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Investigation of the Mechanism Failures of High Temperature Components Occurring Inside Boiler Tubes

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Abstract

Boiler tube leaks are one aspect that is commonly affecting the production of megawatts produced in power stations. Specifically, thermal mechanical fatigue failure has been a very stressful and repetitive failure mechanism within many fossils power stations. This failure mechanism is usually caused and affected by the type of material used on the tubes. It is very important to understand different temperatures applied within the different tubes and components. This assist by giving a much better focus to install the correct material on the tube for the required component. It was found that Mechanical Fatigue cannot permanently be eliminated but rather be prolonged, this is because of the temperature-pressure stresses that experience when in operation. One of the reasons was that the coal that is used is not quality. The quality coal is expensive and is exported to other countries for other usage. The primary failure of Thermal Mechanical Fatigue ID crack length parameters was measured with the use of Steel Ruler and Vanier Caliper for all experiences. The design pressure, operating temperature and operating hours were taken into consideration when performing the metallurgical analysis. It was noted that from the experiments investigated they showed a low minimum thickness value, deformation and change in diameter. The condition of the tubing post in-situ chemical cleaning was taken. The purpose of this was to determine whether the chemical cleaning influenced tubing, and it was found to be one of the major effects of TMF and other relevant failures occurring on tubes.

Keywords
Boilers, Thermal Mechanical Fatigue, Microscope, Metallurgy, Hardness Testing, Failure Mechanisms.

1. Introduction

Globally, there is growing recognition of the role that electricity plays in advancing society, fostering economic growth, and raising living standards (ND 1977; Eskom 2013). It is extraordinary how well relatively simple materials can be engineered and built to work effectively as boiler tubes in high-temperature, high pressure environments, where they may degrade due to a range of mechanical and thermal stresses and where there may be environmental attack on the fluid and fire sides (Alto 1998; Alto 1988). Boiler tube failures (BTF) have been the primary cause of a. vailability issues for utilities reliant on fossil fuel plants (Alto, 1988). Since most BFT's have been recurrent failures, getting a unit back online has historically taken precedence over figuring out the mechanism and underlying cause of each Boiler Tube Leak Failure (Smith 1971). Inadequate initial design operation and maintenance, challenging fireside and cycle chemical settings, and insufficient management support have all contributed to failures (London, 1999). Certain tubes have been known to operate for long without experiencing failures for more than 200 000 hours (R B Dooley, 2006). If there are no changes made from the original design conditions, water touched boiler tubes (waterwalls, economizers), are intended to last virtually forever, provided no deviations from the original design condition occur (Alto 1998). Although lives considerably over 200 000 operation hours are feasible, the situation for steam- touched tubes, such as those that are found in the superheater and reheater portions of contemporary boilers- is slightly different due to the inevitable creep-limited lifetime. (Alto 1996).

The boiler tubes are used for applications where the aim is to vaporize water. They are also used for conducting fluids rather than water (Alto 1998; Petras, et al. 2015). In water tube boilers, water flows in the boiler tubes while the hot gases heat the pipes and vaporize the water (Engineers. 2004; RB DOOLEY 2007). A furnace in the boiler is used as the primary heat source (Hyperwave 2020; moloko, 2021). The thermal conductivity of the tube material is vital for the efficiency of the process (Shukla 2015). Studocu shows the experiments that were conducted to demonstrate the working of boilers and analyze relationship between pressure and temperature in a closed system (SD 2012; John P Dimmer 2006). The tubes experienced 300,500 and 1000 cycling strains before it failed due to TMF (Little J, 2000). Clausius (1822-1888), the German physicist and one of the founders of Thermodynamics was instrumental in deriving the relevant Clausius-Clapeyron relationship. Boilers are designed with Economizer, Evaporator and Superheater depending on the Design parameters. The research study investigated the correct mechanism solution for one of the failure mechanisms, (Thermal Mechanical Fatigue) inside the boiler.

The technical Knowledge of BTF has improved dramatically since the earliest compilations. Within the past years, complete understanding of the basic mechanisms and mitigation options for thermal fatigue and circumferential cracking in supercritical units have been gathered (Alto 1988; Eskom 2013; Petras et al. 2015). The importance of, and the requirements to implement, on a practical basis, the cycle chemistry controls to prevent the known chemistry-controlled damage mechanisms are now known. Further, large-scale, utility demonstration projects have shown that technical knowledge plus a company- wide BTF correction, prevention, and control program can demonstrably achieve significant availability improvements (Eskom 2013). This research study found that one of the primary causes of the mechanism failure is how the boiler started to operate every time it was off. This is very critical because when the boiler is started, the lighten up rate of the boiler must not accelerate too much as this might cause an unnecessary over strain of the boiler material by quick and uneven temperature rises (ND 1977). It was found to be necessary to perform several start/stop sequences to reduce the lighten up rate.

