Title: 1-Way Fluid Structure Interaction Modelling Methodology for Boiler Tube Fatigue Failure

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Keywords: Power-Plant Failures, Boiler Failure(s), Boiler Tube, Thermal Fatigue, Finite Element Analysis

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Abstract: A modeling methodology developed for dealing with fatigue failures on large boiler tube assemblies, as used by power generation industries, is described. Boiler tube fatigue failures are resultant to a coupled combination of fluid flow and heat transfer mechanisms, inducing thermal expansion leading to fatigue failure. A combination of modelling tools is effectively combined for one-way Fluid Structure Interaction, solving for and extracting stress results efficiently. A One Dimensional fluid solver is used to approximate and model the thermal flow components. The study case considered implemented the developed methodology on a quarter boiler hopper section made up of 3,022 tube and membrane structure with a collective length of 4,787 meters. Operating conditions are iteratively adjusted in the one dimensional pipe flow model until a correlation is formed with instrumented data. This validated model enables further use for various postulated plant conditions and operational sequences through transient start-up conditions. The boiler tube temperatures obtained from the one dimensional model are transferred and used as boundary conditions in a full three dimensional finite element analysis where deformations are solved for and stress results obtained due to thermal expansion within the boiler tube walls and the adjacent support structure. The model is used for redesign of sections of the boiler to reduce stress in those areas and subsequently reduce fatigue failures.
1-Way Fluid Structure Interaction Modelling Methodology for Boiler Tube Fatigue Failure

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Cover letter

The work presented by this paper is focussed around accurately solving real industry problems through simulation using accessible flow and structural Computer Aided Engineering (CAE) codes, coupling them and forming a 1-way Fluid Structure Interaction (FSI) model.

A modelling methodology is developed for dealing with thermal fatigue failures on large industrial boiler tube assemblies, as used by the power generation industry. Boiler tube fatigue failures are resultant to a combination of fluid flow and heat transfer mechanisms, inducing thermal expansion leading to structural fatigue failure. Thermal fatigue is induced as a result of the operational sequences, events and procedures followed during boiler start-up and shut-down along with the interdependence of various boiler components. A challenge in modelling such a large system is to capture the thermal transient nature and interdependence of the system accurately.

A case study is presented where a combination of fluid and structural modelling tools is effectively coupled, solving for and extracting flow and stress results efficiently. What makes this methodology unique is the accuracy and size of problems it can solve. Every hopper tube/fin element, forming part of the hopper section within the boiler, is modelled. The domain consists of a combined flow path of 4,787 meters within 3,022 tubes in total. Rather than coupling computationally expensive 3D Computational Fluid Dynamics (CFD) with a Finite Element Analysis (FEA), a 1D fluid solver is used to approximate the flow and coupled with a 3D FEA to allow for a 1-way FSI.

The described methodology developed is shown to not only be limited to power generation boilers but can also be implemented on any heat transfer cycle where a combination of tubes and fins partake in heat transfer. With the emphasis of future power being placed on renewable energy it is expected that cyclic plant operation, for base load coal fired power plants, will become the norm for fossil fuelled power stations in the future. It is imperative that modelling methodologies exist for dealing with large sections or even complete boilers in order to capture and accurately simulate operational space analysis to mitigate any thermal induced fatigue compromising component reliability and plant availability.
Highlights

- A modeling methodology developed for thermal fatigue failures on boiler tubes.
- Modelling tools is effectively coupled for one-way Fluid Structure Interaction.
- Fluid structure Interaction between 1D flow and 3D structural FEA environments.
- Experimental thermocouple data is used for transient model calibration.
- Solution Implementation shows a reduction in fatigue loading by up to 50%.
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Title: 1-Way Fluid Structure Interaction Modelling Methodology for Boiler Tube Fatigue Failure Engineering Failure Analysis

Editors Comments:

- Thank you for your interesting paper. Before proceeding, can you make sure that the references are in the format required by the journal. Details can be found at the Guide to Authors.

References have been amended.

Reviewer #1:

- The Authors attempt to propose a methodology for assessing boiler tube fatigue failures through FSI modelling. Failure mechanism and its root cause of thermally-induced fatigue have been widely known.

The problems are known however solving these problems are not. Fatigue is directly related to the stress at that location. Subsequently in order to solve these problems the stress at a given location needs to be accurately solved. Due to the geometric complexity of boilers it is impossible to accurately solve the stress state at a single location by only modelling a small section of the boiler. The stresses are thermally induced and the thermal field need to be obtained on a large section of the boiler in order to calculate stresses accurately at any location. The proposed method allows for a transient thermal solution over a very large section of the boiler which in turn results in a stress result at a number of locations at any given time. In the paper a given time is chosen in which a high stress is measured to show how a simple design change can result in a significant stress reduction at multiple locations which in turn will lead to a reduction in fatigue at all the identified locations.

