Modelling mechanisms of **stress and strain**

Professor Zihui Xia is currently developing theoretical models that will enable fundamental and economically relevant advances in bitumen processing equipment and operational procedures. Here, he discusses his research background and some of the important issues surrounding his work

Could you describe your background and where your expertise lie?

I have developed research expertise in elastic and plastic stress and strain analysis and in fatigue life prediction methodology for materials and structures. Previously, I helped to develop advanced plasticity constitutive modelling and fatigue life prediction theory.

What issues do you seek to address with regard to coke drums?

The reliability of coke drums has been a long standing industry problem since the introduction of delayed processing coke drum technology in the 1930s. The oil industry in Alberta has an urgent demand to improve reliability of their coke drum equipment. Through contact and discussion with industrial partners, we initiated our current Natural Science and Engineering Research Council of Canada (NSERC) Cooperative Research Project.

What pressures are the drums exposed to?

Coke drums operate at relatively low pressures of 345 to 700 kPa. If only stress from pressure is considered, then coke drums should work in a safe and reliable operational and design condition. However, through current research, it has been found that the governing stress in delayed coke drums is caused by their severe cyclic thermal loading.

How did you gather data? Is it statistically more robust than previous records?

The industry provides some qualitative data through their trade association but there are no specific data in open literature. The readily available data from facility owners, is of low resolution due to the large expense and difficulty in collecting it. There are only a few facility owners in the world who have managed to collect the necessary data in more detail. To our knowledge, there are only three or four such data collections worldwide.

By presenting our research, we have attracted the attention of facility owners who have begun to share their data with us. A manufacturer of coke drums has provided us with extensive data from an ongoing monitoring programme for one of their clients. The dataset comprises the basic information we need to charecterise the local hot and cold spot damage mechanism, which we have shown is one of the reasons for coke drum failures.

Could you explain the concept of a creep test and its practical application?

When a metal is subjected to a certain level of constant load at a relatively high temperature, strain can increase over time. Such deformation is called creep deformation. The purpose of our creep tests is to verify that creep is not a major damage mechanism for the coke drums.

What are the biggest challenges facing your research and industry partners?

One big challenge is to acquire sufficient temperature datasets for carrying out statistically meaningful analysis of the hot and cold spots effect. It is very costly to retrieve such data since it requires the installation of thermocouples on a very large insulated drum. Although we have found a few sources that possess such a dataset, they are, with exception, reluctant to share details. As mentioned, through the demonstration of our research achievements and cooperative research, we have obtained an actual dataset from a coke drum manufacturer, although, understandably, with restrictions on its disclosure. However, the more datasets we can evaluate, the more robust and meaningful our work will be for industry.

Will you be presenting your findings to the wider scientific community? Why is research dissemination important?

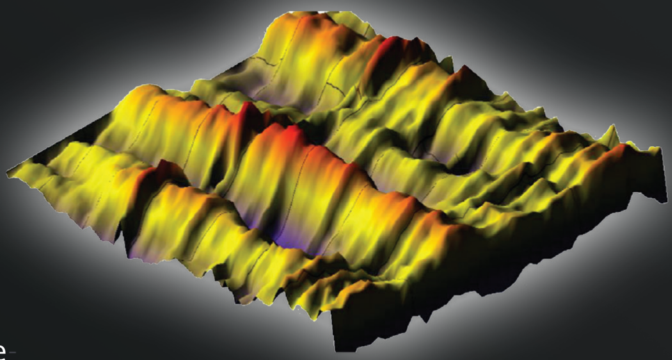
Dissemination is ongoing through the publication of papers in journals and conferences and attendance at industry events. We currently have industry sponsorship and hold regular debriefing sessions on our results.

The goal of the research is to establish the damage mechanism and identify mitigation opportunities in the material selection, design, construction and operation of coke drums so that they operate more reliably in the future. We want to reduce investment and operating costs and improve reliability of these facilities with the current processing technology to improve profitability and equipment reliability and safety in the industry. Freed up capital can then be directed towards other sustainability efforts in the industry.

