won several accolades in the recent past (Exhibit 2).

The R&D head felt great pleasure in being a part of the department as he had plenty of opportunities to solve challenging problems. BHEL had ensured diversity in the department by debuting at least one expert from every field of specialization.

HIGH-PRESSURE BOILER PLANT AT BHEL, TRICHY

The BHEL Trichy plant specializes in manufacturing boilers ranging from 30 to 800 MW capacity. It could manufacture boilers with supercritical parameters of...
Exhibit 2. Recent Recognitions for R&D Efforts of BHEL.

- PSE Excellence Award 2015 for Human Resource Management Excellence and R&D, Technology Development and Innovation in the Maharatna and Navratna CPSEs category by Indian Chamber of Commerce (ICC)
- India Today Award 2014 and 2015 for Best R&D and Innovation in the Maharatna category
- CII Industrial Innovation Award 2015 awarded to the Top 25 Most Innovative Companies in India
- Thomson Reuters India Innovation Award 2015, awarded to the Top 50 Indian Innovator Companies and Research Organizations
- ICC Awards for HR Management Excellence and R&D, Technology Development and Innovation
- PSE Excellence Award in R&D, Technology and Innovation category by Indian Chamber of Commerce in 2012, 2013, and 2014
- National Intellectual Property Award 2014 for research and development conducted in India
- BT-Star Award for the Most Innovative PSU in the Maharatna and Navaratna categories in 2012 and 2013
- Ranked No. 1 company for filing patents in India by Economic Times Intelligence Group
- Golden Peacock Award 2013 for Innovation Management

Source: BHEL documents.

up to 1,000-MW capacity. This unit generally accounts for 20 to 25% approximately of the total revenues of BHEL.

BHEL Trichy employed approximately 10,000 people directly. It had developed a large number of ancillary units that are also its vendors. The products handled are mostly boiler-related, such as fossil-fuel-fired, fluidized, and industrial boilers. The other products are heat-recovery generators, industrial and utility valves, power plant piping, seamless steel tubes, spares, and other advanced technology products. This plant is a leading centre for coal-based R&D in India with hundreds of person-years of expertise in designing boilers for optimum performance.

HEAT TRANSFER IN BOILERS OF A THERMAL POWER PLANT

A boiler is the key equipment of any power plant. A boiler is a closed vessel involving tube panels and heat exchangers, in which water is circulated to convert it into steam. The metal tubes welded as a panel form the walls of the boiler furnace and are called water walls. Steam is produced in it using the heat generated by burning fuel or a combination of fuels. The steam is subsequently expanded to rotate turbines and convert heat energy to mechanical energy. This mechanical energy is further converted to electrical energy or electricity in a generator coupled with the turbine. The heat generated by fuel-burning is transferred to water flowing through tubes, and that converts water to steam. The extent of heat transfer is exhibited by the temperature of gases dropping to 150°C (while leaving the boiler) from 1,500°C (furnace). The combustion of fuel led to molten mineral matter (ash) deposition on water walls.

Exhibit 3. Positions of the Wall Blowers in a Boiler.

Source: Product Catalogue of BHEL, Trichy, India.
CHALLENGE OF OPTIMIZING HEAT TRANSFER

The R&D head struggled with the less-than-desired heat transfer to the water walls that was critical to the boiler’s efficiency. The combustion of fuel led to molten mineral matter (ash) deposition on water walls. These deposits impeded heat transfer and sometimes fuel input was increased to compensate for the decreasing steam parameter. In the event of inadequate heat transfer, gases caused overheating of downstream components (i.e., superheaters and reheaters), making it necessary to spray partially heated water to cool downstream components and prevent a reduction in efficiency of the boiler.

To overcome the decrease in heat absorption due to ash deposition, boilers were supplied with wall blowers that used high-pressure steam jets to remove deposits on tube surfaces. Exhibits 3, 4 and 5 depict the locations of wall blowers in the boiler furnace and a typical wall blower and the number of wall blowers per boiler, respectively.