- The proposed methodology does not clearly address the fatigue problem in water tube boiler. No detailed modelling is presented.

The methodology developed does not attempt to perform the actual fatigue calculations, nor is it focussed on performing FEA analysis. The focus of this paper is the development of a method for obtaining the locations of high stress via simulation. The calculated stress can be used for fatigue calculations. The way in which this is obtained is through the coupling of a 1D fluid domain with the 3D FEA domain. The focus is neither on CFD nor on FEA but the interaction between the two and the boundary value problem that encompass both of the methods of solving the physics on such a large structure. Once the stress state is solved, a myriad of methods for doing fatigue calculation on localised areas in isolation can be done.
• **No appropriate fatigue calculations are elaborated.**

One common problem of doing any fatigue calculations is obtaining the appropriate loading (stress at a given location). This is a challenge especially when the loads are time varying as a result of non-predictable operation of the boiler. The methodology developed can obtain these time varying operational loading through using Distributed Control System (DCS) data as a direct input. The fatigue calculations themselves would not add any uniqueness to this paper; however the method of coupling a 1D CFD with a 3F FEA is unique to extremely large domains such as power generating boilers.

• **Figures 7-9 just show the temperature and strain changes without addressing the failed tube depicted in Fig. 1.**

The purpose of showing a failed tube in figure 1 and figure 2 (Now Figures 2 and 3) is to show how boiler tubes typically fail. These images are used to show the size of the boiler tubes along with what failures typically look like. Boiler tubes typically fail as a result of cracks that originate at the weld toe where a tube and fin joins. They propagate both axially as well as radially. This can be seen when referring to both figures. This is an illustration of failures at any of the locations solved. The metallurgical investigation at any of these locations clearly indicate a fatigue failure i.e. stress induced. Paragraph 4 on page 3 has been extended to provide more information on Figures 2 and 3 and their relevance to fatigue.

• **Figures 10-12 seem to be out of the context.**

Figure 10 (Now Figure 13) are included to show the solved FEA domain. It gives an idea of the thermal field across the boiler tube-fin structure. This temperature field (although a snapshot for a single time step) is the output of the developed methodology. This temperature field induces stress states. Time varying thermal results will yield the required loads to perform further fatigue calculations. Paragraph 1 on page 10 have been amended to elaborate on this figure.

Figures 11 (Now Figure 14) and 12 are an attempt to show the improvements the modifications have done to the included stress. Figure 12 has been removed, as the information is relayed in the text.

Although this paper is more focused on the development of a fatigue load methodology, a secondary outcome to the developed study is a general engineering fault finding tool for large structures. Without the developed methodology obtaining an accurate and validated temperature field is impossible. Paragraph 1 on page 11 has been added to further elaborated on this and to show that these results do not show any specific fatigue results, but are used as an input to both fatigue as well as general engineering fault finding methods.
• Besides cycling duty due to start-up, restart and shut-down or transient thermal loading, cycling steam/water pressures also often contribute to the fatigue problem. The most common root cause is related to the operating condition that is usually as result of cycling operation. Locations containing high stress concentration also promote the basic fatigue problems. Thus simulation modelling can be refined into more focused area by incorporating the operating parameters.

By modelling a large section of the boiler geometric stress concentrations as well as the locally induce stress is taken into consideration. Operating parameters are also taken into account and incorporated into this developed methodology. Transient DCS data is used for the transient 1D flow analysis obtaining a time varying thermal field which is in essence the fatigue load. Data from the DCS used are inlet temperatures as well as mass flow (coupled to pressure variations; there are no steam traveling through the boiler walls – only water and thus the incompressible assumption is correct). Failures on the plant environment are not as a result of steady state operation but the cycling of the plant (i.e. start up and shutdown). This is better explained and elaborated on with a third paragraph added to the conclusion on page 11.

Reviewer #2:

• Although the paper is good explained, it is difficult to identify some boiler components with the explanation offered, so that, more schemes and figures in various sections are required. The methodology offered seems to be effective for that kind of big structures. Fluid structure interaction between 1D flow and 3D structural calculations seems to work out properly (supported by measured data). The analysis here shown could have important consequences in improving the fatigue resistance of that kind of boilers.

• Introduction section, second paragraph: Provide a schematic diagram to visualize the location of the failed part.

Figure 1 has been added and is representative of the support structure and the tube wall itself. Failure locations are shown in Figure 9 along with the thermocouple and strain gauge instrumented locations. This figure has been updated to represent this information more clearly. The Caption of Figure 9 has also been changed to indicate that failure locations are also shown in this figure.