2. Literature Review

The literature review is discussing the detailed definition of thermal mechanical fatigue, how thermal mechanical fatigue failure mechanism is formed, factors influencing the failure and why is it called a repetition mechanism and other way they have been used to reduce the repetition of the mechanism. The literature review will also cover discussing of the coal fired boiler tubes operation and how tubes were tested on previous methods and discussing the affecting and rising factors to the inside and outside part of the tube when put on load operation.

2.2. Thermal Mechanical Fatigue

Thermal Mechanical Fatigue (TMF) is the results of cyclic thermal stresses and strains. These cyclic thermal stresses and strains are caused by temperature fluctuations. These cyclic thermal stresses and strains are caused by temperature fluctuations. This failure is leading mechanism or damage. The Figure 1 shows the example of the TMF.

Figure 1. Thermal Mechanical Fatigue [TMF]

2.3. Boiler light up operation methods

The in-operation boiler slowly dried out before raising the furnace to normal operating conditions. New Boiler contains water which will flash into steam and damage the material if it does not have a chance to evaporate before reaching normal furnace operating temperature. This is done by creating a very light fire in the furnace, sufficient to speed up the evaporation but not to harm the tubes and other boiler supporting components.

Before starting the fire, fill the boiler to the normal level with treated, deaerated water. Leave a vent open to prevent pressure build up during the dry out period**.** Maintain the water level to replace any that leaves the drum due to the heating process. Next, ensure that the furnace has been adequately purged. Then, according to manufacturer's recommendations, start a light fire and maintain it from 48 hours to several days, depending on the amount of refractory replaced

3. Methods

Methods used when performing the Site Inspection Procedures:

1. Opening of Breaker.
2. Force cooling of boiler.
3. Pre and Final environment gas testing of the inside of the boiler.
4. Issuing of Safe entry PTW.
5. Once the Safe entry (full) is verified, then Boiler Repair PTW can be issued.
6. Building of Scaffolding for Sky Jack & Hanging Scaffolding.
7. Installing of jack for high level.
8. Initial Inspection.
9. Issue Program cutting instruction.
10. Cutting out of the damaged tubes
11. Prepare the new tubes & tube bend. Fitting & welding of tubes.
12. Perform X-rays.
13. Perform SFT & Leak Test.
14. Draining of the boiler.
15. Cut out damaged tubes.
16. Perform Seal Welding.
17. Perform NDT & Final.
18. Removing of skyjack.
19. Remove of Scaffolding.
20. Clearing PTW and removing all the debris and tools.

Lab Equipment procedure:

Low-magnification inspection of fracture surface was performed using a stereomicroscope. Microstructure examination was conducted in tube cross-sections prepared by standard grinding, using abrasive. SiC papers up to #1200 grit, were used when obtaining Metallographic observations. Metallographic observations were carried out after final polishing and also after immersion etching in on listed different tube materials used for investigation solutions. Metallographic analysis was performed.

4. Data Collection

On the 13th of May, a tube leak was found on the Front Right Hand Side (RHS), Evaporator Helical Wall Tube E on the spiral to vertical transition at 63m level. The failure location is a known high-risk location for thermal mechanical fatigue related failures. It is noted that similar failures and areas were experienced in the past. The boiler had approximately 136 000 hours of operation at the time when the failure occurred. The hopper is dominant failure location for TMF but the exact location of this failure in this incident was different to the typical TMF location, refer to Figure 2.