These wall blowers are operated ritually once in 8 hours. Although they remove ash deposits, they require manual decision-making, which is cumbersome and individual-driven. In the manual system, all wall blowers are operated sequentially without considering the need or understanding of its impact. The manual process cleans even the nil-deposit areas that make the tube surface face the steam jet’s high impact, thereby causing tube erosion. The system does not sense variations in the deposition pattern and consequent changes in heat flux reduction. As the system is operated at fixed time intervals, the time interval between two operations causes the accretion and sintering of ash deposits, complicating subsequent cleaning. As a result, heat transfer rates vary widely and affect the performance of the boiler.

Concept Formulation

The R&D head needed a solution to remove ash deposits from the water walls as and when they occurred. He was aware that Clyde Bergemann Inc., Diamond Power, and B&W Power Clean manufactured automated wall blowing systems that could achieve the desired outcome. However, he knew that their costs would be prohibitive and would adversely impact profitability. In addition, he was not sure about the ability of these companies to handle the quality of Indian coal nor their performance for boiler conditions in India. Therefore, it was decided that the required technology will be developed by the R&D department, which would also coordinate with various departments to manufacture the product.

The first step towards constructing a solution was to build a dynamic feedback mechanism that pointed out lower than normal heat transfer, which triggered the need for intervention. His experience of working at the Fuel Evaluation Test Facility (FETF) led him to believe that sensors can measure the extent of heat transfer as it followed a reducing trend with the deposit and could facilitate accurate determination of the occasion when blower operation was required. He realized that the solution lay in starting the cleaning of deposits only when heat transfer dropped below the specified level. It was also necessary to ensure that the cleaning process skips the areas where heat transfer could not decrease. The solution required the development of heat-flux sensors, the creation of heat flux profiles along with the furnace height, and data analysis of changes in heat transfer after wall blowing was done.

Development of Water Wall-mounted Heat Flux Sensor

The commercially available sensors were expensive, and using them would have affected the cost competitiveness of the BHEL boilers. However, the costs were projected to rise as nearly 40 sensors were required for a 210 MW boiler. A team of six members was constituted to develop heat flux sensors in-house. Sensors involving thermocouples that collected data to indicate a decrease in heat transfer were the toughest to develop. The conceptualization itself posed a challenge as it involved the selection of a material that would be sensitive to changes in heat transfer, determination of its size as it could not project itself too much inside the boiler and attract ash deposits on itself to become unrepresentative of the boiler conditions. It included smooth welding of the sensor to water tubes so that no air gap developed to prevent conductivity. Its conceptual structure was finalized by the design laboratory of the R&D department. It required a collective effort of engineers from the R&D department and WRI. WRI chipped in with inputs on machining, thermocouple fixing, bracing, etc.

Heat flux sensors were tested, and their performance was recorded at Karnataka Power Corporation Limited (KPCL) power plant for 1 year. The sensors were found

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**Exhibit 4. Number of Wall Blowers as Per the Boiler Size.**

| Size of the Boiler (in MW) | No. of Wall Blowers |
|---------------------------|--------------------|
| 60                        | 26                 |
| 110                       | 40                 |
| 120                       | 40                 |
| 210                       | 56                 |
| 250                       | 56                 |
| 500                       | 88                 |
| 660                       | 98–102             |
| 800                       | 104–112            |

*Source: Product Catalogue of BHEL, Trichy.*
procurement of the hardware and developing the relevant software. It included installing, commissioning, and demonstrating the smart wall blowing system’s functioning at the boiler site.

**Development of Logic for the Software**

The conceptualization of the logic involved grouping of blowers for each sensor within the furnace and dynamic fixing of upper and lower temperatures at which the blower operation should start and stop. Similarly, the heat flux threshold for each sensor was optimized to determine whether a particular zone needs cleaning. The team developed an appropriate logic, and the software for the logic went through several iterations and troubleshooting before final establishment. The final version ensured relevant data acquisition, analysis, dynamic updation of benchmarks, and interpretation to facilitate blowing decisions and communicating actions to the blower control system.