Due to the work being part of a commercial power plant certain information relating to specific component and locations are considered confidential since it can lead to identification of the plant in question. This information is however not essential for understanding the proposed methodology and the result form the methodology.
- Material and methods section, second paragraph: In order to clarify the meaning, it is suggest replacing flu by a synonym. This paragraph may relocate to the introduction section.

(Flu gas) domain is replaced with (coal combustion gas) in paragraph 2 of page 3. This paragraph is not moved to the introduction section as too many referenced information is present relating to work (methods) done on combining 1D and 3D domains. It lays the foundation for the proposed 1D-3D methodology proposed and is appropriately part of the materials and methods section.

- Material and methods section: Authors should provide more technical details of the CFD solver and of the CFD computation. Furthermore, I suggest adding a figure with the CFD domain to be solved.

This paper however is focussed on the methodology of coupling 1D CFD with 3D FEA. Elaborating on too much CFD detail will put unwanted focus on the CFD, whereas the focus is on the coupling methodology as a whole. Figure 5 is added to show the CFD domain. Figure 6 is added to provide more detail on the 1D to 3D coupling method. More detail is also added to paragraph 1 on page 5.

- Material and methods section: Authors should provide detailed information about how to pass the 1D CFD loads to 3D finite element model (I suppose that an interpolation method was used).

Figure 6 is added to provide more detail on the 1D to 3D coupling methodology. Paragraph 2 on page 5 is extended with more appropriate explanations on the 1D to 3D results passing.

- Theory/calculation section, last paragraph: Provide a schematic diagram showing FEA boundary conditions (type and location).

The purpose of the proposed methodology is to solve the thermal fielded that induces stress at specific locations at a specific time. This is the main boundary condition. The other boundary conditions are simple geometric constraints in standard FEA modelling practise. Figure 7 now shows the boundary conditions and a section is added to the text to explain them more clearly.

- Results and discussion section: In order to clarify the meaning, it is suggest replacing "Instrumentation forms..."; "instrumented temperature" ...... "co-inside..." by synonym words or phrases.

Amendments have been made, as suggested of the chosen wording, to paragraph 2 of the results and discussion section on page 8.
Results and discussion section: The information in section of "Results and discussion" is not sufficient to describe the figures shown. It is necessary to discuss and describe figures and results with more technical depth.

The “result” or “outcome” of this paper is the developed methodology of coupling 1D CFD with 3D FEA and the temperature field as now shown in figure 13 forms part of the subsequent fatigue load. Time varying thermal fields is not shown in this paper; although the methodology is developed to fully do so. The results presented are focussed around extracting a single time step from the time varying CFD result and doing the FEA map from a measured high stress time. From the FEA solution the response to the induced thermal field is evaluated, problems identified and mitigations simulated and implemented on the plant. Paragraph 1 of the Results and discussion section has been added to discuss to discuss this.

Results and discussion section. It’s no clear the causes of the unknown event reported at fig. 9. Authors should give an explanation of this event. Temperature trends in Fig. 7 and 8 don’t show any abnormality to cause the even show in fig. 9.

Although some of this information on this event was initially included the authors were instructed that this information is considered confidential by management. Exclusion of this information however does not limit the applicability of the method proposed.

References 2 and 3 should be cited in a proper way, for example Flownex® documentation references should be accompanied by the release version, document book, chapter and page as follow: FLOWNEX® Simulation Software version 8.2.0.1735, 2013, Flownex Library Manual, Heat Transfer, p135.

These references are now cited accordingly on page 12.

Figures: Some figures do not have enough resolution, numbers are not distinguished clearly, and plots could be confused.

Resolutions and colour are updated.

Fig. 4 could be used to provide additional information like failure location and buckstay junction location.

Failure locations are shown in Figure 9. More detail pertaining to layout is now also shown in Figure 1.

Fig. 6. It does not have enough resolution and it is confused, because there is no necessary information. Figure should show clearly where the thermocouple and strain gauge are located.

This figure does show failure location and thermocouple/strain gauge location. Resolution and caption is appropriately updated.
- Figures 7, 8 and 9. Use different color lines and/or symbols to represent the data sets.
  Figures 10 and 11: Enlarge the temperature and stress labels, they are no legible.