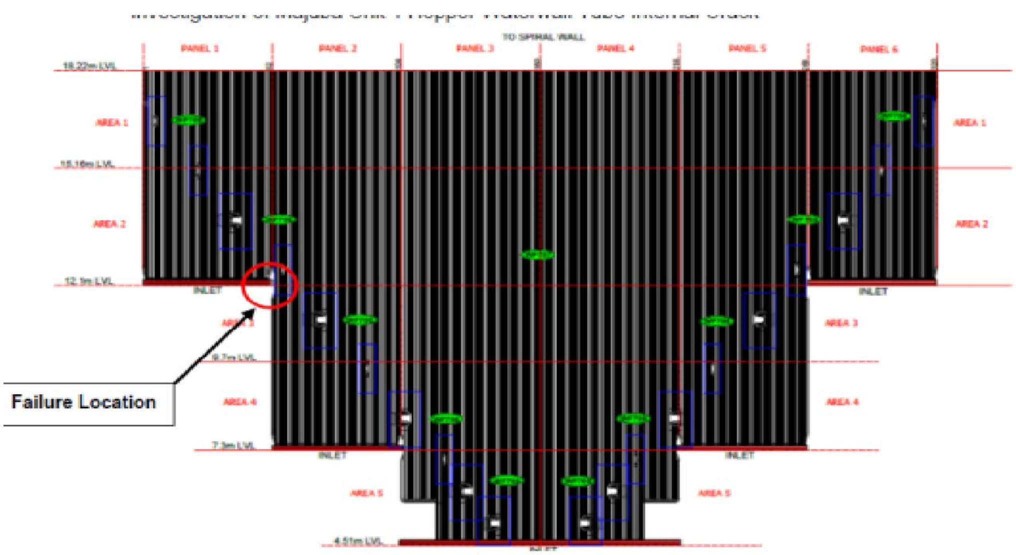

Figure 2. TMF failed tubes location

Unit 6 experienced a boiler tube failure on the 24th of May 2016. The failure was confirmed to be on SH1.1 tubes, SH2 Outlet tubes and RH2 Bundle Coil tubes. Failed SH1.1 and RH2 Bundle Coil tubes were cut out and brought to Eskom Research, Testing and Development (RT&D) for metallurgical investigation. However, SH2 Outlet tubes were not brought to RT&D for metallurgical evaluation. Failure on SH1.1 was confirmed on Tubes 3 and 4 (below the bifurcation) and Tubes 2 and 1 (above bifurcation) during site inspections (as shown in Figure 1). Tubes adjacent to the latter tubes were also removed due to the wall thinning likely from steam washing. RH2 Bundle Coil Tubes 3 and 4 were removed due to failure noted (during site inspection), while adjacent tubes (Tubes 1 and 2) were also removed due to severe wall thinning. Several SH2 Outlet tubes were reported to be removed due to severe wall thinning noted when inspections were carried out in this area (the latter tubes were not brought for investigation). The SH1.1 flue gas screen was found detached from the attaching plates (this was noted during site inspections conducted when the boiler was shut down), see Figure 3. The screen was also not brought for investigation.