MODELS DEVELOPED SO FAR

- New thermo-elastic-plastic constitutive model
- Simplified global stress analysis model
- Simplified local stress analysis
- Bree-type deformation phase diagram for coke drums
- Statistical hot and cold spot distribution model
- Statistical fatigue life prediction theory for coke drums

Refining the bitumen industry



Although bitumen has been refined into crude oil and its derivatives for a long time, this process continues to benefit from ongoing technology improvements. Research at the **University of Alberta**, Canada, strives to contribute to these efforts by improving the reliability of crucial industrial equipment

OIL SANDS, TECHNICALLY known as bitumen sands, are naturally occurring deposits of sand, clay and water saturated with bitumen – a semi-solid hydrocarbon resembling tar. These deposits have been used throughout history for a diverse range of purposes including waterproofing and mummification, but more recently they have become a source of petroleum. They can be injected with steam to recover heavy oil or extracted by mining-type operations to separate bitumen and further processed into unconventional crude oil and refined products. Geographically, bitumen deposits are fairly widespread, with the largest known supplies residing in Kazakhstan, Russia and Canada. Canadian reserves account for over 70 per cent of the world's bitumen supply and because of political and economic concerns, along with dwindling conventional supplies of petroleum, its bitumen sands have become a feasible and increasingly important source for the supply of unconventional oil. As with any industrial process, ensuring efficiency and minimising costs at every step is of fundamental concern. Reducing costs will increase profitability and secure the continuing feasibility of using bitumen as a source for crude oil and refined products.

Zihui Xia, together with his industrial partners Suncor Energy and Husky Energy, hope to better understand the factors that affect coke drum longevity

THE PROCESS IN BRIEF

Oil sands can be mined from the surface of the Earth and then processed to extract bitumen and refined to produce unconventional crude oil and its derivative products (*in situ* methods are used when oil sands strata are deeper). The refining process involves extraction; delayed cracking in a coke furnace to produce shorter hydrocarbon chains; separation and removal of excess carbon as petroleum coke in large containers called coke drums; and finally fractionation, which separates different length hydrocarbon chains from one another, leaving products such as naphtha, kerosene and crude oil. Coke drums form a crucial part of the process and are typically operated in pairs – one drum is kept online, while the other is cooled down and opened to allow residual petroleum coke to be cut from the drum with high pressure water.

Coke drums come with a finite lifespan and eventually become irreparably damaged through their prolonged use; bulging and cracking occurs that limits the fatigue life of the vessel. This is controlled by their operating conditions, which involve severe thermal and mechanical cycles, in which operating temperatures of up to 480 °C are followed by quenching with water. Despite many theories as to why coke drums fail, measures taken to improve the service life of coke drums have proven limited. When a coke drum eventually fails, the costs of replacing the drums along with the associated loss of oil production can cost hundreds of millions of dollars. Solving this specific problem would therefore increase operating efficiency and carry huge economic benefits for the Canadian oil industry.

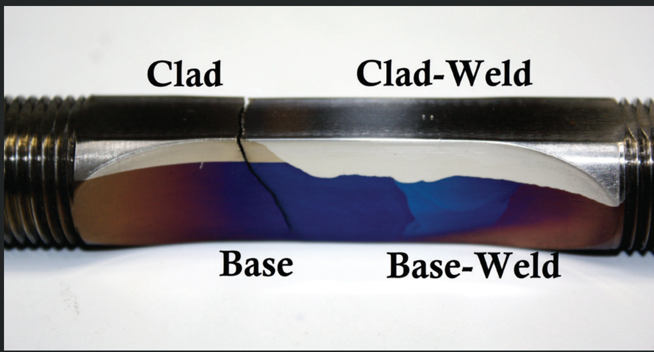
Above: A laser scan of a coke drum showing the bulging topography of the vessel after several cycles of operation.

Left: Thermal-mechanical fatigue test facility in Dr Xia's Lab.

QUANTIFYING THE PROBLEMS

This important issue provides the research topic for Professor Zihui Xia, of the University of Alberta. Together with his industrial partners Suncor Energy and Husky Energy, Xia hopes to better understand the factors that affect coke drum longevity through experimental investigation, the development of theoretical models, finite element method (FEM) numerical simulation and understanding of the factors leading to the initiation and propagation of damage in coke drums. This insight will then be applied to develop improved ways to predict the lifespan of coke drums, while also finding ways to enhance their design. "The first objective of our research is to gain a thorough understanding of the damage mechanisms of the coke drums," Xia explains. "Then a more reliable design methodology including material selection, evaluation of stress and strain history, and assessment of fatigue life and operational procedure can be developed." He also hopes to develop software for engineers and designers to use.

Xia's work has already proven fruitful, demonstrating some important mechanisms that contribute to coke drum failure. The first of these considers the materials used to build coke drums, which consist of two different materials – a base layer that is faced by a corrosion resistant clad layer. Xia's analysis has demonstrated that the selection of clad and base materials has important implications in influencing coke drum lifespan. He has found that coke drums are currently subjected to excessive thermomechanical stress and strain, which arises in the clad layer due to the significant difference in thermal expansion coefficients



Left: Structural specimen containing base, base-weld, clad and clad-weld materials after fatigue test. **Right:** Cylindrical specimen simulating bulging deformation: right, original specimen; left, after thermal-mechanical fatigue test.