Plots are updated in colour and legends are enlarged.
1-Way Fluid Structure Interaction Modelling Methodology for Boiler Tube Fatigue Failure

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Abstract

A modeling methodology developed for dealing with fatigue failures on large boiler tube assemblies, as used by power generation industries, is described. Boiler tube fatigue failures are resultant to a coupled combination of fluid flow and heat transfer mechanisms, inducing thermal expansion leading to fatigue failure. A combination of modelling tools is effectively combined for one-way Fluid Structure Interaction, solving for and extracting stress results efficiently. A One Dimensional fluid solver is used to approximate and model the thermal flow components. The study case considered implemented the developed methodology on a quarter boiler hopper section made up of 3 022 tube and membrane structure with a collective length of 4 787 meters. Operating conditions are iteratively adjusted in the one dimensional pipe flow model until a correlation is formed with instrumented data. This validated model enables further use for various postulated plant conditions and operational sequences through transient start-up conditions. The boiler tube temperatures obtained from the one dimensional model are transferred and used as boundary conditions in a full three dimensional finite element analysis where deformations are solved for and stress results obtained due to thermal expansion within the boiler tube walls and the adjacent support structure. The model is used for redesign of sections of the boiler to reduce stress in those areas and subsequently reduce fatigue failures.

Keywords

Power-Plant Failures, Boiler Failure(s), Boiler Tube, Thermal Fatigue, Finite Element Analysis
1. Introduction

One of the fossil fired power stations in South Africa is experiencing continuous boiler tube fatigue failures in its hopper section of all six units. The hopper forms the bottom part of the boiler where water, coming from the economiser outlet, enters. Failures subsequently lead to unscheduled shutdowns, emergency repairs and subsequent loss of capital. Many of these failures have their root-cause imbedded in the cyclic operation that is followed in order to optimise electricity demand versus production cost of electricity during off peak times. Base load coal-fired plants are designed for consistent operation at full load; however increased fuel costs along with an increased drive towards intermittent renewable generation are encouraging the use of base load plants for cycling duty. With the emphasis of future power being placed on renewable energy it is expected that cyclic operation will become the norm for fossil fuelled power stations in the future. This can lead to component damage and reliability problems. Kumar et al presents a broad overview of power Plant Cycling Costs [1]. This cyclic fatigue load problem is used as a case study where a developed one-way FSI approach is demonstrated.

A complex support beam structure cradles and surrounds the boiler. These horizontal support beams are referred to as buckstay beams. Pivoting attachment mechanisms exist between the support beam structure (buckstays) and the tube wall to allow for thermal expansion while still providing adequate support on all four sides. The boiler can expand up to a meter downwards during a start-up sequence. Buckstays join at corner junction locations of the hopper where the slope walls and front/rear walls joins. They are connected to each other using hinged members referred to as buckstay connection links. These junctions necessitate the rerouting of the surrounding front/rear wall tubes, leading to discontinuities in tube layout. High tube failure rates are identified at these tube manipulations and thus it is identified as possible high stress locations.

Refer to Fig. 1 for corresponding detail of the hopper geometric layout as discussed.

In aid of proving a failure hypothesis, a unique one-way FSI methodology is developed to model and predict the induced fatigue loading during a boiler start-up cycle. Fluid flow and heat transfer is transiently modelled using a 1D pipe flow modelling tool [2] and validated against experimental data. The chosen 1D flow solver used is a thermo-fluid simulations software package used in the industry to predict, design and optimise flow rates, temperatures and heat transfer in fluid systems. The one-way FSI modelling approach allows a transient thermal load, or any user-selected transient step, to be coupled with a 3D FEA [3] where thermal induced stress is solved.

![Fig. 1. Boiler Hopper and Buckstay Support Beam Structure](image-url)
2. Material and methods

One-way FSI coupling between 1D and 3D domains are fairly uncommon although work is ongoing in the bio-medical research field to establish correlations between flow dynamics and arterial diseases, in modelling arterial trees [4], [5] [6]. The described models couples 1D arterial flow with 3D CFD simulations and is based on the continuity at the coupling interface, between a 1D node and a 2D area, in order to solve the 3D CFD domain using a finite volume discretisation scheme. Areas of interest, where the blood vessels pressure distribution is required, are solved for using 3D CFD. Solved arterial vessel wall pressures can then be transferred to an FEA model for structural analysis. This is one form of a geometric multiscale approach.

Investigations using full CFD for boiler combustion and subsequent air flow domains have been done, but these simulations are limited to either a small section of the boiler, containing only a few tubes or with tube detail omitted, and are mostly aimed towards combustion modelling and combustion gas extraction rather than tube life assessment [7] [8] [9] [10]. 3D CFD/FEA coupled simulations for tube flow, although proven successful, has been limited to small domains due to computational expense [11] [12] [13]. A coupled and validated flow and structural simulations of a complete boiler has not yet been done. Recent studies in modelling boiler tube two-phase flow dynamic instabilities, manifesting as density wave oscillations (DWO), have made use of a 1D finite difference flow model [14]. Tubes and membranes are modelled where conduction in tube-membrane structures as well as convective heat transfer through the tube and membrane surfaces exposed to furnace combustion is also accounted for. DWO manifests from the bottom to the top of the boiler facilitating the need to model complete boiler tubes rising up to a distance of 40 meters. A 1D approach for modelling this behaviour is thus favoured.