**Control Systems and Data Acquisition**

Once the operational logic was finalized, the Electronics Division, BHEL Bangalore, developed the data acquisition, control systems, and software to implement the logic. The team working on the project at Trichy provided the following inputs:

A template to mimic the current measured heat flux and data trends to be stored, and the tabular presentation of data. Relevant software development, instrumentation, cabling, and integration of the motor control centre and wall blower control panel were performed jointly by the Electronics Division, BHEL, Bangalore, and the Controls and Instrumentation Department of R&D BHEL, Trichy.

**Smart Wall Blowing System: An Integrated View of the New Product**

Smart Wall Blowing System (SWBS), the new product, performed the wall-blowing operation on detecting a decrease in furnace heat transfer. It operated blowers only in the regions where it had detected ash deposit impeding heat transfer. SWBS was automatic and required no manual intervention. The decisions to start/stop and operate/skip the blowing operation depended on analysing relevant data.

The starting or stopping of the wall blowing cycle was decided after assessing the furnace heat transfer. Heat flux sensors indicated heat absorption level. Sensors calculated changes in heat transfer by measuring the temperature output difference that was likely to be in proportion to absorbed heat flux. Heat transfer data was processed by the data acquisition and control system, and the necessary intervention was made automatically. Exhibits 6, 7, 8 and 9 provide complete details of BHEL SWBS and the stages of its development.
Exhibit 6. About SWBS.

**Source:** Product Catalogue of BHEL, Trichy.

Exhibit 7. Features of Smart Wall Blowing System.

**Source:** Product Catalogue of BHEL, Trichy.

Exhibit 8. Comparison between Conventional and Smart Wall Blowing System.

| Detail                                      | Conventional System                                                                 | Smart Wall Blowing System                                                                 |
|---------------------------------------------|--------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| **Purpose**                                 | Routine operation of all wall blowers to remove deposits settling on the water-wall tubes | To maintain net furnace heat absorption at the optimum range continuously through deposit removal by selective wall blowing |
| **Features**                                |                                                                                      |                                                                                          |
| Trigger for operation                       | Operator initiated                                                                    | Automatic, cross-correlated with the superheater spray flow levels and sensor heat flux levels |
| Periodicity of operation                    | Operated at periodic intervals - normally once in a shift, sequenced one blower after another | Operated on a selective and need basis, only when deposits have reduced furnace heat absorption resulting in increased superheater spray flow |
| Performance feedback                        | The display system is limited to an indication of operating wall blowers               | Displays blower status, cumulative blower operation data, fault indications, alarms, heat flux levels at various elevations, superheater, reheater spray trends, etc. The history of all these data can also be viewed |
| Cognitive capabilities                      | Does not recognize/ differentiate between variations in deposition pattern and consequent heat flux reductions at different zones | Senses the deposit pattern and consequent heat flux reductions at different zones for activating need-based wall blowing. The system provides furnace performance data, which could be used for evaluating wall blower performance, the impact of changes in fuel/ blends, mill combination, tilt, etc., on furnace heat absorption |