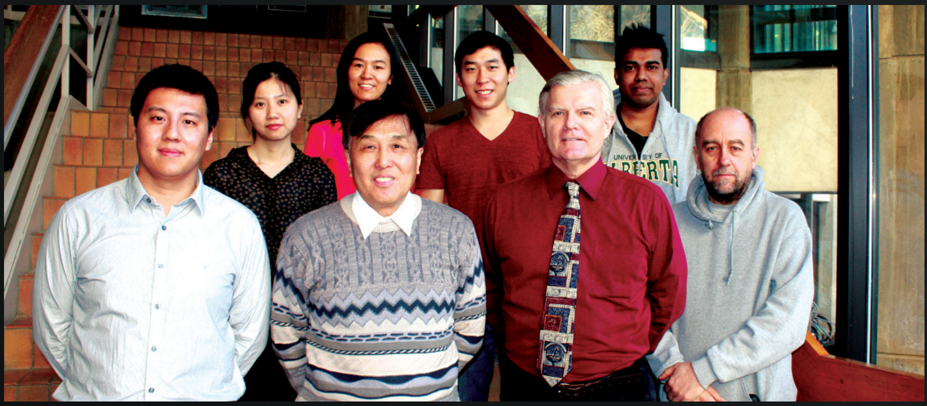
of the two materials. Selection of alternative materials that are more appropriately matched in terms of this coefficient will reduce the strain load imposed on the coke drum as a result.

Xia has also studied the hot and cold spot effect that is known to arise during the cooling and quenching stage of operation. Hot/cold spots arise stochastically due to the irregular filling paths and random flow of water in the residual coke bed during quenching. Through analysis of temperature data of an operational coke drum, Xia has found that damage tends to occur when hot or cold spots occur at the same location multiple times. Since these are associated with an increased mechanical load, as well as the typical bulging damage that is observed in coke drums, this can be problematic and contributes to a reduction in equipment life span. One of the solutions to this problem offered by the researchers is to identify favourable operational procedures and relevant design factors for coke drums to minimise the damaging effects of this phenomenon. Xia has found that operational modifications hold promise to measurably improve the lifespan of existing coke drums. Additionally, conventional design methods do not account for the more problematic localised thermal cyclic loading.

FUTURE CONSIDERATIONS AND IMPACT

This work is ongoing, with completion set for 2015. In terms of future work, Xia hopes to finish developing a statistical fatigue model to predict the life span of coke drums. He can then shift focus towards the practical application of his research contributions, using his findings alongside his industrial partners to improve their drum design, maintenance and operations. In total, Xia has developed six models that allow the analysis and prediction of different features of coke drum damage. These models all consider a wide range of different mechanisms and seek to quantify them. In particular, they are designed to be easy to use for people who work in industry, that is, coke drum designers, operators and engineers. With commercial interest, this software could eventually become a market product.

There are wide implications associated with this work. Not only will it allow the longevity of coke drums to be substantially increased through clever design and adaptive operation, but it may also allow oil sands operators and refiners to increase their output by reducing operational cycle times. This is associated with economic benefits for companies such as Suncor Energy and Husky Energy that will implement such changes, but it should also provide a boost for the wider energy industry. Finally, it has the potential to reduce labour demands through reduced maintenance. Beyond this specific industrial application, it serves as an important contribution to engineering and materials science, satisfying academic curiosity and potentially influencing the design and construction of equipment for use in other applications using clad vessels and piping.



Current coke drum research team at University of Alberta.

INTELLIGENCE

RELIABLE LIFE PREDICTION AND DESIGN METHODOLOGY FOR THERMAL-MECHANICAL FATIGUE OF COKE DRUMS

OBJECTIVES

- To develop a more reliable thermal-mechanical fatigue life prediction and design methodology for the construction of robust and longer life coke drums
- To propose realistic strategies for improving performance and extending service lives of existing coke drums

KEY COLLABORATORS

Suncor Energy Inc.

Husky Energy Inc.

FUNDING

Natural Science and Engineering Research Council of Canada Collaborative R&D – grant no. NSERC CRDPJ 403054-10

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ZIHUI XIA is Professor in the Department of Mechanical Engineering, University of Alberta. He received his PhD from Tsinghua University, Beijing, China. Before immigrating to Canada, Xia worked in a plant as a processing engineer and in a ship research institute as a senior research engineer. Xia's research interests cover a wide range in solid and applied mechanics and material engineering. He has published approximately 150 papers in refereed international journals and conference proceedings.