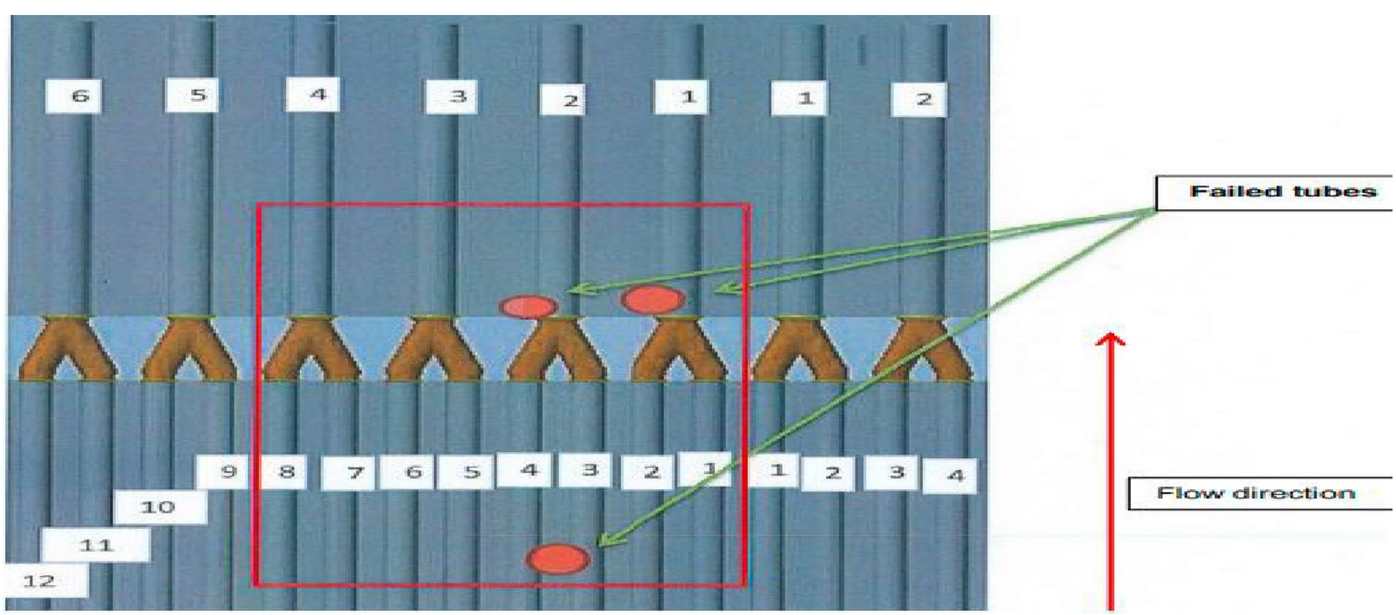

Figure 3. TMF failed tubes location.

5. Results and Discussion

5.1. Hardness Results

The Vickers hardness test was conducted adjacent to the failed area and for all 3 samples. The tests were carried out on a polished surface of each sample by using the verified Leco Macro Vickers Hardness Tester with a load of 10kgf. Verification of the calibration was done by using EP 08109747 hardness block and a verification value of 152 HV10 was obtained and found to be within the required hardness range limits.

5.2. Metallographic examination - experiment results

Metallographic examination was conducted using an Olympus GX71 metallurgical microscope. Prior to that, cross-sections of the failed tube were prepared using hot-mounting, wet grinding up to 2400 grit SiC paper and polishing with diamond suspension. Chemical etching was performed by immersion of the specimens in 3% Nital for 3 seconds, followed by cleaning with methanol and drying with hot-air stream.

The discussion explains and discusses the metallographic results obtained on different Thermal Mechanical Fatigue Failures that were experienced within coal fired boilers. These results were obtained by analyzing the primary failure on cracked tubes and the secondary damage that were affected by the expansion of the primary damage. TMF Failure reading is called transgranular fracture. Transgranular failures are obtained by using microscopes. These fractures are the results of high thermal stress resulting in high energy consumption.

5.3. Graphical Results

Metallographic examination was conducted using an Olympus GX71 metallurgical microscope. Prior to that, cross-sections of the failed tube were prepared using hot-mounting, wet grinding up to 2400 grit SiC paper and polishing with diamond suspension. Chemical etching was performed by immersion of the specimens in 3% Nital for 3 seconds, followed by cleaning with methanol and drying with hot-air stream. Figures 4 present their microstructures in different positions. Optical micrograph showing a single crack that initiated on the inside surface of the tube. Note the crack is straight and narrow and no oxide was noted adjacent or along the crack [50X Magnification]. Figures 4 and 5 presents their microstructures in different positions. Optical micrograph showing a single crack that initiated

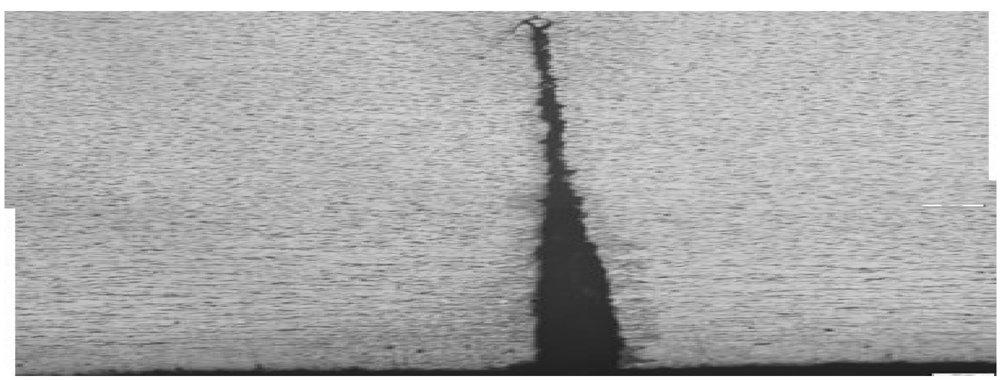

Figure 4. Optical Micrograph Showing Crack.