This paper describes a procedure where 1D flow is used to solve for the entire domain in a similar fashion as done by Kim et al [14], and then coupled directly to 3D FEA without using any 3D CFD interim simulations of smaller areas of interest. The Hopper, as modelled for this study, comprise of 3022 modelled tubes with a combined length of 4787 meters. It is inconceivable that a problem of this magnitude be solved using 3D CFD for internal pipe flow, where the necessity for boundary layer meshes drives up the mesh count drastically. Every tube/membrane is fully modelled in the FEA analysis using a beam shell model of the hopper section. A partitioned one-way FSI solution strategy is followed. This implies that a separate solution is prepared for each individual physics field using two distinct solvers. Bendra et al [15] investigates and describes various possibilities for reducing the computational effort of fluid structure simulations through the implementation of one-way and two-way coupled simulations. The proposed one-way coupling approach, as described in this paper, is highly conducive to boiler thermo-flow problems where the structural field is influenced by the flow field rather than the converse. There exists no need to use a two way coupling approach, although such complexities can be added if needed.

The proposed methodology is developed for aiding the approximation of thermal induced fatigue loads as a result of boiler start-up schedules, operating conditions and sequences. A great number of internally generated metallurgical reports [16] confirm that the failure mechanism is high stress/low cycle fatigue. Refer to Fig. 2 for details pertaining to a failed sample used for metallurgical analysis. This illustration is representative of failures at any of the locations of interest solved, as they all fail as a result of the same mechanism. The metallurgical investigations at all of these failed locations clearly indicate fatigue failure, i.e. induced as a result of cyclic stress. The crack initiation and propagation mechanism is thus deemed to be fatigue related. Oxide dating analysis confirms the crack has existed for approximately three years and four months before the through-wall leak occurred.

A stereo micrograph, as shown in Fig. 3, of the cross section of an etched sample shows the crack to have initiated at the toe of the weld on the tube membrane attachment and then propagated through the tube wall to the inner diameter surface. The investigation revealed that contributory cause for the failure included restrictive designs (welded attachment on the tube) along with the cyclic operation followed.
A boiler is a large-scale heat exchanger where water filled tubes is heated as a result of contained combustion within the enclosure of tube membrane walls. The two separate fluid domains identified is the water filled tubes and the combustion gas domain. It is a dynamic system where various sections of the boiler influence each other, particularly during start-up where water from the economiser enters the hopper and heat transfer takes place as a result of the internally generated heat from coal combustion.

The one-way FSI problem presented is one where two fluid domains exchange heat at non constant rates, causing temperature differentials within the contained structure of the tube walls and hopper support beams, inducing time-varying stress states. The study objective, for which this methodology is developed, is to determine the validity of hypothesised failure mechanisms. This objective is obtained through the development of a 1D to 3D one-way FSI methodology. This is achieved by following a process flow developed, as shown in Fig. 4.
The one-way FSI Computer Aided Engineering (CAE) simulations comprise of a detailed transient 1D thermal flow analysis of a complete sub-cooled boiler hopper quarter symmetry section, at near real-time start-up conditions. The 1D computational domain is shown in Fig. 5. The 1D solver solves the full conservation equations for mass, momentum (compressible and incompressible) and energy. The fluid for the simulation done assumes an incompressible fluid as no steam is present in the hopper tubes. Economiser outlet temperatures obtained from the Distributed Control System (DCS) are utilised as inlet boundary conditions. This includes inlet water temperature, tube mass flow rates and hopper inlet water pressure. Outlet conditions are solved for by the network. Tube temperatures at various locations on the front wall boiler tubes are used for validation of the solved model. Since no data is available for the gas side temperature and heat transfer coefficients, these parameters are iteratively determined in order for the model to resemble the measured plant data. This process, as shown in Fig. 4, describes the inner loop followed by the 1D solver to obtain a validated transient solution.

Once a validated 1D thermal flow model is obtained, a steady state time step is selected, corresponding to peak strain rate changes as observed from the instrumented strain data. The resultant temperature field at this time-step are exported and mapped onto a 3D FEA model in which each tube/membrane is modelled for thermal and structural modelling. The mapping procedure as shown in Fig. 6 involves creating the 1D flow solver line geometry in any appropriate Computer Aided Drafting (CAD) package and exporting it as a pipe component file (*.pcf). This type of file contains beginning and end points of each section of tube as 3D spatial co-ordinates. Once imported into the 1D solver [2] the spatial co-ordinates is automatically appended to as the naming convention of tube nodes. Thermal results along with the nodal names are exported as a text file. As a result special co-ordinate information is appended to a given temperature at any given nodal location and as such is preserved even though 1D solvers do not explicitly represent 3D domains.
This methodology facilitates the examination of various scenarios to the causes of failures without affecting plant operations. It also facilitates the modelling of massive boiler structures that otherwise cannot be solved using 3D CFD simulations. This developed methodology is the only feasible modelling approach taken to capture thermal flow within each individual tube for problems of this magnitude.