(Exhibit 8 Continued)
Exhibit 8 Continued

| Detail | Conventional System | Smart Wall Blowing System |
|--------|----------------------|---------------------------|
| Benefit | | |
| Steam quantity used | Higher | Lesser due to reduced number of wall blower operations |
| SH/RH spray level excursions between successive wall blowing periods | Wide fluctuations in SH/RH sprays. Reaches low on completion of wall blowing, but increases with time after that | Reduced excursions in SH/RH steam temperatures/sprays as well as lower cumulative SH/RH spray levels |
| Creep life of tubes | Creep life is reduced whenever metal temperatures go above the design limit due to higher gas temperature excursions | Increases the creep life of downstream heat transfer components since temperature excursions are controlled |
| Steam erosion of tubes | Higher possibility, as wall blowing is done ritualistically in 'nil deposit' areas as well | Significantly reduced level of erosion, as wall blowing is operated only when a certain level of heat flux reduction due to deposition is sensed |
| Accumulation and hardening of deposits | More likely, due to increase in furnace temperatures from the time of completion of one wall blowing cycle to the start of next wall blowing leading to accretion and sintering of ash deposit | Reduced possibility of accumulation of deposit due to better furnace temperature control and need-based deposit cleaning |
| Operational cost savings | Scope is less | Reduction in the operation of wall blowers (could be around 60%) results in direct savings in steam/water and coal. Reduction in average SH/RH spray flows results in increased steam cycle efficiency. Significant reduction in replacing steam eroded water wall tubes results in reduced overhaul time with |

Source: Product Catalogue of BHEL, Trichy.

Exhibit 9. Stages of the Product Development Process of SWBS.

Source: Product Catalogue of BHEL, Trichy.
The blowing operation began with the uppermost blowers on one of the four walls. If it did not reduce the spray below the lower benchmark, blowers on the next wall at the same elevation were operated. This process continued till the spray settled below the lower benchmark. The next wall blowing cycle started only when the upper limit of the benchmark was crossed. The next operation would begin from the last stage of the previous operation. Thus, SWBS operated to maintain heat transfer within a set range and ensured that the boiler efficiency was not compromised. The upper and lower benchmarks of spray for starting and stopping the wall blowing cycle were auto-selected by the software.

SWBS was a solution that was created by integrating simple hardware and software ideas. The integration exercise included identifying relevant metrics to optimize the system’s operational logic. A large number of experiments were performed before the logic was finalized. The R&D head was elated and was eager to observe the new product’s impact on boiler performance in a real-time operational context.

**Product Trials and Stabilization**

BHEL needed permission from existing or prospective customers to conduct product trials on their boilers. They approached several customers. Considering that installation of heat flux sensors calls for cutting the water wall tubes and re-welding at 80 places for installing 40 sensors, many were reluctant to give permission. BHEL took enormous efforts to persuade and finally, KPCL allowed SWBS to be installed at one of the six boilers at Raichur TPS, at BHEL’s cost where trials were conducted for 1 year. Raichur TPS, the customer, was encouraged to handle SWBS operations to gain confidence and develop the ability to operate it independently. During the trials, the BHEL team debugged the software, performed integration exercises, and replaced faulty sensors for free. The team also conducted an extensive comparison of performances between boilers with SWBS and without SWBS under identical operating conditions.

Boilers operated with SWBS had the following advantages:

1. **Performance and efficiency improvements**
   Substantial reduction in wall-blowing steam to the extent that the plant cycle efficiency increased by approximately 0.25%.

2. **Reduction in steam eroded water wall tube replacement**
   Each blower in SWBS operated only on detecting a reduction in heat transfer due to ash deposits; therefore, the possibility of tube erosion caused by the steam jet passing over a clean surface was reduced. This resulted in a decreased number of eroded tube replacements from 100 earlier to 4–5 annually.

3. **Decrease in annual shutdown period and consequent increase in total power generated**
   The large reduction in water-wall tube replacement proportionately reduced the annual shutdown period. The additional availability of power generation period was a major financial benefit as one additional day of power generation could pay back the entire SWBS installation cost.

4. **Generation of data useful for boiler design**
   The data generated and stored in SWBS was useful to infer the fire-ball locations and performance evaluation of fuels and their blends. The data could be easily applied to boiler design, field problem solving, and be useful to R&D teams. The data could be stored and archived for future comparisons.

Thus, SWBS ended the ritualistic wall blowing practice and provided a pragmatic solution that would automatically start and stop the wall blowing operation and carry out a need-based operation to maintain optimal heat transfer.