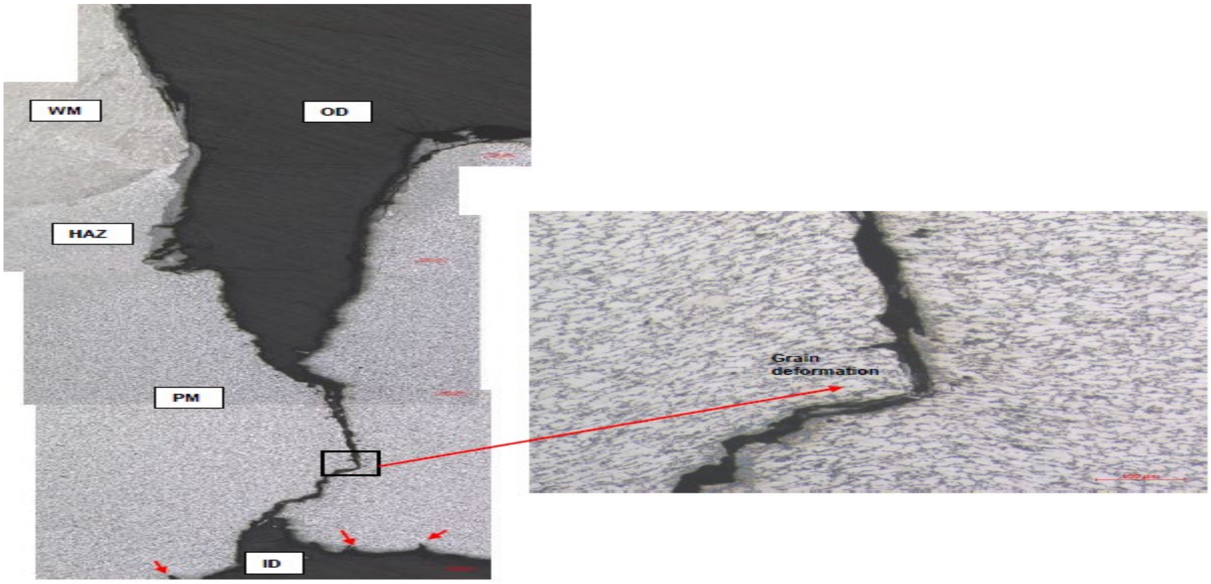

Figure 5. The thermal mechanical fatigue through wall crack that initiated from the outside diameter on the weld toe and propagated towards the inside diameter of the tube.

5.4. Proposed Improvements.

The expected Unplanned Contribution Loss Factor (UCLF) are losses that contribute without expectation such as tube leaks which require the boiler to be shut down, while Planned Loss Factor (PCLF) are losses that occur at times of planned outages. Both UCLF and PCLF are allowed to be 2% and 6% consecutively for a better lifespan of boiler tubes. The expected plant availability efficiency is expected to be at 92%. These losses are in consideration of all other supportive plants to the boiler when generating the Megawatts. However, the experiments conducted were all contributing to the UCLF as they were tube leaks that caused the boiler to be shut down.

5.5. Validation.

Monitoring of the repetition of Sample tubes from similar areas (all boilers) to determine if corrosion fatigue is a generic mechanism in the area. It is important to consider Initiating of the replacement programme if frequency of failures increases in the future to manage and eliminate the fatigue mechanism in this location and prevent similar failures in future: Visual inspection and surface crack testing (preferably MT) should be carried out on other similar, nearby areas and on other units that did not have failure during outage opportunities even though it is expensive as it increase the scope of work. This should be considered to include these areas for replacement during GO/MGO opportunities if the frequency of failures increases. Single feeder operation and split furnace operation must not be allowed. The boiler must be Operated within design parameters.

This research did not give many details on the types of welds used during the repairing and replacing of failed tubes. There are different types of welds that are used when correcting different types of failing materials. There are other failure mechanisms that are experienced during boiler operations such as Soot Blower Erosion. This failure mechanism was not investigated in this in this report. Tests such as phased array testing and its equipment were not discussed in this report. However, this forms part of the tests that are used to read defects at the surface, the volume of a weld with no dead zone and the flows in welds of materials.

6. Conclusion.

Thermal Mechanical Fatigue Failure was concluded to be a mechanism that becomes more problematic on old coal fired power stations, this is because when loading the boiler, the fluctuation in temperatures occurs more, resulting in temperature stresses. This was proven during boiler tube leak forum presentations from Medupi, Kusile, Majuba and Matimba power stations. Since chapter 1 and 2 that incorrect method of boiler loading results to Thermal Mechanical Fatigue Failures in long run. It is important to not bypass the design procedure when loading the boiler, maintaining, and operating it. This results in long-term TMF failures that have no solution to. Power stations that are found with long life span are not having too many TMF failures. This is because of adherence to the right procedures. It was also noted that usage of OEM's plays a big role on eliminating Thermal Mechanical Fatigue. The physical and chemical properties of coal also determine how long it will take before the tubes can be exposed to the TMF Failures.