The hopper Computer-Aided Engineering (CAE) geometry is created in such a way as to facilitate solution interpolation between the 1D and 3D simulation environments. A conceptual FEA modelling approach is followed where beams and shells are used to approximate the 3D buckstay support structure and tube/membrane walls. Shell elements are conceptually a 2D element that has a surface area, but no through thickness visually displayed. The thickness of these shell elements are handled at a solver level with the appropriate stiffness behaviour enforced. This type of element is suitable for analysing thin to moderately-thick shell structures. It is a four-node element with six degrees of freedom at each node; translations in the x, y, and z directions, and rotations about the x, y, and z-axes. Similarly, beam elements are 2D representations of 3D beams. They have a certain length with a conceptual cross-sectional area. This cross-sectional area provides information relating to the second moment of area (IYY and IZZ) as well as volume, and subsequently mass [3] [16]. Higher order quadratic elements are used, containing mid-side nodes.

The combination of beam and shell elements allows the modelling of large structures and assemblies such as this boiler hopper with an acceptable degree of accuracy without drastically increasing the computational time. Fig. 7 shows an image of a quarter symmetry section of the boiler hopper with the appropriate boundary conditions imposed. The Computational mesh contains 485 984 nodes with a further 250 Multi Point Constraint (MPC) joint elements, modelling connectivity between the tube walls and the buckstay support structure. These elements are defined by two nodes and six degrees of freedom (DOF) at each end for a total of 12 DOF. Some degrees of freedom are fixed depending on the desired representation.

As only the hopper part of the boiler is considered in this simulation, the top tube-ends and top-most support beams are constrained so that they can move in the horizontal plane, but are restricted to move down or upwards. This approximates the condition where the hopper is suspended from above. Along with temperatures interpolated onto the FEA structural model, additional boundary conditions are imposed such as gravity and fluid weight. These will not be expanded upon as they relate to the specific case used for this paper. Since the developed methodology can be utilised for any tube-fin heat exchanger, FEA boundary conditions will be case specific and bares no relevance to the developed methodology.

Fig. 7. 3D FEA shell and beam of a quarter hopper geometry assembly
3. Theory/calculation

The 1D thermal-flow solver solves conservation of mass, momentum and energy to obtain the mass flow, pressure and temperature distributions of fluids and solids throughout the complete hopper tube network. This fundamental approach enables the prediction of complex phenomena such as pressure and temperature waves in hopper tubes and buoyancy effects due to elevation variation of the boiler. It accounts and solves for the flow within each individual tube; convective heat transfer to the boiler tube walls from ambient and fire-side; and conduction along the length of each tube as well as between individual fins and separating tubes. The model does have limitations and does not explicitly solve for the flow of internal boiler combustion gasses, nor ambient external air flow around the outside of the boiler, as a 3D CFD solver would. As such, it cannot calculate combustion-side heat transfer coefficients by itself based on this forced external convection; however, internal flow is handled appropriately.

Convection and radiation are the two main heat transfer mechanisms transferring energy into and out of the boiler tube walls. The two unknown variables that will influence convective heat transfer are the averaged heat transfer coefficient ($h$) and the change in temperature ($\Delta T$), as presented by Newton’s Law of cooling \[18\] and shown in equation (1). These two variables are used to calculate the convective heat flux and are adapted in the model in order to give temperature distribution results similar to that obtained from the measured plant data. Radiation is not explicitly solved for but factored in using a lumped mass approach with the heat flux of the convective component. Various lumped models exist and development is on-going \[19\] \[20\], however these models are not always appropriate nor can they easily be implemented in commercial codes. A spatially averaged heat transfer coefficient, as shown in equation (1), can be defined as $\bar{h}$, where $q$ is the total heat transferred and $A_s$ is the total heat transfer surface area. $T_s$ is the surface temperature and $T_\infty$ is a reference temperature of the lumped fluid/air temperature.

$$\bar{h} = \frac{q}{A_s(\Delta T)}$$
$$\bar{h} = \frac{q}{A_s(T_s - T_\infty)}$$

The average heat transfer coefficient, as stated in equation (1) will include a combination of both convection and radiation effects as described by equation (5). Equations (2) and (3) indicate the heat transfer as a result of convective and radiative components. An assumption is made that convection and radiation are the only two possible modes of heat transfer (equation (4)). As such one can determine the magnitude of the role of each mode of heat transfer. To solve industrial thermal fluid flow problems of this magnitude it not of concern to establish correct radiated and convective heat fluxes, but rather establish an overall heat balance that resembles the plant that can easily be implemented in any commercial code where convection is specified as per equation (1).