**Manufacturing of SWBS**

On successful product trials, arrangements were made to manufacture SWBS. Given the complexity of the product in terms of its parts that involved different skill sets, it had to be manufactured at different centres and assembled or integrated at the site of boiler erection. To achieve this end, extensive and detailed documentation was done for every step required in the manufacturing process.

The welding-related tasks like machining, bracing, or fixing were allotted to the Welding Research Institute (WRI), whereas the control panel and the electronic display were assembled at the Electronics Division. Later several vendors were developed/impanelled to manufacture different parts of the product. The laying of electrical circuits, software adoption was done by Controls And Instrumentation Engineering Group at Trichy.

**Demonstration and Commercialization**

It took nearly 5 years since the work commenced to arrive at product development. Customers’ meet was organized at KPCL, Raichur TPS to showcase and demonstrate SWBS. Engineers from power stations across the country were invited to this meet. KPCL, the customer presented a paper highlighting their experiences and the benefits of SWBS. The customer meet was conducted like a workshop to provide a hands-on experience. The working of the SWBS was explained by the staff of KPCL to the workshop participants.
Gaining customer confidence has always remained a long drawn and difficult process. KPCL had witnessed the development of the new product and had enjoyed its benefits. Therefore, KPCL, a satisfied customer, was an asset to BHEL that helped the commercialization efforts made by the R&D department. In fact, KPCL wanted to integrate SWBS to five old and two new boilers. BHEL made presentations to the Andhra Pradesh State Electricity Board (SEB), Maharashtra SEB, Gujarat SEB, Tamil Nadu SEB, and others. Several other power plants in the country soon realized the benefits of SWBS and started demanding its installation to the boilers at their power plants. BHEL received orders from MSEL (New Parli 250 MW, Paras 250 MW), KPCL (Bellay 500 MW), and NALCO 120 MW, Orissa, and RRVUNL (Suratgarh 660 MW). It was soon observed that customers began requesting SWBS as an integral part of the boilers they wanted from BHEL. The product had taken nearly 7 years to reach the commercialization stage. SWBS was an effort by a large number of people across departments of BHEL and KPCL for nearly 7 years.

Recognition for SWBS

SWBS was regarded as an information reservoir, apart from being a permanent solution for boiler performance-related problems. It was an innovative product developed by the creative efforts of various teams at BHEL. To safeguard the process of product development, patents were filed and received. Incentives were awarded to the team, while the R&D head received the coveted BHEL Excel Award. The process of developing SWBS was selected as one of the ‘Best Practices in Thermal Power Station Operational Practices’ by the Committee of Public Undertakings, US Agency for International Development, and ICICI Bank.

Post Commercialization Challenges and Improvements

Sensor failure was a challenge faced by many TPS, as the product and the markets matured. To address the issue, the R&D department, BHEL, Trichy improved the sensor’s construction so that a failed thermocouple could be replaced even when the boiler is in operation. This solution obviated the need for boiler shutdown required to cut and weld water wall tubes to replace the sensor. This product improvement resolved customers’ concerns, and all subsequent orders for SWBS were supplied with improved sensors. Notably, no other problem was reported related to the functioning of SWBS which indicated high reliability of the product.

New Horizons

It was a pleasant day, and just as the newly appointed R&D head entered the office, he was greeted by his deputy, whose face was beaming with excitement. The deputy read a letter aloud from one of the major customers with a strange request. The customer wanted BHEL to supply SWBS as a standalone system for the boilers they had procured from another vendor. He could not contain his excitement at the spinoff benefit and congratulated his team members on the new challenge.