It was found that Mechanical Fatigue cannot permanently be eliminated but rather be prolonged, this is because of the temperature-pressure stresses that experience when in operation. One of the reasons was that the coal that is used is not quality. The quality coal is expensive and is exported to other countries for other usage. The primary failure of Thermal Mechanical Fatigue ID crack length parameters was measured with the use of Steel Ruler and Vanier Caliper for all experiences. The design pressure, operating temperature and operating hours were taken into consideration when performing the metallurgical analysis. It was noted that from the experiments investigated they showed a low minimum thickness value, deformation and change in diameter. The condition of the tubing post in-situ chemical cleaning was taken. The purpose of this was to determine whether the chemical cleaning influenced tubing, and it was found to be one of the major effects of TMF and other relevant failures occurring on tubes. Metallography examination was used to study and analyze the physical microstructure of metals and alloys from all 5 experiments. This was conducted with the use of metallurgical microscopes. Metallographic analysis is essential for understanding the mechanical properties of materials, including their grain size, crystal structure, and the presence of any defects such as cracks or non-metallic inclusions. The noted finding was that water touched tubes are preferably used on alloy steel while steam touched tubes are carbon steel. This also resulted in different microscopic results provided. Alloys have qualities that are preferable to pure metal.

The principal purpose of conducting hardness testing was to determine the suitability of a tube material, and to confirm the failure to which the tube was subjected. The hardness test was performed according to Vickers, Brinell, Rockwell or Knoop Procedures. The hardness test was conducted for 5 different tube leaks experienced mentioned in chapters 3 and 4. The hardness measurements taken along the crack propagation path indicated that strain hardening occurred in all TMF experiments conducted. It was noted that in experiment 1 and 2, the hardness measurements taken away from the failure location are significantly lower than those of the specification range. It is possible that a lower grade material and not 15Mo3 was installed on the tubes on experiment 1. Experiment 3, the hardness values obtained at failure were way above the upper limit due to strain hardening. Experiments 4 and 5 were within the hardness specification.

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Biographies

Ms. Khuthadzo Ramakulukusha is a South African holder of a Masters in Mechanical Engineering from the University of Johannesburg. She is currently working at Eskom as Snr Mechanical Supervisor for Primary Energy Division. Ms. Ramakulukusha has worked for 3 International companies which are Mitsubishi Hitachi Power Systems Africa, Wetback Africa and Eskom holdings within the Boiler Tubes Engineering and Maintenance Department. Ms. Ramakulukusha has supervised may contractors which are Service providers of different Eskom Power Stations, Such as Actom, Kulkohni, Quench, TT Thermal etc. Ms. Ramakulukusha is a candidate for ECSA that is aiming to be a professional soon.

Dr. Motsi Matlakala is a South African holder of a PhD in Mechanical Engineering from the University of Johannesburg and Professional Engineering Technologist (Pr Tech Eng) with ECSA. Dr Matlakala is currently working as a Lecturer at Tshwane University of Technology (TUT). To date he published more than 20 papers and was also selected as a reviewer of paper in three (3) conferences, locally and internationally. Dr Matlakala was studying for a PhD in Mechanical Engineering at the University of Johannesburg. Dr Matlakala is a member of South African Institute of Mechanical Engineering (SAIMECH) and Golden Key Honor Member. Dr Matlakala's primary research areas are System Analysis and Dynamics, Optimization, Computational Fluid Dynamics, Finate Element Analysis and Water Research.

Prof. Madindwa Mashinini is a South African holder of a PhD in Mechanical Engineering from the University of Johannesburg and register as a Professional Engineering Technologist (Pr Tech Eng) with ECSA and South African institute of Mechanical Engineering (SAIMechE). He is currently working as Vice Dean for Teaching and Learning at the University of Johannesburg. Prof Mashinini has presented research work at local and international conferences and published research work at ISI journals. He was once also HoD and Senior lecturer at the University of Johannesburg (UJ), School of Mechanical Engineering and Industrial Engineering Technology. Prof Mashinini is a vibrant mechanical engineer with good communication, research and writing skills, who aim to excel in the field of mechanical engineering through hard work, research, skills development and perseverance.