$$q_{\text{conv}} = h_s A_s (T_s - T_\infty)$$
$$q_{\text{rad}} = h_r A_r (T_s - T_\infty) = \varepsilon\sigma A (T_s^4 - T_\infty^4)$$

$$q_{\text{total}} = q = q_{\text{conv}} + q_{\text{rad}}$$

$$\bar{h} = \bar{h}_c + \bar{h}_r$$

Averaged heat transfer coefficients $\bar{h}$ are kept unity while the flu gas temperature $T_\infty$, forming part of the $\Delta T$ term as stated in equation (1), is iteratively altered until a good thermodynamic resemblance to measured data is obtained. The resultant, iteratively determined, temperature distribution $T_\infty$ is shown in Fig. 8. This distribution, without intent, resembles a boiler start up cycle where gas, oil and coal burners are activated sequentially over time. These interpretations of the results are based on the heat transfer characteristics that are determined for the model in order to match the measured temperature data.
4. Results and discussion

The resultant outcome of this paper is the developed methodology of coupling 1D CFD with 3D FEA and obtaining a stress field to be used as a fatigue loading condition. The results presented are focussed around identifying a single time step from instrumented strain data where a sudden peak in stress is identified. CFD result correlating to this identified time step is used for subsequent FEA analysis. From the FEA solution the response to the induced thermal field is evaluated. Problems are identified and mitigations strategies simulated and implemented on the plant.

Instrumented temperature is a key component to the developed one-way FSI methodology as instrumented temperature data is used for inputs to the 1D simulation (as obtained from the DCS) as well as model validation (as obtained from thermocouples). A total of 16 thermocouples, locations as shown in Fig. 9, are utilised in this study for validation. Fig. 9 additionally indicates the hopper tube failure locations, indicated by black stars. Instrumented locations correlate with these areas where hopper tube failures occur.

![Ambient Temperature Profile](image)

**Fig. 8.** Calculated ambient temperature profile

Fig. 10 shows a temperature hysteresis during start-up at the three header inlet locations to the front wall tube banks. Fig. 11 shows a temperature hysteresis during start-up for a particular buckstay junction location. The transient 1D pipe thermal flow simulation closely resembles data obtained from instrumentation. The determined values are within reason and give confidence that the model closely resembles the actual plant. Fig. 12 shows a hysteresis of strain at the four instrumented locations where boiler tube failure frequencies are highest. After one hour, a strain change is identified for Strain Gauge 1 only; however, at 3h10min a change in strain is noted for SG1, SG2 and SG4. An unknown event is identified at this time and this steady state time stamp is selected for subsequent steady state one-way FSI coupling to a thermal and structural FEA.
1D Pipe Flow Validation - Header Inlet Locations

Fig. 10. Validation: 1D solver results vs. instrumented thermocouple data

1D Pipe Flow Validation - Buckstay Junction Locations

Fig. 11. Validation: 1D solver results vs. instrumented thermocouple data

Strain Gauge Data

Fig. 12. Instrumented strain gauge data
Results from the 1D simulation include both fluid and thermal flow components. Amongst others, results include inner tube pressures, mass flow rates, velocities, temperature distributions and heat fluxes. These are all solution sets that can be exported and used, not only for the developed structural FEA one-way FSI, but also for any subsequent CAE solution coupling. Fig. 13 shows the resultant solved FEA temperature distribution on the tube walls of the hopper, alongside the solved deformations. It gives an idea of the thermal field across the boiler tube-fin structure and aids as a visual validation to expected thermal gradients. Tubes are expected to get hotter the higher their location within the boiler. This temperature field, although a snapshot for a single time step, is the output of the developed methodology and the mechanism that induces the stress states and subsequently the fatigue driver. Although not explicitly done, time varying thermal results will yield the required loads to perform a myriad of further fatigue calculations at localised areas of interest.

The study objective is to establish, through implementation, a hypothesis to fatigue failure as well as to evaluate them using the developed one-way FSI approach. A prior proposed failure hypothesis is that a column of water, from the economiser outlet, will reach the closest tube bank first, the second bank next and so forth. This would cause a significant fluid temperature differential between the first bank’s outermost tube and the adjacent tube of the second bank, still conveying the previous water column. The results from the developed model indicate that the delay in water supply does not induce perturbing stresses as postulated. This is resultant of the thermal inertia of the tube walls and webbing, which causes a smooth transition in adjacent tube wall temperatures. This can also visually be verified using Fig. 13.