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**Exhibit 10. Glossary.**

- Bracing: A metal-joining process in which two or more metal items are joined through melting and flowing a filler metal into the joint. The filler metal has a lower melting point than the adjoining metal.
- Creep Life: Life of component subjected to varying temperatures over a long period.
- Fixing: The process of attaching.
- Furnace: A furnace with reference to a thermal power plant is a chamber surrounded by water- or steam-carrying tubes where fuel is burnt to generate the heat required for producing steam from water passing through the tubes forming the walls of the chamber.
- Machining: The process of removing materials to obtain the required shape and dimensions of an object.
- Power Plant: A place where all required equipment and resources are integrated and electrical power is generated.
- Sintering: Sintering is the process of compacting and forming a solid mass of material by heat and pressure without melting it to the point of liquefaction.
- Supercritical pressures and temperatures: Each fluid has a particular pressure and temperature, at which the specific heat capacity is maximum. This particular pressure and temperature point are called the critical point of the fluid. Pressures and temperatures of the fluid exceeding this critical point are called supercritical pressures and temperatures.
- Superheater: It is a heat exchanger which receives heat from flue gas passing around it and increases the heat capacity of steam which is passing inside the tube coils.
- Thermocouple: A temperature-measuring instrument formed by joining two dissimilar metals. When the joint is in contact with a hot object or environment, an electromotive force is produced between the other ends of the wires proportional to the temperature. This behaviour is used for measuring temperatures using thermocouples.
- Tungsten inert gas (TIG) welding: In this process, an electric arc is produced between a tungsten electrode and the metals to be welded, and the molten metal pool formed by the heat of the electric arc is covered by inert gas to avoid contact with oxygen in the environment and prevent oxide formation in the weld joint.
- Welding: The process of joining of metals by melting with or without the addition of filler materials.

**Source:** Khanna (2015).
DECLARATION OF CONFLICTING INTERESTS

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ORCID ID

Abhishek Kumar https://orcid.org/0000-0002-2658-1187

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Abhishek Kumar teaches design philosophies at Anant National University, Ahmedabad. He earned his Ph.D in Management from Pondicherry University. He is an Economics graduate from Calcutta University and MBA from BIM Trichy. He has published more than 20 articles in reputed international journals, has authored two books, written articles and columns for newspapers and is quoted on issues related to leadership and marketing by various media platforms. His research work comprises construction of brand personality scale for media, aesthetics and phenomenological design. His recent publications are on philosophy of a photo-graph, hermeneutic reality of product and on philosophy of intimate spaces.

R. Dhanuskodi has nearly 40 years of R&D experience at BHEL, India in technical areas applicable for thermal power plants. He is a life member of The Institution of Engineers (India) and The Combustion Institute. He has won two BHEL’s Excel awards under the best author category for technical papers. He has visited France, Netherlands and Germany under Indo-Europe Clean Coal Development Program. He has guided 42 UG, PG and PhD project works. He holds 11 patents, 40 copyrights and 2 design registrations. He has presented papers in 20 conferences and published in 10 national and international journals.

R. Kaliappan completed his bachelors in electrical and electronics engineering and Masters in Computer Science. He has 36 years of research experience in different fields of power generation and power plant subsystems such as heat transfer studies on boiler circulation, efficiency improvements of boiler subsystems, product improvements/ enhancements and setting up test facilities for research studies. He has published a number of technical papers on MHD power generation and heat transfer studies in various national and international journals. He has more than 25 patents and copyrights on products development related to power boilers. He has won BHEL’S gold medal for product development for Smart Wall Blowing system.

K. Nandakumar has more than four decades of R&D experience starting from substitution of oil/natural gas by low calorific coal gas for boiler start up and low load flame stabilization to coal water slurry technology, coal characterization and to smart wall blowing system. He has carried out several ‘root-cause analyses’ in pulverized coal fired boilers. He developed a fuel evaluation test facility at BHEL and a high-pressure entrained flow reactor (HPEFR), to test solid fuels, up to 30 bar and 1450˚c later at Penn State, USA. He has won three BHEL’S excel awards, once for SWBS development and twice for technical papers. He has 11 publications, 32 presentations in conferences and 6 patents.