Furthermore the effects of structural support members in the form of welded support plates at the buckstay junction locations are evaluated. The developed methodology facilitates comparisons between two cases considered; firstly where the buckstay sliding joint plates are present and secondly a case where these plates are removed. A contour plots coloured by Maximum Principle Stress at this buckstay junction location is shown in Fig. 14 for both cases where the sliding joint plate is present and removed. This figure shows the improvements the modifications have done to the induced stress. Removal of this plate greatly reduces tube wall stress while structural integrity of the surrounding structure is conserved. The proposed modification has been implemented with initial data indicating a reduction in strain at the damaged locations. Strain data collected over a two year period prior to solution implementation is compared to data collected after. From the time averaged data it is shown that average strain and subsequent stress induced fatigue loads have been reduced by approximately 50%.

The ability to eliminate, through simulation, non-contributors to failure and or identifying potential new failure mechanisms proves to be a powerful engineering tool. The developed one-way FSI methodology proves to be effective where the problem of thermal induced stress fatigue loading as a result of fluid coupled thermal flow needs to be addressed. Obtaining a thermal field from 3D CFD, as used for structural FEA boundary conditions, is near impossible due to the size of these problems considered. 1D to 3D one-way FSI coupling is not only a feasible alternative to 3D/3D CFD/FEA coupling, but proves to be both effective and efficient. This methodology is not limited to
power generation boilers, but can be used in a variety of heat exchangers where tube flow is strongly coupled to structural behaviour of components and systems. Although this paper is more focussed on the development of a fatigue load methodology, a secondary outcome to the developed study is a general engineering fault finding tool for large structures. Without the developed methodology obtaining an accurate and validated temperature field is impossible. More will be elaborated to include the fact that these results have nothing to do with fatigue, but can be used for general engineering fault finding.

Fig. 14. Maximum principle stress at buckstay junction location

5. Conclusion

The methodology presented is a result of the necessity for solving a large complex problem in order to obtain an industrial solution. The complexity of the problem and the need for an alternate approach arises from the scale of the problem that needs to be solved. The primary objective of this paper is to illustrate, through a real case study problem, a developed one-way FSI methodology for coupling 1D thermal pipe flow to 3D FEA in aid of calculating the induced fatigue stress loading in heat exchangers. The secondary objectives are to establish, through implementation, a hypothesis to fatigue failure experienced at one of Eskom’s’ power stations as well as evaluating them using the developed one-way FSI approach.

The thermal-flow, transient 1D pipe model corresponds well with the measured instrumented thermocouple data. Furthermore, the location of the highest induced stress in the boiler hopper corresponds to where tube wall failures occur at the plant. These results yield confidence in the thermal flow modelling approach followed and the subsequent one-way FSI methodology developed. It is proved that the initial hypothesis formed, where a difference in temperature of adjacent front wall tube banks cause thermal induced deformation, is a non-contributor to failures. The maximum temperature differential is calculated to be only 2.2°C. This is as a result of the thermal inertia of tubes and webbing, which causes a smooth transition in adjacent tube wall temperatures. The thermal-flow, transient 1D pipe model corresponds well with the measured instrumented thermocouple data. Based on results obtained structural amendments are implemented and are alleviating high stress in regions where boiler tube failure frequency is highest.

Failures in the plant environment are not as a result of steady state operation but the cycling of the plant, i.e. start up and shutdown. By modelling a large section of the boiler, geometric stress concentrations as well as locally induced stress is taken into consideration. Operating parameters are also taken into account and incorporated into this developed methodology. Transient DCS data is used for the transient 1D flow analysis obtaining a time varying thermal flow field which is in essence the fatigue load. Data from the DCS used are inlet temperatures as well as mass flow (coupled to pressure variations; there are no steam travelling through the boiler walls – only water and thus the incompressible assumption is correct).

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References

Interetek APTECH Sunnyvale, California – NREL; April 2012.
Figure 1

Flow Within 320 Tubes (4,787 meters)

90 Hinged Links (Tube-Wall to Buckstays)
250 Mechanical Joints

8 Hinged Links to Ground

4 Buckstay Linkage beams (Front Wall to Slope Wall)
Boundary Conditions
- Instrumented Temperature Data
- DCS (Distributed Control System)

1D Thermal Fluid Simulation
- Solves Thermal Field
- Solves Pipe Flow

Validation
- Instrumented Temperature Data

3D Thermal/Structural FEA Simulation
- Solves 3D Thermal Field
- Solves 3D Deformations/Stress

Future Validation
- Instrumented Strain Data
Top Tube Ends & Top Buckstays: (X-Y Plane Free; Z-Constraint)

Slope Wall:
Tube Bank Distributors
(Y-Z Plane Free; X-Constraint)

Rear Wall:
Tube Bank Distributors
(X-Y Free; Z-Constraint)
1D Pipe Flow Validation - Buckstay Junction Locations